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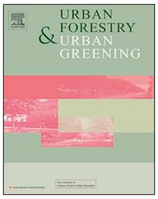

Quantifying tension and deflection in pre-tensioned speedlines carrying a load

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ABSTRACT

Arborists use speedlines to move debris; efficiently between the tree from which the debris is generated and the landing. To maintain vertical clearance over obstacles, speedlines are pretensioned, but there are no rigorous empirical data to quantify the tension in a pretensioned speedline when it carries a load. Neither has its deflection under load been quantified. We measured the mid-span deflection and tension at both anchors of a speedline under three added loads and three pretensions. Tension at both anchors increased with pretension and added loads up-line tension consistently exceeded down-line tension; and even for the greatest pretension and least added weight, mid-span deflection was substantial. Despite the increased tension in the speedline, bending stress at the anchors was comparatively low. Our results were largely consistent with analyses of logging skylines, despite the differences between components of each system.

1. Introduction

Arborists use speedlines to move debris efficiently between the tree from which the debris is generated and the landing. Using speedlines to rig trees is considered an advanced technique that requires specialized equipment and experience (Donzelli and Lilly, 2001). Arborists often use speedlines to clear obstacles (such as structures and landscape features) while rigging. To maintain clearance over a given span, the speedline must be pre-tensioned (Adams, 2006a,b). When the speedline carries the weight of debris, tension in the rope and forces at the anchors increase (Detter et al., 2008). From a simple static analysis, maximum deflection of the speedline should occur when the load is at mid-span (Detter et al., 2008), and empirical data from skylines (used in yarding systems) confirm this analysis (Fabiano et al., 2011). When using a speedline, the forces generated on the rigging system—including the trees anchoring the speedline—may be large (Donzelli and Lilly, 2001; Adams, 2006a,b; Detter et al., 2008), but to the authors' knowledge, no rigorous attempts have been made to quantify them empirically.

Two primary risks exist when using speedlines: (i) failure of the rigging (including the anchors—one of which is often the tree from which debris is generated or a nearby one) and (ii) not clearing the obstacle around which one must work. Regarding the former, it is important to know the tension in the speedline, which can vary with several factors such as pre-tension and weight of debris (Fabiano et al., 2011). For the latter, it is important to know the deflection for a given pre-tension once the speedline carries a load.

Analogous to speedlines, skylines are used by loggers to move logs from the harvesting site to the landing by machines. There are several important differences between speedlines and skylines. For example, skylines typically involve longer spans, often with multiple spars (poles to support the skyline, analogous to utility poles in cities), and are constructed with wire rope, sometimes of large diameter (Fabiano et al., 2011). In addition, the carriage or trolley that rides on a skyline is much heavier and more elaborate than that which arborists use on a speedline. Also, yarding systems typically involve hoisting logs from the ground up a slope, rather than lowering logs from higher elevation. Analytical approaches with iterative solutions have been developed to determine maximum payload capacity in skylines (Brown and Sessions, 1996), and stress in spars (Pyles and Pugh, 1987). However, there are few empirical data to inform the analytical approaches (Fabiano et al., 2011). Adopting analytical approaches from skylines may be problematic when considering speedlines because of rope elasticity.

Ropes used for speedlines are typically double braid rigging lines (Donzelli and Lilly, 2001) that elongate in the range of one to three percent. But wire ropes used in skyline systems stretch much less. Not accounting for rope elasticity may underestimate the log capacity in skyline systems (Brown and Sessions, 1996).

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Considering the absence of empirical data to quantify forces in pre-tensioned speedlines and the severe consequences that might be associated with speedline failure, our objective was to determine the effect of pre-tensioning and adding a load to the speedline on (i) tension at the anchor points, (ii) mid-span deflection of the speedline, and (iii) bending stress in the trunk of the upline anchor tree.

2. Methods

In May 2010, we set a speedline between two red pines (*Pinus resinosa* Ait.) 67 cm in diameter at 1.4 m above ground growing in Amherst, MA, USA. The height above ground of the anchor points was 10.7 m and 1.10 m, and the horizontal distance between the trees was 33.6 m. The speedline made an angle of 15 degrees from the horizontal. The speedline was a length of Stable Braid (1.43 cm in diameter, 59.2 kN minimum breaking strength, 1.1% extension at 10% of breaking strength, Samson Rope Technologies, Ferndale, Wash., USA).

For each trial, we tensioned the speedline to one of three intended pre-tensions (667N, 1112 N, and 1556 N) using a rope tensioning device called a come-along. Since pre-tensions measured at the high (up-line) and the low (down-line) anchors of the speedline did not always equal the intended value, we recorded up-line and down-line pre-tensions simultaneously using Dillon EDXtreme dynamometers (accurate to 11 N, Weigh-Tronix, Fairmont, Minn., USA). We refer to measured up-line and down-line speedline tensions as "T_U" and "T_D", respectively. We also measured the mid-span speedline height (h_P) at each pre-tension. After pre-tensioning the speedline, we loaded it at mid-span from a single pulley with one of three loads (658 N, 858 N, 1014 N), consisting of a rigidly secured stack of barbell weights (Fig. 1). After adding the load, we re-measured T_U, T_D, and h; we refer to loaded height of the speedline as h_L. Mid-span speedline deflection (δ) is the difference: $h_P - h_L$. Throughout the tests, we did not observe any stem deflection or rotation of the root-soil plate of either tree. We tested intended pre-tensions randomly blocked within each load, releasing tension in the speedline between tests. We repeated each combination of intended pre-tension and added load three times and analyzed the means.

Fig. 1. Stack of weights hanging from a webbing sling attached to a pulley at mid-span of the speedline. The friction hitch and micro-pulley were used to position the stack at mid-span. The rope attached to the pulley holding the stack is the haul rope.

To calculate bending stress (σ) in the trunk, we used Eq. (1):

$$\sigma = 32M\cos\beta/(\pi d^3) \quad (1)$$

where M is the moment induced by up-line tension; β represents θ or φ for T_D and T_U, respectively; and d is trunk diameter at 1.4 m above ground. We used trigonometry to calculate θ and φ from the initial angle (α) and length of the speedline and δ (Fig. 2).

Including measured pre-tension as a covariate, we used analysis of covariance (ANCOVA) to determine whether the following variables differed among the three added loads: (i) T_U and T_D, (ii) the ratio of tensions measured before and during loading the speedline ("tension ratios"), and (iii) mid-span h before and during loading. For ANCOVAs (i) and (ii), we analyzed up-line and down-line tensions separately because the values were not independent. To separate least squares means of significant ($p < 0.05$) effects in the ANCOVAs, we used Tukey's Honestly Significant Difference test. We conducted all analyses in SAS (SAS Institute Cary, N.C., USA).

3. Results

As expected, T_U and T_D increased with greater pre-tension (Fig. 3) and greater added load (Table 1). The increase in T_U and T_D with greater pre-tension was similar for all added loads (Fig. 3). Depending on the pre-tension and added load, the tension ratio ranged from 1.92 to 4.88 (Table 1). Measured up-line or down-line, and for each intended pre-tension, the tension ratio after adding 1014 N was always greater than after adding 658 N, but not always after adding 858 N (Table 1). Tension ratio decreased as pre-tension increased (Table 1). The slope (± standard error) of the best-fit line describing the decrease in tension ratio as pre-tension increase (-0.002 ± 0.000) was the same measured up-line and down-line, and it was significantly less than 0 ($p < 0.0001$). As expected from the free body diagram in Fig. 2, T_U consistently exceeded T_D for all pre-tensions and added loads (Fig. 3, Table 1).

As pre-tension values increased, both h_P and h_L increased slightly (Table 2). Equations of best-fit lines follow (± standard error) : $h_P = (0.0003 \pm 0.0000)W + (5.27 \pm 0.044)$; $h_L = (0.0007 \pm 0.0000)W + (2.11 \pm 0.164)$, where W is the covariate added load. Slopes of both equations were significantly greater than 0 ($p < 0.0001$). Within each intended pre-tension, h_P was similar for each added load, but h_L decreased as added load increased (Table 2). The percent reduction in mid-span speedline height during loading decreased with increasing pre-tension (Table 2). Within each intended pre-tension, the percent reduction in mid-span speedline height during loading was greater for loads of 1014 N than loads of 658 N (Table 2).

4. Discussion

This is the first study to measure tension and deflection in a speedline, and our data have immediate practical application. Although practitioners will not likely use a dynamometer to quantify pre-tension in the speedline, it is helpful to know that tension in the loaded speedline at both anchors can be nearly five times greater than, and is minimally almost twice as large as, the pre-tension. Donzelli and Lilly (2001) recommended that practitioners assume that the loads experienced by a pre-tensioned speedline when it carries a log are similar to the dynamic loads associated with shock loading while rigging. In a rigging experiment involving shock loading, the maximum rope tension per unit mass of 1.83 m long red pine logs was 52.9 N/kg (Kane et al.,

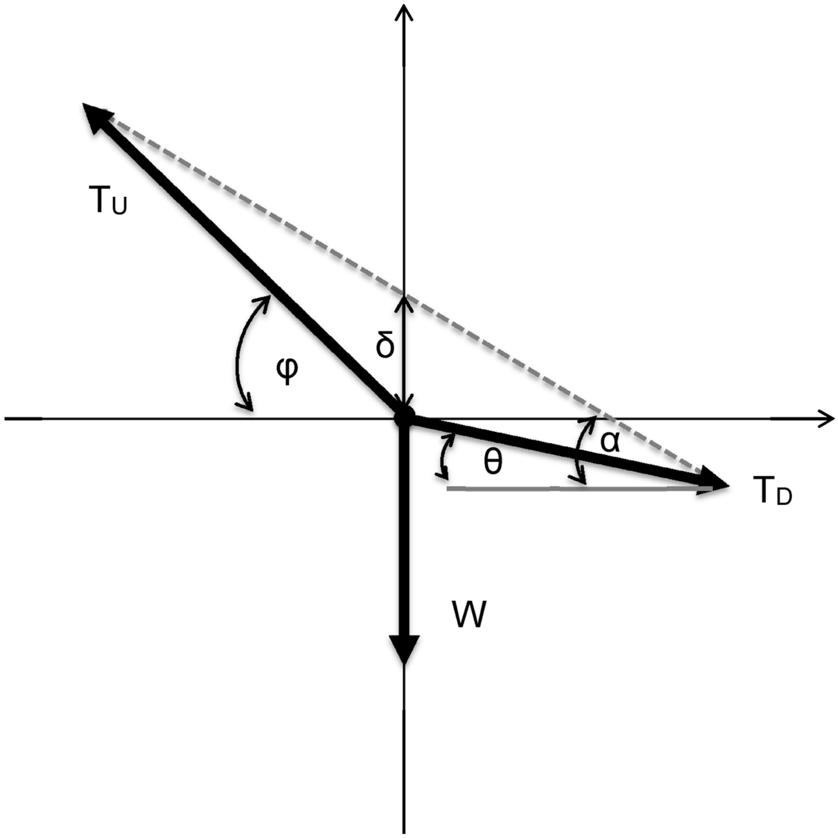

Fig. 2. Free-body diagram (not drawn to scale) illustrating the unloaded (light, dashed line) and loaded (heavy black lines) speedline, as well as the added load (W). Arrowheads on heavy black lines indicate the direction and line of action of W and the up-line (T_U) and down-line (T_D) tension in the speedline. We used trigonometry to calculate φ and θ from the length of the speedline, α (15°), and measured δ.

2009). Multiplying this value by the masses we added to the speedline (67 kg, 88 kg, 103 kg) yields tensions of 3540 N, 4660 N, and 5450 N, respectively, which are 12%, 28%, and 36% greater than measured in the speedline at the maximum pre-tension. Following Donzelli and Lilly's (2001) guideline seems prudent, given (i) the importance of safety, (ii) the uncertainty associated with the parameters that govern speedline tension under load, and (iii) the lack of empirical data quantifying forces in speedlines and rigging.

Despite the large increases in T_U and T_D during loading, bending stress in the trunk of the high-anchor tree remained small compared to the modulus of rupture (MOR) of the wood of red pine, which is 40 MPa (Kretschmann 2010). Reducing that value by 20%, consistent with Kane and Clouston's (2008) observations, the maximum bending stress at 1.4 m above ground was only 4% of MOR and 15% of the mean bending stress induced by rigging (Kane et al., 2009). If the cross-section of the trunk at 1.4 m above ground were 80% concentrically decayed, bending stress induced by the maximum measured tension in the speedline would be 6% of MOR.

The maximum measured tension in the speedline was 7% of nominal minimum breaking strength of Stable Braid. But assuming a 20% reduction in tensile strength that occurs when a rope is hitched to an anchor (Kane, 2012), the maximum measured tension was 35% of the hitched breaking strength of Stable Braid, a safety factor of 2.9. In skyline systems, safety factors in wire rope are typically between 2.5 and 3.5 (Fabiano et al., 2011). But given the reduction in hitched rope strength for speedlines, and uncertainty associated with the load-bearing capacity of the tree used as the up-line anchor, greater safety factors should be considered for speedlines.

Our results are consistent with those from single-span skylines, for which pre-tension of the skyline and the added load predicted 98% of the variance in skyline tension, regardless of span length (Fabiano et al., 2011). The findings that tension ratio (i) decreased as pre-tension

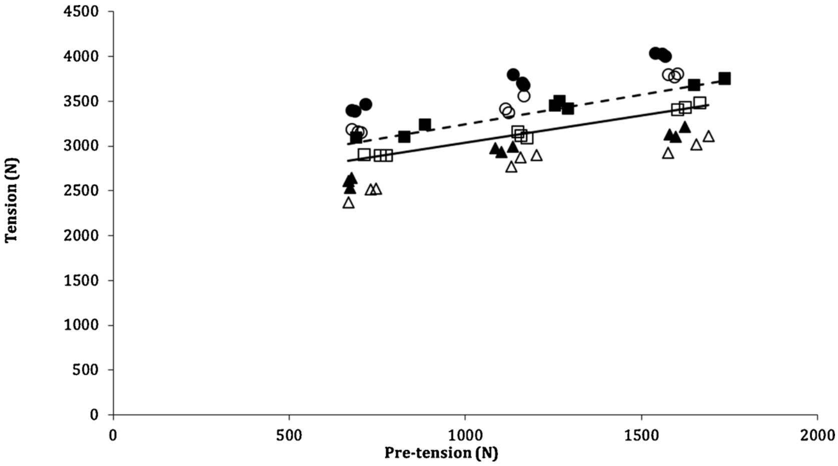

Fig. 3. Up-line (T_U, filled markers) and down-line (T_D, open markers) tension induced by each added load (W) (658 N: ▲, △; 858 N: ■, □; 1014 N: ●, ○) plotted against measured pre-tension. Best-fit lines follow (± standard errors): $T_U = (0.60 \pm 0.05)W + (2240 \pm 56)$, $T_D = (0.60 \pm 0.05)W + (2080 \pm 61)$. Slopes of both best-fit lines were significantly greater than 0 ($p < 0.0001$), but did not differ among added masses ($p > 0.30$), so only one line is shown for T_U (dashed) and T_D (solid) measurements.

Table 1

For each intended pre-tension (N) and added load (N), best-fit estimates from the ANCOVA (followed by standard errors in parentheses) of (i) down-line (T_D) and up-line (T_U) tension (N), and (ii) the ratio of measured tension of the loaded to the unloaded speedline.

Pre-tension^z	Load	$T_D{}^y$	Down-line Ratio^y	$T_U{}^y$	Up-line Ratio^y
667	658	2480 (31)a	3.46 (0.11)a	2630 (28)a	3.77 (0.11)a
	858	2840 (32)b	3.92 (0.12)b	3060 (34)b	4.12 (0.13)a
	1014	3140 (31)c	4.49 (0.11)c	3400 (30)c	4.88 (0.12)b
1112	658	2740 (19)a	2.69 (0.07)a	2900 (18)a	2.87 (0.07)a
	858	3120 (19)b	3.03 (0.07)b	3350 (19)b	3.25 (0.08)b
	1014	3450 (19)c	3.40 (0.07)c	3710 (18)c	3.65 (0.07)c
1556	658	3010 (27)a	1.92 (0.10)a	3160 (27)a	1.97 (0.11)a
	858	3390 (27)b	2.15 (0.10)ab	3640 (23)b	2.36 (0.09)ab
	1014	3770 (29)c	2.32 (0.10)b	4020 (28)c	2.42 (0.11)b

[z] Values indicate the intended magnitude; we used measured pre-tension as a co-variate in the ANCOVA.

[y] Within each pre-tension value, estimates followed by the same letter are not significantly different ($p > 0.05$) by Tukey's Honestly Significant Difference test.

Table 2

Best-fit estimates of mid-span speedline height (m) before (h_P) and during (h_L) loading, and percent reduction in speedline height, for each intended pre-tension (N) and added load (N). Standard errors in parentheses follow estimates. Within each intended pre-tension, estimates followed by the same letter are not significantly different ($p > 0.05$) by Tukey's Honestly Significant Difference test.

Pre-tension^z	Load	h_P	h_L	Reduction^y
667	658	5.47 (0.02)a	2.73 (0.03)a	50% a
	858	5.53 (0.02)a	2.52 (0.03)b	54% ab
	1014	5.48 (0.02)a	2.37 (0.03)c	57% b
1112	658	5.61 (0.01)a	2.92 (0.02)a	48% a
	858	5.63 (0.01)a	2.70 (0.02)b	52% ab
	1014	5.60 (0.01)a	2.57 (0.02)c	54% b
1556	658	5.74 (0.02)a	3.12 (0.03)a	46% a
	858	5.72 (0.02)a	2.87 (0.02)b	50% ab
	1014	5.73 (0.02)a	2.77 (0.03)c	52% b

[z] Measured pre-tensions were used in the analysis.

[y] Calculated as $1 - \frac{loaded\ height}{pre - loading\ height}$.

increased and (ii) increased as added loads increased aligned with Fabiano et al.'s (2011) findings for skylines. This lends some confidence that speedlines and skylines behave similarly, despite large differences in span length, rope elasticity and the magnitude of pre-tension. Thus, although we did not alter the span and angle of the speedline, the increase in the ratio of pre- and post-tension for skylines with longer spans (Fabiano et al., 2011) likely applies to speedlines, too.

Span length, rope elasticity, and speedline geometry will affect mid-span deflection. Despite more than doubling the pre-tension among trials, pre-tensioning achieved only a small increase in height above ground. Pre-tensioning did not overcome the approximately 50% reduction in height after adding loads. Given the disparity between the increase in clearance from pre-tensioning and the reduction in clearance after adding loads, it may be unrealistic to expect that pre-tensioning can meaningfully compensate for the reduction in clearance after adding loads. Choosing a rope with minimal elasticity would be important to maintaining clearance. And even though the tension ratio decreased at greater pre-tensions, which is consistent with wire rope in skylines (Fabiano et al., 2011), the absolute increase in tension after adding loads may greatly increase the likelihood of failure of the speedline or tree used as the high anchor (Detter et al., 2008). Rope elasticity and speedline geometry both affect deflection; increasing the span or elasticity increases deflection, and pre-tensioning may not be able to safely overcome the anticipated reduction in clearance after adding loads.

5. Conclusion

Although the likelihood of failure of the speedline or tree was low, our results are limited in two important ways. First, we considered a small range of pre-tensions and added loads. For example, the maximum added load, 1014 N, is the weight of a log of red oak (*Quercus rubra* L.) 30 cm in diameter and 1.4 m long. Arborists sometimes use speedlines to move much heavier debris, which would increase the likelihood of failure of the speedline or the tree used as the upline anchor. Secondly, we tested a single speedline geometry, and the angle that the pre-tensioned and loaded speedline makes with the tree serving as the upline anchor affects the magnitude and distribution of different types of stress in the stem below the anchor point (Pyles and Pugh, 1987). More empirical studies are needed to address the limitations of our work so that better theoretical models for tension and deflection, which are based on Fig. 2, can be developed.

Conflict of interest

The authors declare that they have no conflicts of interest related to this work.

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