BUSHWALKERS WILDERNESS RESCUE

BUSHWALKERS WILDERNESS RESCUE is the Rescue Section of
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PREFERRED KNOTS FOR
USE IN CANYONS

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Abstract

On behalf of the Bushwalker's Wilderness Rescue Squad (BWRS) Rock Squad, the author is conducting a series of tests in a voluntary capacity to determine the preferred knots that could be used in recreational canyoning. This paper will be of interest to all abseilers who have to retrieve their ropes. The project is planned for three stages. Stage one is now complete and this paper focuses on the tensile strength and slippage of various knots. Cyclic loading and rope pull down issues have also been investigated. 139 hours of actual testing has been conducted to date. This time does not include the considerable time to plan, analyse and write up the report.

This paper was presented at the Outdoor Recreation Industry Council NSW conference in Sept 2001.

For further information regarding BWRS visit the web site at http://www.bwrs.org.au

Introduction

Recreational canyoning groups are questioning the traditional knots to join tape or rope. It has been argued that the traditional Double Fisherman's Knot (Figure 1-a) to join ropes is very tight to undo after use and often catches on obstacles during rope pull down. The Tape Knot (Figure 1-b) can be difficult to adjust and now some groups have started using unconventional knots such as the Overhand Knot for joining rope or tape (Figure 1-c & d).

There is also evidence that some groups have been using smaller than usual size tape or cord for anchors, in order to reduce cost. This is done on the pretext that their group will only use the anchor sling once and they believe it is strong enough. It is commonly regarded that 50mm flat tape or 25mm tube tape is acceptable for use in anchor slings. The project will explore if smaller size slings could be used, such as flat 25mm or maybe even 19mm polyester tape.

The proposal for this project was outlined in March 2000. This paper discusses tests conducted to determine various knot strengths, slippage and ease of rope pull down for various rope/tape materials.

Literature Review

Existing Information on Ropes, Aging and Knot Strength/Slippage
The author has researched published information on the strength and slippage of knots in rope and webbing. There is significant data on the rated strength of new tape and rope as indicated in

the sample of catalogues and specifications (see references). However only a couple of references have been sighted that provide data on strength of knots tied in Kernmantle rope. Warild (1990 p33&34) provides information on recommended and non-recommended knots showing the static strength and falls taken for each knot. He states "the performance of most knots is variable and depends on many factors, rope diameter, wet or dry, knot packing and to a lesser extent temperature" (p33). He suggests the bulky knots appear to have a clear advantage especially in 8 or 9 mm rope and the Overhand Loop (knot) performs inconsistently. Whilst Warilds' tables are very helpful, the current author has not been able to access the test data on which they were based, and there are no test results for knot slippage. Luebben (1996, p7) also provides some data on the strength of knots, but no supporting references are provided. Long (1993, p54), mentions that the Water (Tape) knot should be checked frequently, as it has the tendency to come untied.

Much testing has been conducted by the international organisation of alpine clubs, Union Internationale des Association d'Alpinisme, (UIAA) on falling climbers and the equipment that breaks their fall. It is important to understand what causes the severity of the fall and so understand what is called a fall factor. Benk & Bram (Edelrid) describe the fall factor (FF) as the proportion of fall and the length of rope run out. The fall factor describes the severity of the fall and determines the load on the entire system. The most serious fall a climber could take in normal circumstances is FF2, that is the length of free fall (say 20m) divided by the length of rope paid out being (say 10 m) therefore 20/10 = 2. This means 10m of rope must absorb the fall energy of a 20 m free fall. Abseilers do not take such extreme shock loads on their equipment. Warild (1990 p 15) argues that the worst fall factor a caver (abseiler) could take if one of the two anchor bolts snapped would only be FF0.6. The probability of a FF0.6 fall is extremely low and the most abseilers should ever expect for a well rigged rope is FF0.3. Warild states the most convincing evidence that caving (static) ropes are strong enough is the complete lack of accidents due to ropes failing under shock loads from caving (or abseiling in canyons).

Warild (1990, p 17) mentions ropes could be damaged by mechanical deterioration by 10 FF0.1 minor shock loads, caused by prusiking or rough abseiling and suggests this is an avenue for investigation. One of the future tests in Stage 2 will explore this issue, as old ropes (that are too stiff to abseil on) are often used as back up anchor ropes.

Polyamide static ropes used for canyoning can be old. There is no "use by date" based only on age. The Blue Water Technical Manual (2001) provides information on when to retire your static rope, such as damage from sharp edges, glazing from fast abseils or soft hollow or lumpy sections in the rope. Replacement is based on wear and tear. Age is not mentioned as a limiting criteria. What has been observed for ropes over 10 years old is that they often become too stiff to handle and abseil on. This is due to the mantle shrinking and so becomes less pliable. Blue Water recommends the shelf life for one of their unused dynamic ropes as five years. Blue Water admits there is no conclusive evidence from nylon manufacturers regarding aging of unused ropes. Warild argues on p 17 that age does affect used ropes and gives data for a 4.5 year old 9mm BWII rope that indicates it can only withstand four FF1 falls, where a new rope can take 41 such shocks. AS4142.3 (1993) requires new 11mm static ropes used for rescue to withstand two FF2 falls. Provided the abseiler does not intentionally shock load the rope the way a climber could, age is not an issue, as polyamide static ropes can withstand some shock loading. Even with the worst normal abseiling shock load of FF0.6 the old rope should survive one such shock load, as Warilds tests indicated the 4.5 year old rope could withstand four of the higher FF1 falls. It appears aging affects a ropes ability to survive shock. The five-year rule only apples to dynamic ropes as they are designed for high shock loads. Static ropes are not required to be condemned when they reach five years old as they are not intended to take high shock loads.

Many rope manufacturers treat their rope with a "dry treatment". This involves coating the nylon fibres of the rope with either silicon or teflon. Details on the process are difficult to obtain from manufacturers. This process is done so the rope will absorb less water when wet and therefore maintain its strength. Warild (1990, p16) discusses that water absorption in nylon rope makes it less abrasion resistant and reducing its static and shock strength by up to 30%. Some of the Edelrid ropes tested in this study were "dry" treated.

For natural laid fibre rope Marks Engineering Handbook (1987, p88) states that the shorter the bend in standing rope, the weaker the knot (based on Millers experiments 1900). However it appears to be a different story for nylon ropes. A report (the author wishes to remain anonymous), discovered that knots in Kernmantle (polyamide) rope failed at the point of maximum compression due to the knot compressing one strand of the rope sufficiently that the heat generated by friction caused the strand to become plastic and then fail.

Petzl (2000) (an outdoor gear manufacturer) provides some information on alternative knots on their web page technical manual, such as recommending the Abnormal Figure 8 Knot to join two abseil ropes together. There is no supporting data for this recommendation. There is also useful data at this web site for UIAA limits and design criteria, such as that harnesses should not be loaded to more than 15kN.

Delaney (2000) from the Australian School of Mountaineering states he is not aware of any testing of aged tape and rope as typically found in canyons and suggests there is only limited information on knot slippage, but he could not provide any supporting test data.

Manufacturer's Rated Strength
The rated strength given by the product manufacturer is the minimum strength that the material will fail at, normally given in kilonewtons (kN). Most of the older equipment was rated in kilograms force (kg).

To convert to kg, multiply by 1000 (newtons) then divide by 10 (gravity rounded up).
For example; a karabiner is marked as 22kN. 22kN x 1000 = 22000(N) /10 = 2200 kg. A quick simple rule is just multiply kN by 100 to get kg.

Adequate testing of the product has been conducted by the manufacturer to determine the mean breaking strength. Therefore the minimum or "rated" breaking strength can be determined. US and European companies that have extensive production undertake comprehensive testing of large samples from many batches. Therefore an accurate statistical figure can be determined. Some products like karabiners have a "Sigma 3" rating which is three standard deviations back from the mean. However many overseas companies only use two standard deviations back from the mean for rope and tape products.

To explain standard deviations (std dev), Freund (1988 p76) defines for the results that create a normal (bell shaped) distribution as follows:
>About 68% of the values will lie within one standard deviation of the mean, hence about 16% are outside the 1 std dev on the low side.
>About 95% of the values will lie within two standard deviation of the mean, hence only about 2.5% are outside the 2 std devs on the low side.
>99.7% values will lie within three standard deviation of the mean, hence only about 0.15% are outside the 3 std devs on the low side.

Some Aust/NZ rope/tape manufacturers do not use statistical calculations to determine their rated strength for the materials used in this study. Toomer (2000) has clarified that the rated

strength used by Australian rope manufactures is based on a number of batch tests, using the lowest breaking specimen. Usually the rated strength is rounded down to the nearest 100 kg. Small (2000) from Donaghys Industries (a New Zealand webbing manufacturer) stated the webbing (WPM25-OPG63 &WPM50-OA900) tested in this project is uncertified. The only testing conducted by the company on these products were by random sample and the "rated" load stated in the specification sheet is based on the minimum strength from the random testing. The random sample is based on three specimens from the end of a batch run. Batches were only tested when the company had altered a part of the manufacturing process or for some other reason. No statistical methods are employed to determine the minimum break load for random sample tests.

Working Load Limit
The working load limit (WLL), sometimes referred to as the safe working load, is the maximum static load that should be applied to a rated piece of equipment. Dividing the rated strength by the Safety Factor (SF) will give the WLL for that piece of equipment. Our example of a karabiner rated at 2200kg divided by SF5 for hardware will give a 440kg WLL.

Understanding Safety Factors
Most rope and hardware manufacturers give their product a rated strength. To determine the WLL a Safety Factor (SF) is used. Jensen (1974) describes safety factor as the ratio of ultimate stress (rated strength) to allowable stress (WLL). The safety factor is based on a number of considerations including risk to human life, wear and tear of the product, aging and the type of loading that may be encountered. To understand how SFs are determined, he gives examples ranging from 2 to 10 depending on the machine and application. Engineers have agreed that 5 is acceptable for lifting loads involving humans. SF5 has been adopted as the SF used for abseiling equipment hardware. Bateman & Toomer's (1990) Australian Lightweight Vertical Rescue Instructors (ALVRI) verbal advice during the course as recorded by the author, discuss that SF5 is acceptable for hardware, however rope and tape must include a factor to account for loss of strength due to the knot.

ALVRI use a strength loss of one-third (33%) for any knot used in rescue. That is 0.67 strength remaining in the rope. The original rope strength with no knot is divided by the strength remaining due to knot of 0.67. This gives a ratio of 1.49. Multiplying the SF5 by this ratio of
1.43 will give a figure of 7.46. This figure has been rounded up to give SF8.

Based on this rationale, AS 4142.3 (1993), notes the SF as not less than 8 is considered appropriate. It is noted that the American Blue Water (2000) catalogue use the US Fire department's SF15.

An appropriate SF is important. An excessive SF may add a significant weight or volume penalty to the equipment you have to carry if you wish to maintain the existing WLLs. A SF that is too low may lead to equipment failure with possible loss of life.

What else needs to be done?
From the literature review it is clear there is still a lot to learn about knot strength and slippage in rope and tape. The tests conducted in this study provide further data on these issues however are not exhaustive. Such a study would require access to research databases covering strength of rope materials to determine the extent of research already conducted on this subject and how best to build on this knowledge.

Project Design
This project aimed to determine the best possible knot for joining ropes and slings together in a canyon. A useful side benefit was to identify any hazards evident in alternative knots. A process

of elimination determined the preferred knots. The knots being considered were eliminated in a step by step process based on the results from tests of A to E (listed below). The preferred knot (for each application) is the one that has the best results and has not been disregarded due to a safety issue.

The first stage of the process examined the static forces involved. The definition of "static" in this case, is load not subjected to dynamic forces.

Objectives: Stage One
A.   To determine the tensile strength and slippage of standard knots in slings.
B.   To determine the tensile strength and slippage of alternative knots that could be used to join tape and rope.
C.   To determine the tensile strength of certain single strand ropes without knots.
D.   To determine if knots used to join slings or ropes slip under normal (cyclic) loading.
E.   To determine the ease of double rope pull down using various rope joining knots.

Section A is used as a baseline for the strength of standard knots. Section B compares the strength of the alternative knots to Section A. Section C attempted to confirm the strength of the rope/tape used in Sections A and B, without the influence of the knot on rope strength. Any knots that were found unsafe after completion of Sections A to C were deleted from the remainder of the tests. Sections D and E are the final set of tests to examine the preferred knots for canyon use.

A further two stages of the project are planned to consider the shock forces and aging process. More information on these topics is provided under "Further Research" latter in this paper.

Method

Testing Requirements
In order to maintain repeatability, reliability and validity of the tests the author has referred to appropriate Australian standards. No standard could be found that gave a procedure for tensile testing of endless loops, therefore the author has adopted the philosophy of AS 4143.1(1993) for endless loop tests and has described the procedures followed in a later section of this paper.

For single strand rope testing AS 4143.1 (1993) is directly applicable and requires a gauge length of one metre (the distance between bollards) at the required pre-tensioned load. This indicates a test bed with a stroke of two to three metres would be required. Toomer (2000) from Spelean (an Australian rope manufacturer) indicated that the one metre length is important in order to have enough material between the gauge lengths when compared with the material wrapped around the bollards. The machines that the author had access to only had a maximum stroke of one metre. In an attempt to solve this problem the author noted that in AS 2001.2.3 (1988) which is one of the standards for testing seat belts, the procedure only required a gauge length of 200mm. For this reason single strand tests using a gauge length of only 200mm were attempted.

There are no standards for conducting the cyclic and rope pull down tests in this project. Again the author has described the procedures followed in a later section of this paper.

Clem (2000) (former chairman of the Life Safety Section of the Cordage Institute, USA) provided useful advice on the testing requirements for tensile and dynamic testing of knots. His findings indicate apart from obvious criteria such as rope material and diameter, that more subjective issues can come into play. These include which side the tail comes out of the knot. ie if the knot is tied right or left hand. The author has noted these concerns and attempts have been

made to record any unusual events during the tests by video recording a number of the tests and taking individual notes on test records. Clem advises the absolute minimum size of the sample would be six specimens of the same material. It is acknowledged that the sample should be larger, however due to resource constraints the author has chosen six specimens per sample based on Clem's advice. Although a sample of six is less than ideal, AS 4143.1 (1993) only requires a report based on two successful test specimens. Therefore the authors sample is three times greater than the relevant standard requires.

Units used.
The metric system of measurement has been used for this study.

> Length measurements: millimetres (mm) are used for measurement up to one metre and metres (m) for measurements greater than one metre.

> Force measurement: kilonewtons (kN) have been used for the tensile tests. For the cyclic and rope pull down tests kilograms (kg) were used. As manufacturers rate their equipment in kN it was decided the tensile tests would remain in that unit. Although Force (Newtons) equals mass (kg) times gravity, it was decided for the other tests that simulated the weight of people and arm strength required to pull ropes down, it would be simpler to express the results of measurements as kg mass units.

The Tests of stage One
A. Tensile Strength and Slippage of Standard Knots in Slings
A tensile test machine was used to test the rated strength of new tape and old rope made up into an endless sling by a knot. The slings were tested to failure. The joining knots were the Tape Knot for tape and the Double Fisherman's Knot for rope.

B. Tensile Strength and slippage of Alternative Knots in Slings
A tensile test machine was used to test the rated strength of alternative knots in tape and rope made up into endless slings.

C. Single Strand Tensile Strength
Single strand of rope is the terminology used by rope manufacturers to describe a single length of rope, it is not a single fibre of rope. The testing conducted in A & B was for endless slings, the rating given in the manufacturer's specification was doubled as a consequence. The doubled rating was compared to the second standard deviation back from the mean breaking strength from each sample. This is not ideal due to statistical differences in the size of the two samples being compared. To produce accurate values of strength loss due to a knot from the knot tests conducted in A& B, additional tests were conducted without a knot for the same material. This would make it possible to compare the results to determine a true strength loss due to a knot. Single strand tests are required for this. It is also reasonable to compare the breaking strength of the aged material without a knot to the rated strength to determine the strength loss due to age of the material.

D. Knot Slippage caused by Cyclic Loading
Knot slippage under cyclic loading may be a more serious problem than slipping under a constant load. Repeated predetermined loads were placed on the tape or rope slings. The knots were measured for any slippage after each load application.

E. Canyon Rope Pull Down
In canyon abseils a double rope is slung around the anchor point and one end is pulled down to retrieve the rope after use. Tests were conducted to measure the force to pull a knot joining two ropes over various edges.

Knots Selected for Testing

There are many knots capable of tying rope or tape together. A knot used in a canyon environment must be safe. Safety in this context can be broken down into four sub headings. 3 & 4 are considered safety issues due to the extra time to correct problems.
1. Acceptable strength and slippage
2. Easy to check
3. Easy to tie and untie
4. Suitable for the intended application. That is, the knot won't catch on an edge during pull down. These criteria were used to select the
knots.

The following knots may meet the criteria. The project plan aimed to determine which knots met all of the above criteria.

(a) Double Fisherman's Knot in rope (b) Tape Knot in tape
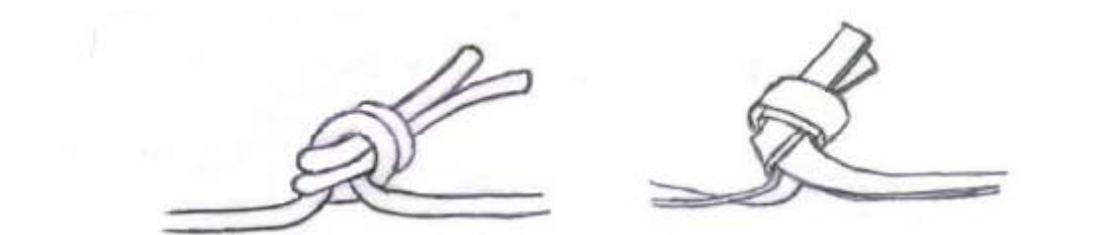
(c) Overhand Knot in rope (d) Overhand Knot in tape
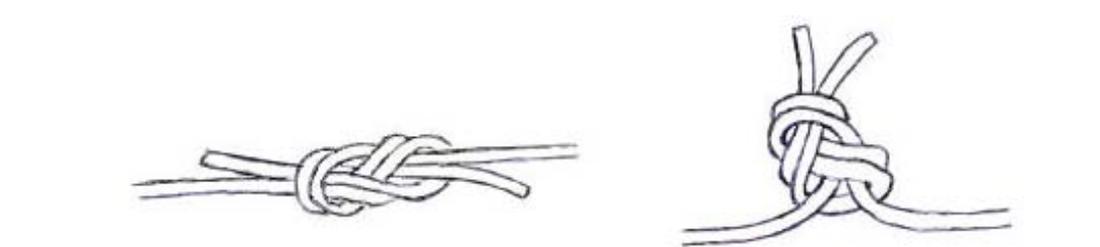
(e) Rethreaded Figure Eight Knot (f) Abnormal Figure Eight Knot

(g) Alpine Butterfly Knot (to tie ropes together)
Figure 1

Where applicable the knots were tied right-handed. There is an exception for one of the Overhand Knot pull down tests that also included a left-handed knot.

The Single Fisherman's and Bowline to join ropes together were considered inappropriate due to known slippage issues. The Rethreaded Overhand knot (a Tape Knot for rope) did not have any obvious advantage over a Double Fisherman's and so was not considered. Obviously dangerous knots such as the Reef Knot or various slip knots were dismissed.

Other knots such as the Reef Knot backed up with a Double Fisherman's Knot and also the Double Fisherman's Knot to tie tape were eliminated before the testing began. The Reef backed up with a double fisherman's has been used by some groups to overcome the issue of the Double Fisherman's Knot being too tight to undo after use. It is considered this knot is too complicated and would be even more difficult due to its size to pull over a hard edge in rope pull down tests.

The author has heard of parties tying anchor tape with a Double fisherman's knot. It is assumed they consider this knot "fool proof" regarding slippage, however this knot uses a large amount of tape to tie and most canyoners do not distrust the Tape Knot enough to use this alternative knot. Therefore the author has decided not to test this knot.

Materials, Knot Packing, Preparation & Conditioning

Materials defined as new were purchased for the testing and were unused at the time of testing. Due to difficulties in accessing retailers purchase records, no attempt was made to determine the time lapse between actual manufacture date and purchase date. The actual manufacture date was not printed on the tape reels. Dates of known ropes/tape of known age are based on the purchase date.

Old rope is considered acceptable to use in these tests as this rope is sometimes used as canyon slings and always used as abseil ropes. A new rope can only be used new once! Variables were kept to a minimum to improve repeatability such as:
      -Knowing the brand and age of the rope.
      -Ensuring the 6 specimens per test are cut from the same piece of rope.
      -Checking that any core or mantle damage is within the ALVRI guidelines.

Testing of some Sisal rope has been conducted, as canyoners may use this rope as slings in rarely visited canyons. This is done on environmental grounds, as it is believed sisal rope will rot and break down faster than nylon rope/tape when left in a canyon.

The material to be tested was formed into a sling (endless loop) by a joining knot. Figure 2 details the naming convention of the knot. The "Tails" are the rope/tape knot tail ends and the "Tension" is the section of rope/tape that form the sling.
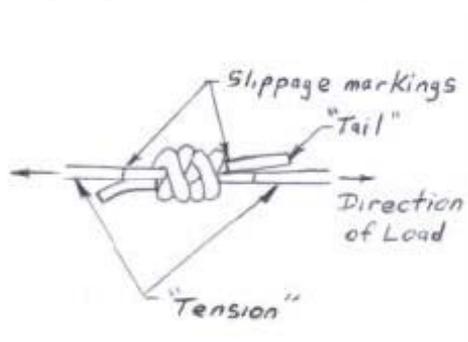

Figure 2   Knot Definitions

All knots in tape and rope were packed according to ALVRI guidelines. The guidelines recommend there shall be no cross overs in any part of the lay of the knot and the knot shall be pulled hand tight on each protruding section out of the knot to remove any rope slackness in the knot. The tails should be long enough to tie a thumb knot. When these procedures are followed, the knot should look neat in appearance and should not have any unnecessary slippage occurring under normal load.

Although the length of a sling does not influence the load at which it will break, the author considered it would still be useful to standardise sling length. This was achieved by the use of a bollard jig for each machine. Due to the physical dimensions of each machine a standard size sling was not possible for this stage of the project. The CIT machine sling length was 380 □15mm. The ADFA machine sling length was 255 □15mm.

Conditioning of dry samples to AS 4143.1 (1993) requires a standard atmosphere of 20 □2 $^{\circ}$C and a relative humidity of 65 □2%. Whilst not all testing was conducted in an air conditioned facility, the temperature and relative humidity were monitored and testing was postponed if the relative humidity rose above 70% or the air temperature was less than 15 or greater than 30°C

Conditioning for the tensile test wet samples was in water between 14 and 17°C, for a duration of between 45 to 60 minutes which is considered appropriate to simulate a rope in a waterfall whilst people are abseiling. For the tensile tests refer to Annex B Sheet 2 to determine which wet samples were dry treated.

For the cyclic tests the rope/tape samples were not "dry" treated. Wet test specimens were tied into slings whilst dry, then placed into a bucket of cold water for approximately 10 minutes before the test. As each set of tests took 3 hours to conduct, cold water was poured onto the 6th and 10th cycle to prevent drying out. Dry tests were only conducted when the relative humidity was less then 67%, due to humidity possibly affecting the results by moisture tightening the knot and thus reducing slippage.

Equipment

Tensile Testing Machines
Two tensile testing machines were used to conduct the tensile tests. One is located at the Mechanical Test Laboratory; Bruce Canberra Institute of Technology (CIT) (ACT). The other is at the Civil Engineering Test Laboratory - Australian Defence Force Academy (ADFA) (ACT).

Bruce CIT The machine at Bruce CIT (Figure 3-a&b) is a Shimadzu universal tensile testing machine, rated to 25 tonne and is currently certified by the National Association of Testing Authorities (NATA) as a Class A machine for all loads in range. This machine can produce load elongation graphs, unfortunately they can not be scaled and are only to be used as a guide. On this machine the gauge length was measured between the cross heads on the machine. The author worked in collaboration with the technical officer responsible for the operation of the machine. The CIT laboratory is maintained to the necessary temperature and humidity requirements.

(a) The CIT tensile testing machine cross heads (b) Dial controls (The rope is to hold the pipe bollards in place when the specimen breaks)

Figure 3 Unfortunately the stroke of this machine was only 300mm. Due to the elongation of the material the machine often required a reset before the material broke (in some cases 2 or 3 times). This practice involved the hydraulic rams being reset whilst attempting the keep the cross heads in the current position. The specimen was unloaded about 10 to 20% for each reset. Fortunately nearly all specimens could have the elongation measured at 3.67kN before a reset was required. The author has been reassured this practice does not affect the accuracy of the final breaking load, however it did affect the measurement of elongation at failure. The reset issue was the primary reason why access to another tensile machine was sought.

ADFA The machine at ADFA was used to conduct the remainder of the tensile tests that could not be conducted using the Bruce CIT machine. This machine (Figure 4-a) is an Autograph tensile testing machine, rated to 10 tonne with a stroke of 950mm. It can be fitted with special bollards that are designed to minimise bollard stress concentration. For sling tests the 65mm outside diameter bollards (Figure 4-b) (which are free to rotate) have a 10mm machined radius to cradle the rope. The gauge length was measured between the bollard centres. For single strand tests the 65mm outside diameter fixed bollards (Figure 4-c) have a 10mm machined radius spiral into the bollard to cradle the rope for the required three wrap turns. This machine can produce scaled load elongation graphs. The machine has been certified by NATA as a Class A machine for all loads in range. Although not currently certified, the author has witnessed that the machine has been verified to within an accuracy of 100N to the requirements of the NATA certificate. The ADFA Lab is air-conditioned, but a roller door (located 20m away) to the outside was often open, which may have affected humidity.

(a) The ADFA Tensile Testing Machine   (b) Sling bollard   (c) Single strand bollard Figure 4

Knot Cyclic Testing Rig

A rig has been built to simulate the cyclic loads that occur when a rope is abseiled on, several times. The rig was set up to measure any slippage in knots caused by this type of cyclic loading. A sling tied with the knot to be tested was suspended from an overhead structure.(Figure 5-a) Each knot was marked so any slippage in the tail or out of the sling could be measured. Measurements were taken in the unloaded condition. Either 50 or 100kg of weight were hung from the sling. Any slippage was measured when the sling was loaded (Figure 5-b). The sling was then unloaded using appropriate mechanical advantage, and was shaken for five seconds to simulate possible knot loosening by wind or handling by an abseiler. The sling was then reloaded and another set of measurements taken. This process was repeated 15 times. The Figure of 15 was considered appropriate for a maximum number of people likely to be abseiling the pitch.

(a)   (b)

(a) The cyclic testing rig showing the sling, the weight and the rope mechanical advantage for lifting the weight.
(b) Sling tape showing the slippage marks on the "Tension" side.

Figure 5

Rope Pull Down Friction Measurement Rig

Any one who has been canyoning will know how varied the required force to pull down abseil ropes can be. Force can range from one hand for a 5m drop through to three people hanging off the rope under a waterfall to slowly move it down past 50m of friction points. Due to all the possible variables it was decided one standard cliff site would be used. Trial tests at Wee Jasper indicated a 15m cliff was acceptable to provide the required friction within the spring balance range.

Two sets of tests were planned using a natural and an artificial 90° hard edge for both dry and wet conditions. The first waterfall on Bungonia creek was selected as a good site to conduct the tests.

The 9mm static ropes used in this series of tests had no dry treatment applied.

Permission was gained from the Bungonia NPWS ranger to conduct a BWRS Rock Squad testing day held at the first waterfall in Bungonia Creek. The cliff edge consisting of volcanic quartz has two points of contact for the rope with the edges at 25° and 20° off vertical. The anchor sling was angled at 40° above horizontal. The natural edge does not have a problem with excessive friction. As can be seen from Figure 6-a, a V shape groove could catch certain knots. There was a ledge 12.5m from the top edge to take load measurements from.

Two knot pull down tests were conducted, one on the natural cliff edge and for the second a Bessa block was used for the hard edge tests. Unfortunately the Bessa block could not be

secured sufficiently to prevent movement, therefore the hard edge tests were invalid. Lack of time prevented the wet tests from being conducted.
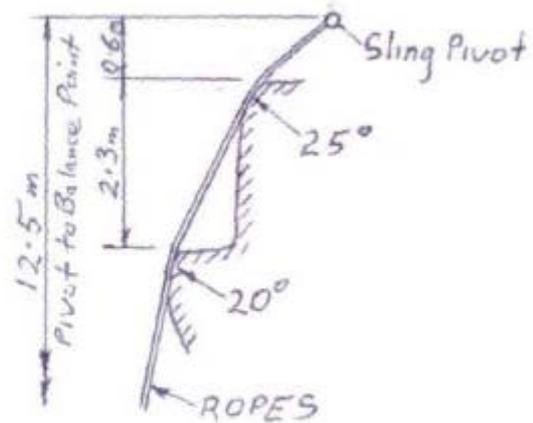
(a) The Bungonia cliff detailing the knot going (b) Profile of the Bungonia cliff edge.
over the 25° edge Figure 6

In order to complete valid hard edge tests, the authors garage roof (Figure 7-a) was selected. The roof is 2.7m high and 2x4m lengths of 9mm static ropes tied together with the knot to be tested were used. A concrete Bessa block was secured so it would not move under rope loads. A second block was used to position the anchor pivot point. The tests were standardised by using the block in the same position for all tests. A Spring balance has been used to measure the force required to start moving the knot over a 90° reverse edge and going over the 90° obtuse edge. Significant friction within the measurement range of the spring balance was obtained without the need to simulate the weight of hanging rope. Trial tests determined that the 1.5kg weights (to simulate 25m of free hanging rope) on each rope end were not required due to the 45kg spring balance exceeding its limit.
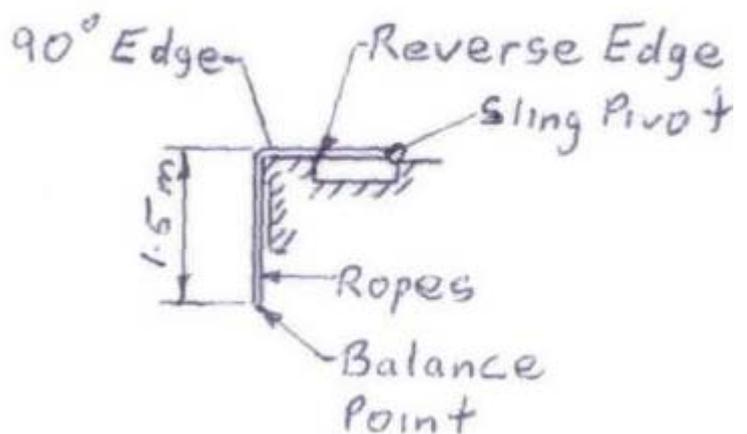
(a) The author using a spring balance to measure the load (b) The profile of the edges used for
when pulling a knot over a 90° edge at his garage. the garage Figure 7

The rate of travel used in this series of tests was determined to be approximately 2 seconds per metre of rope pulled, ie 0.5m/s. This rate of travel was considered appropriate in order to read

the spring scales. In actual canyon rope pull down situations the rate of travel of a person pulling down the ropes may be twice the speed for small pitches. There was evidence that fast rope pull downs sometimes required less load to pass over the edge. Unfortunately trial tests determined it was not possible to measure the load on the spring balance in the fast rope pull down tests, therefore the results obtained may be conservative.

The hard edge (Figure 7-b) is considered one of the harshest edges that could be encountered so it is a good edge to test the knots being examined. For the wet tests a garden hose was used to continually spray water over the Bessa block.

Loads & Test Weights
In simulating the loads that could be applied in canyoning, the load of two people abseiling at once on a double rope (twin person or assisted abseiling) is used, as this load is the heaviest load that should be applied in the recreational activity of canyoning. ALVRI use a standard weight of 100kg for one person. Therefore the load of 200kg (1.96kN) is used to simulate two people on the abseil rope. The 200kg weight should be the WLL of ropes and tape used for canyon abseiling.

AS 4142.3 (1993) states 3.67kN (375kg) is the WLL for a rescue rope. Collecting strength and slippage data at this load will be of use to the rescue community.

Slippage measurements have been recorded when the tensile test machine reached a load of 1.96kN and 3.67kN. A final set of records have been taken when the test specimens failed. Load verses elongation graphs have been produced by the tensile test machines.

For the Cyclic Loading tests, the aim was to determine if greater slippage at the knot would occur by the repeated application of a lighter load when compared to a standard 200 kg load applied only once. A load of 50kg representing a teenager and a load of 100kg representing an adult has been used in this series of tests. The cyclic loading test weights are made up of a cluster of calibrated 10kg and 20kg weights provided by Bruce CIT.

Test Apparatus and Measurement Equipment
The tensile test machines were pretensioned, as required by AS4143.1 (1993). For each 9mm rope and tape specimen pretensioning was set at 0.1kN. For 11mm rope specimens the setting was 0.15kN. With the specimen pretensioned between the bollards of the tensile test machine, the gauge mark length was measured with a tape measure. This was the zero load measurement. The gauge length is defined as a mark on each bollard structure to which measurements were taken to determine sling elongation. Elongation measurements were taken at zero load, 1.96 kN (200 kg), 3.6 kN (375 kg) and failure.

The tensile test machines crosshead rate of travel was set at 40mm per minute.

All tensile tests had the knot positioned mid away on the sling between the bollards. Refer to Figure 4-a, photograph of the ADFA machine that shows a typical sling set up.

Vernier callipers were used to measure knot slippage. The specimens were marked at the four protrusions from the knot with a suitable contrasting coloured pen (that would not affect the strength of the material). The tail lengths were measured at zero load, as it was expected the tails would shorten and the marks would move within the knot. Tail lengths were then measured at each predetermined load. The mean "Tail" slippage could then be calculated. The "Tension" slippage data provided is the summation of the two measurements taken between the mark and the knot. Measurements were taken at each predetermined load by stopping the tensile testing machine long enough to record the dimensions. Care was taken to place the vernier callipers on

the same section of the test specimens for all the readings. Accuracy is believed to be within □1 mm.

A spirit level, adjustable protractor and a 30m tape measure were carried into the Bungonia waterfall site to survey the cliff edge (Figure 6b). A Bessa block was carried in (and out) for the hard edge tests.

Two spring balance scales rated to either 25kg or 45kg were available for the rope pull down tests. If loads were higher than 25kg then the 45kg scale was used. The load on the scale was noted as the knot moved each time. Reading accuracy was assessed to be within □1kg using this method. The 25kg spring balance was calibrated using test weights of 5kg 10kg & 20kg and was found to be accurate. The 45kg spring balance was calibrated using test weights of 5kg, 10kg, 20kg, 30kg & 40kg and found to require a correction for accuracy. A correcting factor has been applied to the results of the 45kg spring balance readings.

Results

Refer to the Annexes A to E for tables and graphs of the results of this study. Annex C is not used as this series of tests was not successful.

Discussion

The knot strength losses quoted in this report are for percentage strength loss due to a knot compared to the rope strength. Manufacturers tend to provide rated strength as percentage remaining in the material. Annexes A&B also tabulate the strength data as percentage strength remaining in the rope for reference only.

Statistical data is given for strength data to determine the lowest breaking strength based on 2 standard deviations (std devs) back from the mean. 2 std dev was chosen as the sample was too small for 3 std devs to give a meaningful number. Additional most overseas manufacturers use 2 std devs for their ratings.

The ramifications of relatively small samples and the approach to comparisons means there is some statistical uncertainty. It is therefore not possible to state the values for knot strength in absolute terms. However, the strength data provided can be used as a general guide.

Slippage data discussed in the paper is at the abseil working load of 1.96kN. The slippage data provided in Annex A & B is given at the loads of 1.96kN (200kg), 3.67kN (375kg) and failure. The slippage data is a guide only. Standard deviation calculations were completed for these measurements but have not been reported. There was significant scatter from the mean (up to 30%) and it is believed the sample would have to be much greater to provide conclusive statements about rope/tape slippage.

The slippage data presented in Annex A & B for the1.96 and 3,67kN loads could not be obtained for some materials when using the CIT machine. This was due to the large cross heads obstructing access to the specimens. Refer to Figure 3 (a) for a photograph of the cross heads.

The remaining factor of safety of the material is determined relative to a 1.96kN (200kg) load. Dividing the knot's 2 std dev breaking strength back from the mean by the 1.96kN load derives this safety factor. The equation for this is SF=(Mean breaking load –2 std devs)/Abseil WLL

For this case the breaking load includes the weakness of the knot. Therefore an additional knot factor is not included in this safety factor. As a result of this logic, the safety factor for any material should always be greater than 5. (SF5 is for loads involving humans)

Knot	Age & Material	Results Sling Breaking Strength 2 Std Dev back from Mean (kN)	Mean "Tail" slippage at 1.96 kN (mm)	Total "Tension" slippage at 1.96 kN (mm)	Analysis Loss of Strength due to knot
Tape	New 50mm flat tape	24.64	Not recorded	Not recorded	52%
Tape	New 25mm tube tape	21.52	Not recorded	Not recorded	42%
Double Fisherman's	1 year old 11mm static rope	36.43	5	48	42%
Rethreaded Figure 8	1 year old 11mm static rope	30.11	1	45	52%
Overhand	new 50 mm flat tape	17.94	25	Not recorded	65%
Overhand	1 year old 11mm static rope	22.05	12	51	65%
Abnormal Fig 8	15 year old 11mm static rope	24.10	16	203	62%
Alpine Butterfly	1 year old 11mm static rope	29.97	14	54	52%

Table 1
Summary of Strength Loss due to Knot & Slippage
For detailed information refer to Annex A & B

Table 1 provides an abridged summary of the strength loss due to knot & slippage data that is provided in Annex A and Annex B. The following discussion refers to these Annexes, this table is provided for quick reference.

A. Tensile Strength & Slippage of Standard Knots in Slings

Double Fisherman's Knot (Figure 1-a) (refer to sheet A-2)
One year old Blue Water 11mm rope had a strength loss due to the knot of 42%. The 18 year old Blue Water 11mm rope had a strength loss of 70%. The difference between the 1 and 18 year old rope tied with the same knot is 28%. It appears the aging of the old rope may account for a ≅30% strength loss.

Graph A-4 is typical of the slope of elongation verses load which was generally non-linear.

For new 10mm & 12mm Sisal rope the strength loss due to the knot was 36% & 9 %. The 9% may be explained, if the manufacturer's rated strength included a knot. It could also be explained if the manufacturers rated strength for the rope was 3 standard deviations below the mean rope breaking strength. Then a sample of rope well above the rated strength would give the low apparent strength reduction.

Graph A-5 is typical of the slope of elongation verses load which was very jagged due to the rope fibres in the knot beginning to fail, as well as minor slippage in the knot.

New 7mm & 9mm Riviory rope gave unexpected results of 2% & 6 % strength loss due to the knot.

The abseil working load "Tension" slippage averaged out at 49mm for both 9mm and 11mm rope. The "Tail" creep was 6mm at this load. The sisal rope slipped less than the kermantle rope. Its "Tension" slippage was only 30mm due to the laid strands locking and thus reducing slippage.

The remaining SF for 10mm Sisal rope was only 4. All other materials tested had SF s in excess of 5

Tape Knot (Figure 1-b) (refer to sheet A-1)
These results indicate new Polyester flat tape (19 & 50mm) had a strength loss due to the knot of around 50%. The 25mm flat had the greatest strength loss due to knot of 58%.

New Polyamide 25mm tube tape, had a strength loss due to of the knot of 42%. Graph A-3 is typical of the slope of elongation verses load which was generally linear until failure, however their were noticeable dips in the graphs believed to be due to slippage in the knot as it became tight.

Slippage data was not recorded for most of this series of tests. However, the cyclic tests on tape do provide further data on slippage.

The remaining SF when using 19mm or 25mm slings tied with a tape knot is only 3. The remaining SF for 50mm flat and 25mm tube was good at 13 and 11.

B Tensile Strength & Slippage of Alternative Knots

Overhand Knot for rope (Figure 1-c) (refer to Annex B sheet B-1)
One year old Blue Water 11mm rope had a strength loss due to the knot of 65%. Graph B-4 is typical of the slope elongation verses load which was generally exponential until failure. At near failure it was noted one specimen displayed a partial roll back in the knot. (Similar to the abnormal Figure 8 Knot) This was an unusual event and should be examined with further testing.

The strength loss due to knot for the six year old 9mm rope was high at 75%. It is unclear whether rope age is affecting the results here. The remaining SF when using a 1.96kN load was acceptable at 5. The remaining Factor of Safety for one year old Blue Water II 11mm rope was good at 11.

There was only a 5% difference in strength or slippage between the wet and dry tests for the 6 year old Edelrid 9mm static rope. The Edelrid "dry" treatment is likely to have protected the rope from moisture and so loss of strength.

The abseil working limit "Tension" slippage averaged 65mm for both the 9mm and 11mm rope. "Tail" slippage was 10mm.

The Overhand Knot had acceptable standard deviation figures for strength. This goes against Warild's (1990) observations that reported the strength of this knot as being inconsistent.

For new 12mm Sisal rope the strength loss due to the knot was low at 41 %. Graph B-5 is typical of the slope of elongation verses load, which was jagged as the rope fibres began to fail, as well as minor knot slippage.

Of the Overhand Knot samples tested on the tensile testing machines, the majority appeared to fail at the point of maximum compression inside the knot. The knots geometry uses a chocking effect for gripping the two ropes which may be the reason why it is not as strong as the other knots tested. The chocking action may concentrate all the load onto a small area thus causing a compression point which leads to failure. The Double Fisherman's Knot, which also failed at the point of maximum compression just inside the knot, was not affected by a chocking action but rather a gripping action over a greater proportion of the knot. Hence the Double Fisherman's Knot is stronger than the Overhand Knot.

Overhand Knot for tape (Figure 1-d) (refer to sheet B-1)
For new Polyester flat tape (25mm & 50mm), the strength loss due to the Overhand Knot was between 61 to 65%. The remaining SF when using a 1.96kN load for the 25mm flat and 25mm tube tape was only 3. For the wet and dry 50mm flat samples, the remaining SF was between 9 and 10. There was no major difference in strength or slippage between wet and dry tests for 25 or 50mm flat polyester tape.

The result for the three-year-old Polyamide 25mm tube tape, which had a strength loss due to the knot of 82%, was alarming. Mean breaking strength was only 7.16kN and the standard deviation of the sample tested was very small at 0.42 (indicating very repeatable results). If the material were new, it is estimated the breaking strength would be 12.6kN. The results give a breakage 56% less then what was expected. It seems unlikely the ageing effect would be this bad for tape that was only bought in June 97. The sample had been used as a club hand line during that time and had been stored appropriately when not in use. Although the sample tape was dirty (It was washed and dried before testing) no serious abrasion was detected apart from some minor fluffing.

Graph B-3 is typical of the slope of elongation verses load which was generally linear until failure.

Rethreaded Figure Eight Knot (Figure 1-e) (refer to Annex B sheet B-2)
One year old BW 11mm rope had a strength loss due to the knot of 52%. The new 7mm and 9mm Rivory rope had a low strength loss due to the knot of 24% and 30% respectively. The remaining SF with the 1.96kN load for the 9mm and 11mm ropes were excellent at 13 and 15 respectfully and acceptable for the 7mm cord at 8.

The abseil working limit "Tension" slippage averaged at 44mm. Average "Tail" slippage was only 1mm. This knot had the least slippage (especially tail) when compared to the other knots of the same material.

Abnormal Figure Eight Knot (Figure 1-f) (refer to Annex B sheet B-2)
Breaking strength was similar averaged at 14.8kN between the two Edelrid wet and dry samples. This was probably due to the "dry" treatment on this rope. Strength loss due to knot was between 62% to 64%, however this rope was aged. The breaking strength of the older Blue water 9mm rope sample was a lot stronger at 24.1kN compared to the two Edelrid samples that were not as old.

All 9mm rope specimens tested had at least one roll back, four rolled back twice and one specimen rolled back three times. The lowest first roll back occurred at 2.1kN (the weight of two abseilers) Graph B-6 is typical of the slope on the graph of elongation verses load, which was dramatic, as the knot displayed either partial or complete roll-backs.

Significant "Tension" slippage was already occurring at the abseil-working load, with an average "Tension" slippage of 165mm. "Tail" slippage was only an average of 10mm.

Average "Tension" slippage at failure for the 3 sets of tests conducted was 410mm. On one specimen the "Tail" had slid in 120mm to the point where the tail was flush with the knot before it broke. Another specimen had a "Tension" slippage of 633mm at failure. No significant slippage difference was noted between wet and dry samples.

Another example of how dangerous this knot can be is to tie the knot with inappropriate tail lengths and have the knot poorly packed. In this configuration, it is possible for two people

pulling in a tug of war fashion (which equates to approximately a 50kg load) to pull the knot completely apart. For the reason of roll back and knot failure this knot was deleted from further testing.

Alpine Butterfly Knot (Figure 1-g) (refer to Annex B sheet B-2)
One year old 11mm rope had a strength loss due to the knot of 52%. The six year old rope was between 59 and 66%. Remaining SF with the 1.96kN load was very good, being between 12 and 16. From a strength point of view, this knot performed very well. The large majority of the specimens broke at the top or bottom bollard indicating the knot was very strong. The lower strength of the older rope may be due to an aging factor.

It was interesting to note the difference between the dry and wet samples. All specimens from the dry sample had uniform slippage as load was applied and there was still some slippage as load approached failure. The wet sample was interesting in that the knot would hold then slip all of a sudden, hold then slip again. Graph B-7 is typical of this noted occurrence.

The abseil working limit "Tension" slippage averaged at 74mm. Average "Tail" slippage was 14mm.

Horrocks (2000) discovered this knot (when used to tie two ropes together) could easily be tied the wrong way resulting in the knot possibly undoing under load with obvious deadly results for any abseiler on the rope. This fact was pointed out to the author soon after this set of tests was completed. Two people pulling on the rope in a tug of war fashion can demonstrate this. It is not apparent to casual visual inspection that the knot is tied incorrectly. Due to this issue, the Alpine butterfly knot was deleted from further testing.

Knot Strength Comparisons
      The results of Section A and B have been summarised into Table 2 as sourced by the author. This table also compares the present data to other published sources.

Source	TYPE OF ROPE JOINING KNOT					
	TAPE	OVERHAND IN TAPE	DOUBLE FISHERMAN'S	RETHREADED FIGURE 8	OVERHAND	ALPINE BUTTERFLY
DROHAN	42% & 52%	65%	42%	52%	65%	52%
Wild Sports (11 & 9mm)	-	-	12% & 22%	-	-	24% & 34%
Luebben	30-40%	-	30-35%	-	35-40%	-
Warlid (mainly 10mm)	55%	-	45%	50%	55%	53%

Table 2
Knot Strength Comparisons
Percentages given are for strength loss due to a knot
Drohan's results are for New Donaghys 50mm tape and 1 year old BWII 11mm rope

The present results compare well to Luebben (1996) and Warild (1990). While this appears to validate the current results, it must be remembered the current study's method of testing is not considered statistically accurate because of the small sample size and inability to test single strands. The accuracy and statistical significance of Luebben and Warild's results are not known.

Wild Sports (1996) knot strength loss figures are far less than the other quoted sources. For example, the Double Fisherman's knot has a strength loss due to knot of only 12% for 11mm and

22% for 9mm, whereas the other sources state between 30 and 45%. Luebben and Warlid may have compared breaking strength to manufacturer's rated rope strength, as has the present study.

A report has been sighted that the author requests not to be quoted, that suggests Wild Sports testing procedures compared knot breaking strengths to single strand test results for the same rope. This method provides a more useful measure of strength, therefore these results should be more accurate.

Safety Factor Concerns for Knots
Table 2 indicates many of these knots are weaker than the standard 33% allowed for strength loss due to a knot. Currently SF8 is applied to tape and rope by many outdoor and rescue organisations. Whilst SF8 is considered appropriate for the Double Fisherman's knot due to its adequate strength, these results indicate SF8 may not adequate for some of the other knots.

Using the logic discussed in the "Introduction - Understanding Safety Factors" (on p4), Sheet B8 calculated the required SF for the knot strength loss from the data in Table 1. From these results only the Double Fisherman's Knot from three of the four sources of test data support SF8 as appropriate. All the other knots require a greater safety factor.

The Tape Knot and Overhand Knots, are of interest to the author. Table 3 provides a summary of their safety factors based on Drohan, Luebben and Warild's results

	Tape Knot	Overhand Knot
Drohan	8.6 & 10.4	14.3
Luebban	8.3	8.3
Warild	11.1	11.1

Table 3: Summary of Knot Safety Factors

Table 3 indicates only Luebban results are approaching SF8. Until absolute values can be determined, it would be wise to consider the other figures. The Tape knot ranges from SF8.3 to SF11.1. Noting the range of data SF10 is considering a good compromise for this knot. SF10 is also a good figure for field calculations to determine the WLL. As Warild's data is unclear on how the figures were determined, less importance has been placed on that figure. The Overhand Knot using Drohan's higher figure of SF14.1 should be rounded up to SF15. Considering the other Overhand knot test data on aged rope presented in this paper, SF15 is considered appropriate until more comprehensive testing can confirm the issue.

A SF15 will have impact on the WLL, for example: A 9mm BWII static rope rated at 1820kg tied with an Overhand Knot is divided by SF15. This will give a WLL of only ≅120kg (ie no more than two 60kg people are to be on the rope at any one time). This would rule out planned double loadings such as assisted or twin person abseiling. In a self rescue situation where a leader has to rescue a jammed abseiler by the use of prussiks, the safety factor will be compromised. For this reason 9mm ropes used in canyoning must be in good condition.

Knot Slippage graphs
Sheet B-9 graphs the comparison of the slippage of various knots at 3 different loads. All knots were acceptable at the two limit loads except the Abnormal Figure 8 Knot. The Double Fisherman's does slip up to 50mm in tension at a 1.96kN load. The Abnormal Figure 8 had alarming slippage in tension of 203mm at the 1.96kN load. The Rethreaded Figure 8 had the least slippage and the Overhand knot (Graph 12) slippage was acceptable.

In attempting to use smaller size rope or tape for abseil anchor slings, it is important that the strongest knots are used in order to maintain sling strength. Therefore the Double Fisherman's Knot should be used for rope and the Tape Knot for tape. Of the tests performed on non standard sling material, only the 12mm Zenith brand Sisal rope and 7mm Riviory brand cord are satisfactory, provided they are not shock loaded and are used only once by the party who placed them.

Single Strand Tests

Due to lack of access to a tensile test machine with a stroke of over two metres, the single strand tests could not be successfully conducted.

This series of tests was very disappointing. Only one series of tests with new 25mm tube tape was conducted where the specimens broke before the machine reached the limit of stroke. This was due to tape not stretching as much as rope, however all the specimens broke at the bollard which according to AS 4143.1 (1993) indicates a failure of the test.

The single strand testing conducted on rope was a failure, due to lack of stroke on the tensile test machines available. The special spiral bollards on the ADFA machine did improve the situation by reducing stress concentrations in the rope, but the specimens still did not break prior to maximum stroke extension.

AS4143.1 (1993) requires three wrap turns of rope around each fixed bollard and then locking off by clamping. Throughout the tests the clamping arrangement did not move more than a few millimetres. The problem was the rope in the three wrap turns between the clamp point and the gauge mark began to stretch out as load was applied. This occurred to the point where the machine was out of travel.

The procedure from AS4143.1 (1993) was followed, except for gauge length of specimen. The standard requires the gauge length to be 1m. With the specimen pretensioned, the machine allowed only a 250mm gauge length in order to attempt breakage before the maximum stroke of the machine was reached.

Due to the unsuccessful single strand tests, the author is of the opinion that further statistical analysis to determine the precision of the strength of knots is not warranted.

D Cyclic Tests

50 kg cyclic load	Tape knot	Overhand knot in tape	Double Fisherman's	Rethreaded Figure 8	Overhand in rope
Mean Tail slippage (mm)	-6	40	9	3	26
Total Tension slippage (mm)	55	117	27	34	50
100 kg cyclic load					
Mean Tail slippage (mm)	-	31	15	10	14
Total Tension slippage (mm)	-	90	41	63	40

Table 4: Summary of Cyclic loading data for various knots
Slippage data is after 15 cycles of loadings have been completed.

Table 4 provides an abridged summary of the cyclic loading data that is provided in Annex D. The following discussion refers to these Annexes, this table is provided for quick reference.

Refer to Annex D1 to D11 for graphs of the cyclic loading. "Acceptable slippage" is defined as not being noticed or causing alarm to the user.

50kg cyclic loads on knots in dry 9mm static rope
All knots tested had acceptable slippage in the range of the tests especially in the critical area of "Tail" slippage.

The Rethreaded Figure Eight Knot (Graph D3) had the least "Tail" slippage of only 3mm after 15 cycles. The Double Fisherman's Knot (Graph D1) had acceptable "Tail" slippage of 9mm after 15 cycles. The Overhand Knot (Graph D5) had the most "Tail" slippage at 26mm after 15 cycles. "Tension" slippage was acceptable for the knots tested, with the most being the Double Fisherman's (Graph D1) at 27mm after 15 cycles.

100kg cyclic loads on knots in dry 9mm static rope
All knots tested had acceptable slippage in the range of the tests especially in the critical area of tail slippage. Again the Rethreaded Figure Eight Knot (Graph D4) had the least "Tail" slippage of only 10mm after 15 cycles but it had the most "Tension" slippage of 63mm.

The overhand knot performed the opposite way to the other two knots tested, in that the 100 kg load slipped less than the 50 kg load (Graphs D5 & D7) ("Tension" slippage 14mm verses 26mm). From this it appears the Overhand Knot can slip more if there is not adequate weight to lock up the rope.

Wet tests on rope knots
The wet tests (Graph D6) undertaken in both load ranges had significantly less slippage. The rope specimens had no "dry" treatment. It appears that when wet, the ropes expand about 0.5mm in rope diameter in the knot and so lock up more tightly.

50kg cyclic loads on knots in dry 50mm flat tape
The Tape Knot (Graph D8) was interesting in that after 15 cycles the "Tail" had increased by 6mm in length as the knot tightened up. This is due to the construction of the Tape Knot, in that as the knot tightens the tail does not move from its existing position and so actually gets longer simply as a result of the knot becoming more compact. All other knots tested had a decrease in tail length.

The Overhand Knot in tape (Graph D9) had significantly more "Tension" slippage than the same knot in rope. "Tail" slippage was 40 and 31mm for the two load tests. The "Tension" slippage was also significant at 117mm with the 50kg load. It is expected that continued slippage would occur with additional load cycles.

Wet test with overhand knot on tape
The wet test undertaken with the 50kg load (Graph D10) had significantly less "Tension" slippage than the dry (69mm verses 117mm). It appears the polyester tape may expand when wet and so lock the knot more tightly.

100kg cyclic loads on knots in dry 50mm flat tape
As with the rope the Overhand Knot in tape (Graph D11) "Tension" slippage was slightly less with the 100 kg load than the 50 kg load ("Tension" slippage was 90mm verses 117mm). The overhand knot in tape can slip if there is not adequate weight to lock up the tape.

E Rope Pull Down tests

Comparison of Sites
Annex E Sheet E-1 provides the results for the simulated 90° edge. Sheet E-2 provides the results for the Bungonia cliff edge. The graphs depicting the commencing rope pull and 200mm movement show little difference between the three knots tested, for the simulated cliff edge against the Bungonia waterfall. This shows the simulated edge appears to accurately model the starting inertia and rolling friction. There was significant difference in edge knot pull over results between the two series of tests. This was expected due to the vastly different shape of the two edges.

Results from actual and simulated cliff edges
Sheet E-1 indicated that the Double Fisherman's Knot did get caught on all hard edges especially the reverse edge. (Figure 12 depicts a reverse edge). This is due to the cylindrical shape of the knot where the knot jams against the hard edges. This knot required significantly more force (nearly 40kg) than the other knots to move over a 90° reverse edge.

It was noted on sheet E-2 for the natural edge the Rethreaded Figure 8 Knot required slightly more load than the Double Fisherman's Knot to move over the edge. This may be due to the Rethreaded Figure 8 Knot jamming more in the natural groove (refer to Figure 6a) than the Double Fisherman's knot. However the Double Fisherman's Knot did jam (Figure 8) and needed far greater force to move over all the simulated edges than the Rethreaded Figure 8 Knot. Based on this evidence, further rope pull down tests on the Double Fisherman's Knot were discontinued.

The Double Fisherman's Knot jamming on the edge. The arrow indicates the direction of pull.
Figure 8

Comparison of the Rethreaded Figure to the Overhand knot
Two series of rope pull down tests were conducted on the Rethreaded Figure Eight Knot (Figure 9) and the Overhand knot (Figure 10). Graphs E-3 & E-4 indicated that the Overhand Knot required less force than the Rethreaded Figure Eight Knot on all the edges tested. In all cases the Overhand Knot required about 50% less force to pull down over the edge.

Figure 9 Rethreaded Figure 8 knot jamming Figure 10 Overhand knot clearing Knots

being pulled down over an edge. The arrow indicates the direction of pull.

As a result of this test the Rethreaded Figure Eight Knot was deleted from further pull down tests.

Focus on the Overhand Knot

With the Overhand Knot appearing to be the preferred knot, a more intensive series of tests was conducted.

Starting Inertia loads: It was observed the Overhand knot required more force than any other knot if the knot is against the sling. Graph E-5 comparing a Rethreaded Fig 8 to the Overhand Knot, indicates that the starting break free load of the overhand knot can be around three times higher if the knot is against an anchor sling. This is due to the knot clasping itself around the sling (Figure 11-a). Only the Overhand knot of the knots tested had this issue. If the knot is away from the sling this does not occur (Figure 11-b).

(a) The Overhand knot against the sling (b) away from the sling
The arrow indicates the direction of pull. Figure 11

Comparison of the Tail direction: Tail orientation can make a difference for the overhand knot. Figures 12-a& b below depict knot tails leading and trailing

(a) Tails leading   (b) Tails trailing
Knot tails on the reverse edge.   The arrow indicates the direction of pull. Figure 12

Reverse edge-Graph E-6 shows there is little difference for the tails up position for leading or trailing, but as expected it is a different story for the level or down position. Refer to the photos below for a definition of tails up (Figure 13-a), level (Figure 13-b), or down. (Figure 13-c). For the down position, the tails leading required significant less force to pass the reverse edge than tails trailing. Surprisingly the tails level made more of a difference between the leading to trailing position than the tails down position.

(a) Tails up   (b) Tails level (c) Tails down
Knot tails on the reverse edge.   The arrow indicates the direction of
pull. Figure 13

It appears the geometry of the knot against the edge comes into play. Figure 14 is a profile view of the Overhand Knot with tails leading in a down position when the knot first comes into contact with the 90° reverse edge.
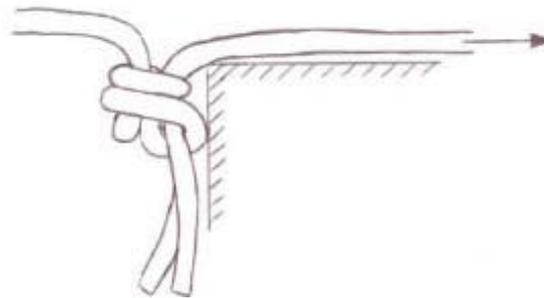

Figure 14   Overhand Knot with tails leading in a down position against the reverse edge Arrow indicates direction of pull.

First Test

For one set of tests with tails leading the knot pivoted about the corner of the reverse edge. This took reasonable force to pull over, a mean of 25kg, before the knot cleared by lifting itself over the edge as shown in Figure 15.
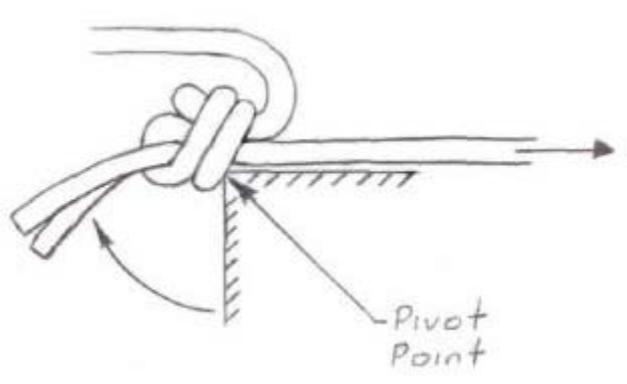
Figure 15   Overhand Knot with tails leading against the reverse edge being pulled over Arrows indicates direction of pull and knot lifting.

Second test

Another set of sets with tails leading in a down position gave a surprising result for how the knot cleared the reverse edge. When under load the tails righted themselves to an upright position, which required less force to pull past the reverse edge. Only a mean of 11kg was required to clear the edge. Figure 16 of the end view of the knot with an arrow indicating how the tails

rotate themselves to an upright position. The bulk of the knot against the edge is diagonal in shape, this appears to give a turning moment so the tails can right themselves.
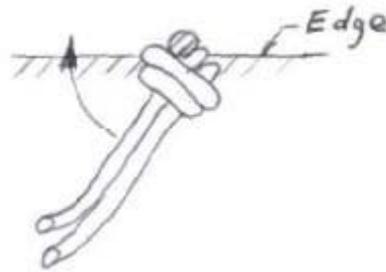
Figure 16 End view of the Overhand Knot Tails leading against a reverse edge with tails down. Arrow indicates direction of knot lifting.

The comparison of this first and second set of tests was not planned, it was only by chance. In order to conduct a left hand test, (tying the knot left handed) the second set of right hand tests was also conducted for comparison. It was noted the first set of tests were different to the second. No reason is known as to why the two sets of tests, gave the two types of response. Tail lengths were similar, at approximately 100mm. The only suggestion could be that as the two tests were done over a week apart, it is possible the rate of travel in the rope pulling was not constant.

Third Test
For tails trailing in a down position (Figure 17-a) the mechanism that the knot cleared the edge was by pivoting over the edge. It was also observed (Figure 17-b) the bulk of the knot against the edge is symmetrical when against the reverse edge. This square on abutment with the tails down required similar force (mean of 19kg) to the first set of tests (tails down and leading) to clear the edge as the knot can not so easily right itself by rotating as in the second set of tests.
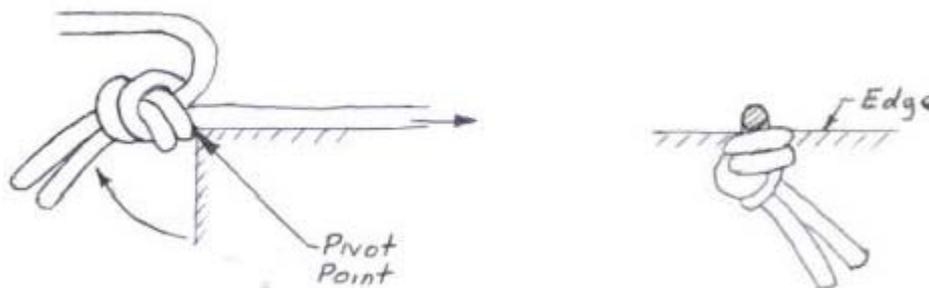
(a) Profile (b) End view
Overhand Knot with tails trailing against a reverse edge with tails down
Figure 17

90$^{°}$ Edge Graph E-7 shows that even going over the edge, the tail leading position required less force than the tails trailing. The tails up leading position required 24% less force than the tails trailing. Observation indicated the last section of the knot (labelled as the tripping point) on Figures 18 & 19 caused the load build up before the knot slipped over. But why the difference between tails leading to trailing?

For tails leading: (Figure18) perhaps the distance between the knots tripping point and the edge which was measured at 7mm may have allowed the knot to slip over the edge with less force.
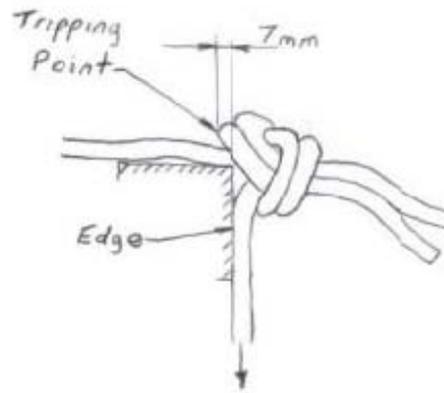
Figure 18 Profile of the Overhand Knot with tails leading going over a 90° edge. Arrow indicates direction of pull.

For tails trailing: (Figure 19) the distance between the knots tripping point and the edge was measured at 9mm. Although only 2mm greater than for tails leading, it may explain why this knots configuration requires more force to slip over the edge.
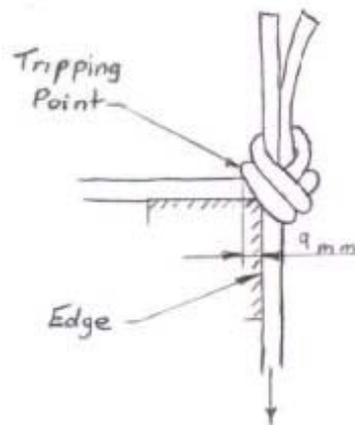

Figure 19 Profile of the Overhand knot with tails trailing going over a 90° edge. Arrow indicates direction of pull

Comparison of Left Hand to Right Hand Tying of the Overhand Knot
Two sets of tests were conducted to observe if the hand the knot was tied would make any difference on the edges. The results were generally within 2kg of each other, therefore it appears it does not matter if the knot is tied right or left handed.

Comparison of the Overhand knot between Wet and Dry Conditions
The final test was to determine if flowing water acted as a lubricant for the ropes being pulled down. Graph E-8 indicated the opposite was true. Wet ropes with no "dry" treatment require about double the load to pull over the edges than the dry ropes for the two tail positions tested. It appears the weight of the sodden tails makes the knot harder to right itself. The weight of the entire rope is also heavier when wet, which also adds to the force to pull over the edges.

Conclusions and Recommendations

Disclaimer
Conclusive strength or slippage statements can not be made for this project, as the sample size of testing conducted was not large enough. However, an indication of what to expect can be drawn from these results. The results in this paper are not a substitute for proper training.

Knot Strength
The Double Fisherman's was the strongest knot tested for joining rope. The Rethreaded Figure 8 knot was the second strongest knot tested. All knots tested had acceptable strength for recreational abseiling. There may be an issue with the strength of the Overhand Knot when used on older rope.

It appears very old rope strength is affected by age, as one set of tests indicated a 30% strength loss when compared to the same tests using a newer rope.

More testing is required to confirm if there may be a safety issue when the Overhand Knot is subjected to a shock load.

Due to the wide range of published data on the strength of knots, the author recommends a more in depth literature review of knot strength, together with additional research on knot strengths.

Safety Factor Concerns
Due to the weaker strength of some knots, it is recommended the safety factor for the Tape knot should be increased from SF 8 to SF 10 and the Overhand Knot should be increased from SF8 to SF15. SF8 for the Double Fisherman's knot is acceptable, as it is a strong knot

Slippage
The Rethreaded Figure 8 Knot had the least slippage of the knots tested. The second best was the Double Fisherman's Knot. The Overhand Knot is acceptable.

Smallest Size Material for Anchor Sling
Of the tests conducted on non standard sling material, the smallest size anchor sling that is safe for one off use in a canyon provided it is not shock loaded is 12mm Zenith Sisal rope and 7mm Riviory cord.

Knots for Anchor Slings
The Tape Knot for tape and the Double Fisherman's for rope are still considered the preferred knots for tying anchor slings together due to strength and slippage considerations.

Unsafe Slings
From the results of this study, 19mm or 25mm flat tape are not recommended to use for sole abseil anchor slings, as these loops have only SF3 at the maximum abseiling load, which is not adequate.

Unsafe Knots for Joining Two Ropes/tapes
The Abnormal Figure Eight Knot is unsafe. The tensile tests confirmed that this knot rolls back on its self when loaded. It is possible that a rope joined with a poorly packed Abnormal Figure Eight Knot with small tails can completely undo with loads as low as 50kg as demonstrated by two people pulling either end of the rope.

The Alpine Butterfly Knot used to tie rope together can be tied incorrectly in a way that is not apparent to casual visual inspection. When incorrectly tied it is possible the knot may result in

complete separation of the two ropes when loaded as low as 50kg. This can be demonstrated by 2 people pulling in a tug of war fashion. Therefore this knot is considered too risky to use for joining rope.

The Overhand Knot should not be used on tape due to the progressive slippage when loaded.

Preferred Knot for Tying Canyon Ropes Together
The Overhand Knot appears to be the best knot to join two canyon ropes together when considering cliff friction issues. However canyoners should ensure knot tails are leading towards the edge and do not drop down on reverse edges as this increases the load required to pull the knot over the edge. When setting up a canyon abseil rope ensure the Overhand Knot never engages the anchor sling or link, otherwise it will take greater load to start pulling.

If the ropes are wet, the rope pull down load can be doubled.

The Double Fisherman's Knot has traditionally been the knot used to join two ropes. Whilst the strength of this knot can not be questioned, its performance in rope pull down tests was poor and for that reason this knot is not recommend for joining ropes in canyoning where rope jam could be an issue.

Overhand Knot Hypotheses
A hypothesis is proposed that the knot geometry of the Overhand Knot is responsible for the issues of rope pull down ease, as well as strength and slippage. The author understands that a number of reports state knot geometry is responsible for strength and slippage. Unfortunately none have been sighted due to the limitations on the literature review undertaken in this study. Based on the work in this paper, the overhand knot appears to be the most suitable knot that abseilers can use for joining their ropes together in recreational canyoning. The geometry appears to be the reason why the Overhand Knot performed so well on edges where as other knots performed poorly.

Further Research

To prove the hypothesis put forward in this paper, an in depth study is required to explore the Overhand Knot in greater detail. This will prove if the geometry of the knot is responsible for its performance and should provide conclusive strength and slippage data.

Due to the premature failure of the Edelrid 25mm tube tape with an Overhand Knot, further tests are required to determine the strength of aged tape.

Additional rope pull down tests could be conducted in wet conditions to determine if a dry treated rope would require less load to pull down than a non dry treated rope when using the Overhand Knot.

A question should be put to Riviory in France as to how the rated strength of their rope is determined.

Additional research could be conducted on tape and rope. If suitable test machines are available, then stage two of this project plans to investigate shock forces and stage three plans to investigate the aging process. The objectives in detail are listed below:

Stage Two
☐   To determine how many cycles an old static rope can take using a FF0.1 and FF0.3 fall and a 200 kg load.

◻ To determine the dynamic strength of alternative knots that could be used to join rope.

◻ To determine the dynamic load required to damage tape and rope over a 90° edge. In addition to the tests planned for stage two, additional testing of the Overhand Knot should be conducted especially on old 9mm ropes using shock loads that could be generated by abseilers.

Stage Three

◻ To determine over a three year period the effect of ageing on the tensile strength of tape and rope when left in a simulated canyon environment.

Future of the Project

BWRS has raised some funds for next stage of the project, however for donations would be gratefully accepted. Due to other commitments, the author will not be able to commence work on further research until the year 2003. A tensile testing machine with a stroke of at least two metres will be required if the project is to continue. The author is not aware of such a machine being available in Canberra. It may be possible to build a machine using a suitable hydraulic ram with two to three metres of stroke and a load cell mounted on the cross head. A suitable structure that can mount an appropriate load cell will also be required for the shock tests planed. ADFA have given tentative support to use their testing equipment, provided the tests can be scheduled around their other planned work.

Acknowledgments

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