TWINE TENSION IN HIGH-DENSITY LARGE SQUARE BALES

J. R. McAfee, K. J. Shinners, J. C. Friede

ABSTRACT. *When greater density bales are made, baler manufacturers recommend using twine with greater knot strength. When twine fails, bale integrity is lost, harvesting costs increase, and productivity suffers. Twine failure typically occurs in the knot on the top strand of the twine. A better understanding of twine tension in the top strands could help reduce failures, allow for improved knot strength recommendations, and ultimately lower baling costs. A system was developed to measure the tension of the top strands while baling a variety of crops with a high-density large square baler. Depending on the bale chute design, twine tension was greatest as the bale cantilevered from the chamber but had not yet touched the chute or just as the bale fully exited the bale chamber. In either case, the absolute maximum recorded tensions were typically less than 60% of the twine specified knot strength. Pulses in synchronization with the plunger frequency were superimposed on the nominal twine tension. Tension was usually greatest in the outer left twine and the other right twine because for each, there was only one neighboring twine to share the load. Average twine tension over the first 60 s after the bale rested on the ground was linearly related to bale density. Crop stress relaxation reduced tension up to 20% within 20 min after the bale was placed on the ground. Top strand tension approached 60% of knot strength for only a short duration as the bale exited the chamber and after that, the tension was much less than the specified knot strength. Therefore, design changes or strategies that reduce tension during the critical period when the bale exits the chamber could reduce maximum knot strength requirements and lead to lower baling costs.*

Keywords. *Bales, Density, Tension, Twine.*

The large-square bale (LSBe) is currently the dominant package used to harvest and store commercial hay and biomass feedstocks. Greater bale density reduces costs associated with bale aggregation, handling, storage, and transport (Kenney et al., 2014). To produce higher-density bales, manufacturers have modified balers to have greater bale chamber convergence, longer bale chambers and more robust drivelines. Manufacturers typically recommend twine with greater knot strength be used when making high-density bales. Previous research has shown that resilient forces exerted by bales of lint cotton were linearly related to moisture content and bale density (Anthony and McCaskill, 1978).

Large-square bales typically resist the resilient forces of the compacted material using a series of polyethylene twine loops which are parallel to the bale's longitudinal axis. Each individual strand of twine is supplied from two sources on the baler – one strand each laid on the top and bottom of the bale as it moves rearward through the chamber. The top and bottom strands are initially tied together so that twine is laid across the leading vertical face of the bale as it moves rearward. When the bale has reached the required length, the twine needles bring the bottom twine upward, placing the twine across the trailing face of the bale. The needles then capture the top twine and the two twines are directed toward the knotter. The knotter ties the top and bottom twines together, completing the loop around the bale. After the first knot completes the loop, a second knot is immediately tied to reconnect the top and bottom twine to start the loop of the next bale. This "double-knotter" system was first patented by White (1978) and is now virtually universal on large-square balers (LSBrs). The completed twine loop is slack right after the loop is closed and gradually becomes taut as the bale moves rearward and begins to expand.

Twine failure is an important issue for hay producers and biomass enterprises. Even when the bale has six to eight parallel strands of twine, the failure of a single twine can cause adjacent twines to fail and lead to bale disintegration. When bale integrity is lost in the field, costs can increase considerably. The operator must first remove the broken strands, and then spread the bale flakes by hand to make a manageable windrow. Then the windrow must be rebaled, typically at a very slow rate to prevent plugging the baler pick-up. Finally, the rebaled material typically does not form as well defined a bale as previously unbaled material, so these bales must be handled gently during subsequent aggregation. Twine failure results from knotter mechanical issues or excessive twine tension.

Although tensile failure of the twine strand can occur anywhere, it is well documented that failure of rope, yarn or

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twine typically occurs inside or near the knot (Ashley, 1944; Saitta et al., 1999; Pieranski et al., 2001). The exact location of knot failure is not precise and is affected by many parameters such as the type of knot or the parent material. Some research suggests the knot will fail first at the entrance to the knot where the filament curvature is the greatest (Saitta et al., 1999; Pieranski et al., 2001) while other research suggests failure occurs within the knot (Uehara et al., 2007). Identification of failure location is complicated because the knot becomes smaller while stretching, so any given position within the knot moves continuously. Progressive knot squeezing also leads to deformation of the strand diameter, which influences the breaking mechanism of the knot (Uehara et al., 2007).

Because twine is most likely to fail at the knot, knowledge of baler twine knot strength is more useful than the strand tensile strength. The ASABE Standard for Agricultural Baling Twine for Automatic Balers (S315.4, 2017) provides the appropriate range of LSBe knot strength from 1070 to 2670 N. Manufacturers of LSBrs are now producing high-density balers (AGCO, 2017) so twine manufacturers now offer twine with knot strength greater than 2900 N to support these high-density balers.

Knowledge of the actual twine tension would be useful to solve twine failure issues. However, there is a lack of published work reporting tension in twine as the bale is produced. Therefore, our objective was to (a) develop a methodology to measure twine tension during baling, and (b) measure twine tension across several crop materials and bale densities.

MATERIALS AND METHODS

Tension in a rope or cable can be measured by placing a load cell in series between the end of the rope or cable and an end fixture. However, this approach is impractical for measuring twine tension which uses a closed loop around the bale. Our approach was to apply a load-cell in parallel with the twine using a two-point bending load cell (fig. 1). The clamp-on load cells chosen were model DLWS-1t from Load Cell Central (Milan, Pa.) with 9800 N capacity and which weighed 860 g. Tension was measured by the bending force created by the twine tension on the two loading points of the clamp-on load cells, and twine did not have to be cut. The Krone HDP twine used (Krone North America, Memphis, Tenn.) had specified knot strength of 2750 N. Using this baler twine, calibration relationships between twine tension and load cell output were determined using an MTS Insight universal tension tester (MTS Systems Corporation, Eden Prairie, Minn.). A Campbell Scientific (Logan, Utah) model 21X datalogger was used to excite the load cells and then record load cell output at 5 Hz.

Twine tension was measured on bales formed with either a Krone model 1290 HDP or model 1290 HDP XC baler. The latter baler had a pre-cutter that, if used in an experiment, was configured with 22 knives with 44 mm spacing between the knives. The outside two knives on each side were removed to help maintain bale integrity. The bale chute was parallel to the bale chamber but in a plane offset 11 cm below the bottom of the bale chamber. The drop height from the end of the bale chute to the ground was 64 cm and the chute was 222 cm long. The chute featured five rollers but the two rollers closest to the chamber were locked to create a longer dwell time on the chute. Longer dwell time is recommended by the manufacturer to produce a more accurate scale reading. Both balers used six twines, so six load cells were used for each test. Each twine formed a closed loop of fixed length and was defined to have four strands–top, bottom, and two face strands. The knots were located on the top strand so twine tension was measured on this strand.

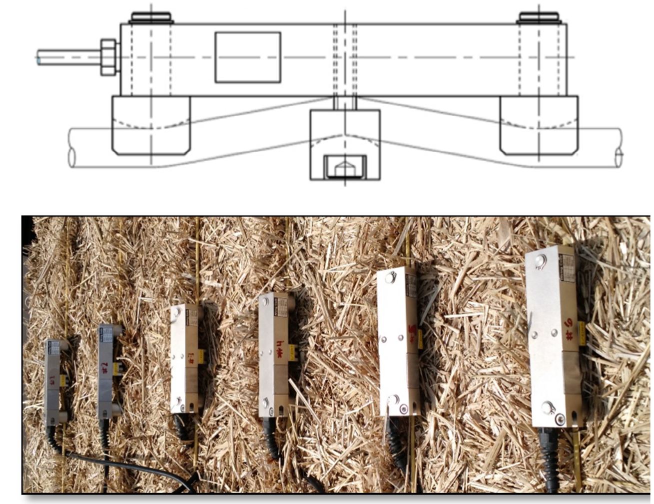


Figure 1. Two-point bending load cell used in parallel with the baler twine to quantify the tension (top) and orientation of the load-cells on the top strands (bottom).

Densification in an LSBr is caused by resistance to bale movement created by the variable convergence of the bale chamber, and the load on the plunger crank arms is used to measure the force to overcome this resistance. The plunger load sensors measure the force applied to the bale face, and the LSBr processor then controls the pressure to the chamber convergence cylinders to adjust the bale density based on the plunger force (Afzalinia and Roberge, 2012). Therefore, bale density was changed by setting the baler's performance monitor to vary the plunger load, expressed as a fraction of the maximum force on the plunger allowed by the baler manufacturer. It was hypothesized that greater bale density as achieved by increasing plunger loads would result in higher twine tension, so plunger loads studied were always at least 60% of maximum (table 1), but if more crop was available to accommodate more tests, then lower plunger loads were also used. The balers were powered with either a John Deere (Moline, Ill.) model 8275R (164 kW PTO) or model 8345R (212 kW PTO) tractors. After a few bales were made to allow the plunger force to reach equilibrium, a bale was allowed to protrude about 30 cm out of the bale chamber and then baling was halted. At this time, there was some tension in the twine. The load cells were then affixed to the top strands of the twine, the datalogger was secured to the bale, the data collection was initiated and then baling recommenced. The time required to attach the load cells and datalogger was variable, but typically required several minutes, so some unavoidable bale stress relaxation likely occurred.

Table 1. Details of twine tension experiments conducted.

Crop Type	Avg. Moisture (% w.b.)	Plunger Loads[a] (% of maximum)	Baler Pre-Cutter[b] Used	No. of Replicate[c] Bales
Spring harvest[d]				
Switchgrass	11.1	30, 50, 70, 90	No	4
Reed canarygrass	15.6	30, 50, 70, 90	No	3
Forage sorghum	21.4	30, 50, 70, 90	No	3
Summer harvest[e]				
Alfalfa (2nd cutting)	15.6	30, 45, 60, 75	No	4
Fescue	15.5	45, 60, 75, 90	No	3
Wheat straw	10.3	60, 75, 90	No	8
Wheat straw	8.3	60, 75, 90	Yes	3
Fall harvest[f]				
Switchgrass	14.1	60, 75, 90	No	3
Switchgrass	15.7	60, 75, 90	Yes	3
Native grasses[g]	14.4	60, 75, 90	No	3
Native grasses[g]	12.2	60, 75, 90	Yes	3
Corn stover	16.0	60, 75, 90	No	3

[a] Target plunger load as fraction of maximum allowed by manufacturer.
[b] Pre-cutter had 26 knives with 44 mm spacing.
[c] Number of replicate bales per plunger load.
[d] Crops had overwintered and were harvested in April, 2016.
[e] Baled in the summer of 2016 (wheat) or 2017 (fescue and alfalfa).
[f] Baled in October, 2016.
[g] Mixture of Indiangrass and big bluestem.

Data collection continued as the bale exited the chamber, rode on the bale chute, fell from the chute, and then for an additional 60 s as it rested on the ground. The load cells were located above the twine so the load cell did not stretch the twine away from the bale surface (fig. 1). Each portion of the crop fed into the bale chamber was called a flake. Baling speed was adjusted so the baler pre-compression system delivered one new flake to the bale chamber for each plunger stroke (45 strokes per min). Typical travel speed was between 10 and 13 $km \cdot h^{-1}$. The number of flakes per bale was visually recorded from the baler performance monitor.

Crops for which twine tension was measured included alfalfa, fescue, switchgrass, native grass mix (big bluestem and Indiangrass), reed canarygrass, forage sorghum, wheat straw, and corn stover. When sufficient crop and time were available, the use of the baler pre-cutter was used as an additional variable (table 1). At least three replicate bales were made at each plunger load during each experiment.

An additional test was conducted to compare twine tension on the top and leading face of the bale. Crops used were wheat straw and corn stover, the baler was operated at 90% plunger load, and four replicate bales were made. On the same twine, one load cell each was placed on the top strand and leading face strand and this arrangement was repeated on two adjacent twines. Other aspects of the test were similar to those discussed above.

Several other non-replicated experiments were conducted to observe how twine tension behaved under specific conditions. The open distance between the bale chamber rails was just wider than the load cells, so attaching the sensors here risked load cell damage. However a few tests were done in this way to quantify the manner in which the twine transitioned from slack to taut. In an additional test, twine tension was recorded for a long period on a few bales to observe how twine tension decayed due to bale stress relaxation. In another test, modifications were made to the bale chute to remove the 11 cm vertical offset between the bottom of the chamber and the bale chute. This prevented the bale from cantilevering from the chamber before it was supported by the chute. Finally, tension was measured on a few bales as they were lifted and moved using a conventional three-tine bale spear on a tractor-loader or skidsteer loader.

Bale mass, length, and moisture content were quantified to determine the bale density on a dry basis. The bale length was measured to the nearest 2 cm. The bales were weighed on a 1,800 kg capacity platform scale with a resolution of 0.5 kg. Each bale was subsampled for moisture content with a 50 mm diameter by 80 cm long boring tool. Samples were then oven dried for 24 h at 103°C according to ASABE Standard S358.2 (2012).

Maximum tension in the top strands of the twines was quantified in two ways. The average maximum tension ($T_{max\ ave}$) was calculated by:

$$T_{max\,ave} = \left(\sum_{i=1}^{n} T_{i\ max} \right) \div n \quad (1)$$

where $T_{i\ max}$ was the maximum tension measured on any individual twine of an individual bale (i) and n was the number of replicate bales per treatment. Also determined was the absolute maximum tension measured across all twines and replicate bales within a treatment. Since this parameter yielded only a single value per treatment, no statistical analysis was possible. The average tension for the first 60 s the bale rested on the ground was calculated for each bale. The total horizontal restraining force was estimated by first finding the average tension of each of the six twines during the first 60 s the bale was resting on the ground, then summing the average tension from all six strands and finally multiplying this sum by two. This estimate assumes the tensions of the top and bottom strands were equally pulling on the bale ends to hold the bale together and ignored the restraint provided by friction of the bale on the ground surface

Twine tension pulsed in synchronization with plunger frequency, creating dynamic loading of the knots (figs. 2 and 3). The average maximum tension pulse ($TP_{max\ ave}$) was calculated by:

$$TP_{max\,ave} = \left(\sum_{i=1}^{n} TP_{i\ max} \right) \div n \quad (2)$$

where $TP_{i\ max}$ was the maximum amplitude of a tension pulse measured on any individual twine of an individual bale (i) and n was the number of replicate bales per treatment. The absolute maximum tension pulse measured across all twines and replicate bales within a treatment was also determined. Since this parameter yielded only a single value per treatment, no statistical analysis was possible.

An analysis of variance was used to determine if bale density had a statistically significant impact on the twine tension parameters with each bale considered as an experimental unit. Statistical differences were based on a least significant

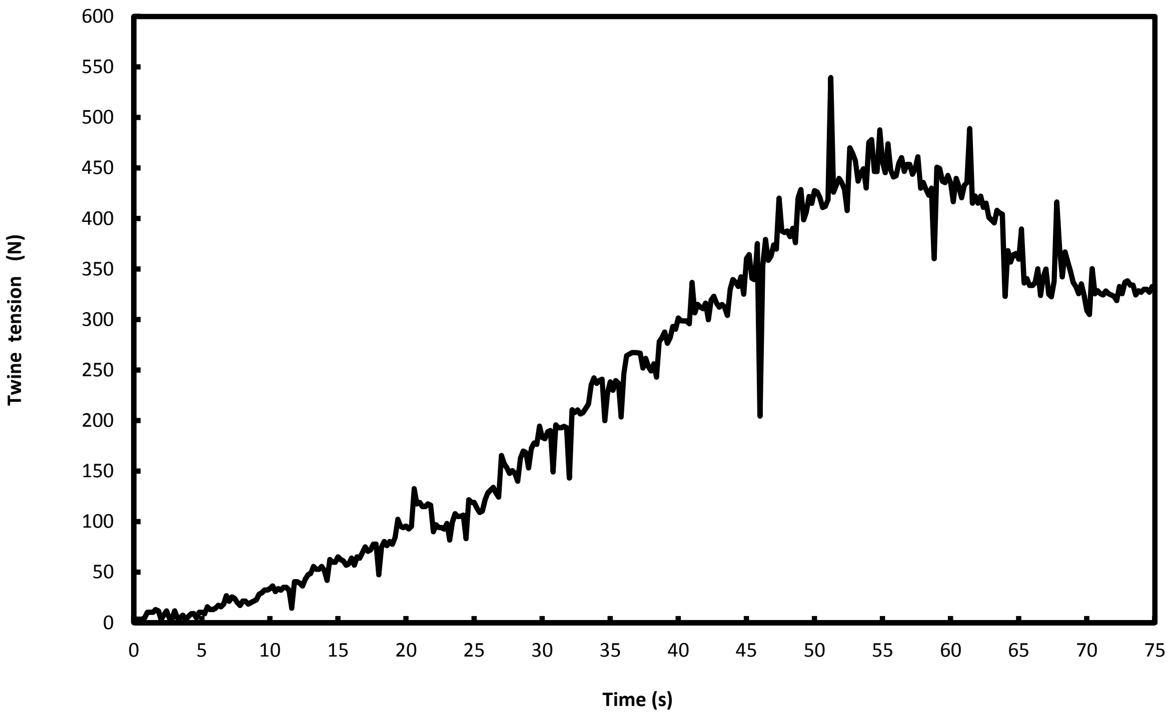


Figure 2. Twine tension averaged across all six load cells for a typical switchgrass bale. Measurement started when the bale was still fully in bale chamber and the twines were slack.

difference (LSD) at the 5% significance level and the analysis was conducted using the Data Analysis package in Excel (Version 2010).

RESULTS

Twine tension increased gradually as the bale moved from the bale chamber until it fully exited the chamber and rested on the bale chute (fig. 2). Although twine tension increased gradually, there were pulses in twine tension synchronized

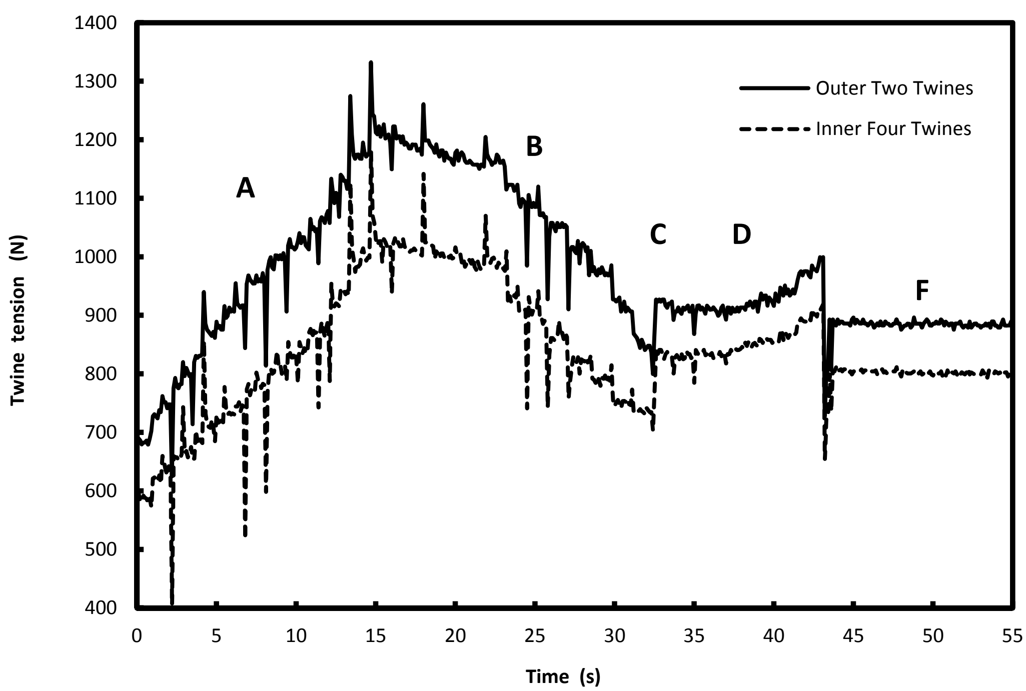


Figure 3. Mean twine tension for outer left twine and outer right twine (outer two twines) and mean twine tension for remaining four twines (inner four twines) for a switchgrass bale. Region (A) bale exits chamber and leading portion bends downward; (B) bale reverse bends as leading edge of bale contacts chute; (C) bale fully exits chamber; (D) bale begins to cantilever off chute; (E) bale drops to ground; and (F) bale resting on the ground.

with plunger frequency (figs. 2 and 3). When tension dropped and then recovered to its original value, it was assumed the plunger compressed a new flake onto the untied bale being formed but the tied bale did not move further out of the bale chamber. The resistive forces from static friction at the rear of the converging bale chamber were greater than the plunger force, so the tied bale was compressed, reducing twine tension. Tension recovered to its original value when the bale re-expanded toward the front of the baler. When tension increased and then recovered to its original value, it was assumed the plunger force was sufficient to overcome static friction, forcing the tied bale to move rearward. The bale then incrementally exited the bale chamber, causing tension to increase to due to bale expansion and momentum generated by the sudden movement of bale.

The tension pattern had seven distinct phases. Tension grew gradually as the bale began to exit the chamber (fig. 2). As bales exited the chamber they cantilevered from the chamber and were initially unsupported by the bale chute. In this situation the leading portion of the bale deflected slightly downward, increasing the tension in the top strands (region A, fig. 3). The maximum twine tension usually occurred in this region. As more of the bale exited the chamber and the leading edge contacted the chute, the bale started to reverse bend, bending concave upward and top strand tension declined (region B). When the bale fully exited the chamber the top strand tension increased quickly (region C). This was likely due to the bale now resting flat on the chute and the elimination of the reverse bending effect. Tension stayed relatively constant for a short duration while the bale rested fully supported on the chute. When the leading edge of the bale started to move off the end of chute, the leading portion again bent downward and top strand tension rose again (region D). There was a momentary drop in top strand tension due to reverse bending when the bale impacted the ground (region E). Finally, the tension remained relatively constant once the bale rested on the ground, although stress relaxation in the baled material caused a slow tension decline (region F).

To facilitate weighing bales with load cells, the baler manufacturer configured the bale chute to be approximately parallel to the bottom of the bale chamber, but with a vertical offset of 11 cm below the chamber floor. To achieve an accurate weight measurement, the bale on the chute cannot contact the bale still in the chamber, and this vertical offset helps accomplish this. With some crops, more of the bale length cantilevered from the chamber before the leading edge of the bale contacted the chute, compared to other crops. This occurred more for crops with large, stiff stems (switchgrass, native grasses, corn stover, sorghum, wheat straw) than crops with small, more supple stems (alfalfa, fescue). This phenomenon was also more pronounced at greater bale densities caused by greater plunger loads. Bending stress and twine tension were greater on bales which exhibited greater unsupported length as the bale exited the chamber.

When modifications were made to the chute to eliminate the vertical offset with the chamber, top strand tension rose steadily as the bale moved out of the chamber (fig. 4). When the vertical offset was removed, no longer evident were the high initial tension due to downward bending, the tension reduction due to reverse bending, and the sudden spike in tension as the bale exited the chamber. In the limited number

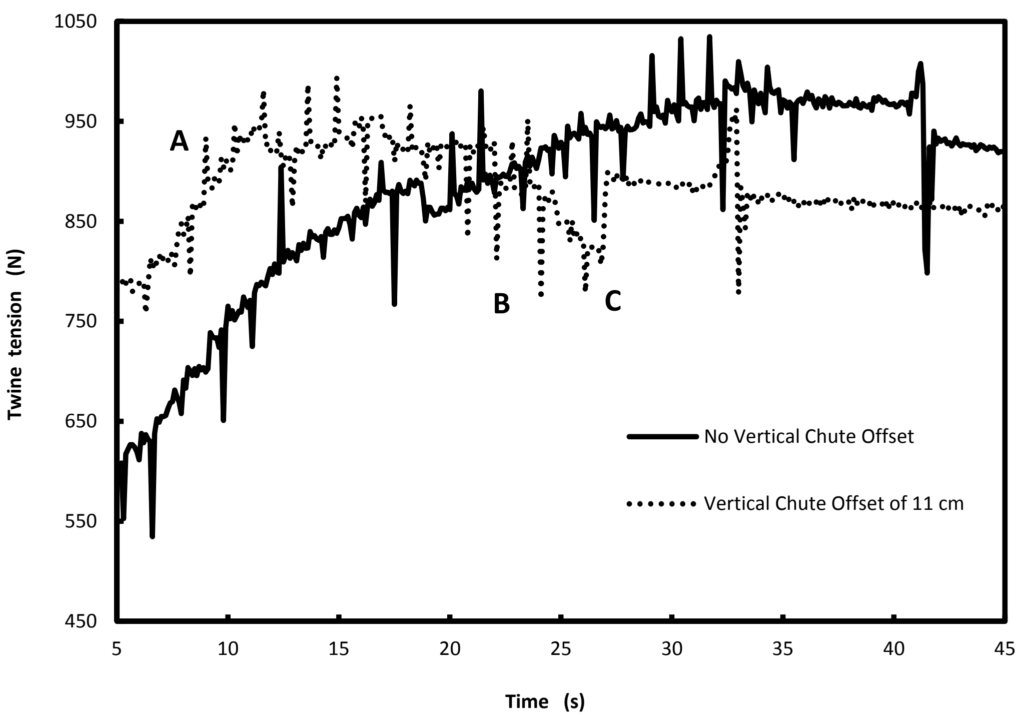


Figure 4. Average twine tension for two wheat straw bales (166 kg DM·m^{-3}). When the bale chute was not vertically offset from the chamber, tension increased gradually, eliminating cantilever loading (region A); reverse bending (region B); and sudden spike in tension as bale exited the bale chamber (region C) as exhibited on the bale made with an 11 cm vertical bale chute offset.

of bales made with no chute offset, there was no indication that this chute configuration resulted in appreciably different maximum twine tension than when the chute was offset.

Tension often varied considerably from twine-to-twine on any given bale. Generally, the tension was greater in the outer left twine and outer right twine primarily because there was only one neighboring twine to share the load, although differences in bale density between the edges and center of the bale might also contribute to this observed result (fig. 3). However, sometimes an interior twine had the greatest tension. The range of tension could vary by several hundred Newtons on any given bale (fig. 5). This variation could partially be due to side-to-side non-uniformity of the thickness of the flakes or differences in the tendency for the twine to penetrate the bale corners.

Twine does not form a sharp right angle at the bale corners, rather it "digs-into" and penetrates the corners to form a rectangle with rounded corners. We approximated the rounded corners as straight lines with equal length legs (x) forming a right triangle (fig. A1). When the twine just becomes taut, the twine length is equal to the bale perimeter. As described in Appendix A, the loop of twine is assumed to have a fixed length. If the fixed-length loop of twine penetrates equally on all four corners, then the bale length must increase by the following (see Appendix A):

$$\Delta L = 2x \cdot \left(2 - \sqrt{2}\right) \quad (3)$$

Twine-to-twine differences in corner penetration would therefore affect the load carried by each twine because the bale would have different expansion at each twine.

In our experiments, twine rarely failed, but an example of when twine failed at the knot is shown in figure 5. The 1050 N tension at failure was considerably less than the specified knot strength (2750 N). Tension in the neighboring twines increased right after failure, with the greatest impact on those twines closest to the twine that failed.

The maximum twine tension – either average or absolute – almost always occurred as the bale began to exit the bale chamber and deflected downward toward the chute creating bending stress in the top of the bale (region A, fig. 3). In this region, twine tension was affected by many factors, so a direct correlation with bale density would not be expected. These factors included, but were not limited to, differences in the length the bale cantilevered from the chamber before touching the chute and dynamic loading from field irregularities.

The amplitudes of the tension pulses were not well correlated with plunger load and there were few statistical differences. The tension pulses increased twine tension by 20% to 30% for the crops like alfalfa, straw, and grasses but increased by 40% to 50% for the crops like stover and sorghum with thick, heavy stems.

Bale density was significantly affected by plunger load in most experiments (tables 2 and 3), and bale density was linearly related with plunger load (table 4). The pre-cutter had the greatest impact on bale density in wheat straw, especially at the greatest plunger load where use of the pre-cutter increased density by 14%. Use of the pre-cutter in the grass crops increased density by only 2% to 5%. Average twine tension for the first 60 s when the bale was on the ground and estimated total restraining force were linearly related

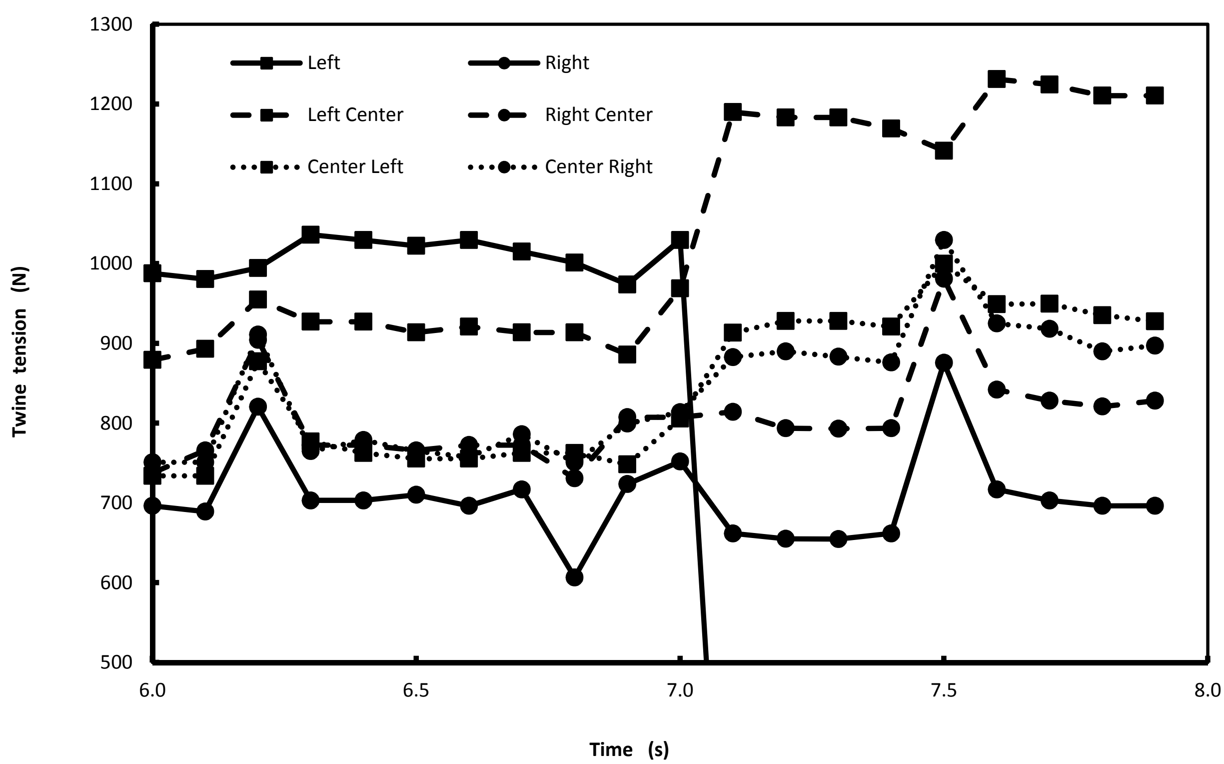


Figure 5. Twine tension across all six twines for switchgrass bale. The left most twine failed at the knot at 7 s into the test.

Table 2. Twine tension for crops baled in the spring after overwintering.

			Twine Tension (N)				Amplitude of Twine Tension Pulse (N)	
			On Baler		Resting on the Ground			
Plunger Load[a]	Bale Length (cm)	Bale Density (kg DM·m^{-3})	Average Maximum[b]	Absolute Maximum[b]	Average Maximum[c]	Restraining[d]	Average Maximum[e]	Absolute Maximum[e]
Switchgrass[f]								
30%	244	132 a	853 a	1000	592 a	7104 a	166 a	216
50%	250	161 b	1083 b	1174	806 b	9672 b	179 a	274
70%	250	176 c	1142 b	1220	889 b	10668 b	196 a	276
90%	250	198 d	1188 b	1433	916 b	10992 b	187 a	263
LSD[g] (P = 0.05)		4	173		138	1656	75	
Reed Canarygrass[f]								
30%	258	129 a	985 a	1020	632 a	7584 a	207 a	293
50%	256	158 b	1127 b	1192	790 b	9480 b	185 a	259
70%	250	182 c	1255 c	1282	912 c	10944 c	227 a	303
90%	260	214 d	1395 d	1438	995 c	11940 c	201 a	294
LSD[g] (P = 0.05)		17	83		109	1308	72	
Sorghum[f]								
30%	248	139 a	750 a	789	508 a	6096 a	286 a	361
50%	256	167 b	882 b	899	631 b	7572 b	336 ab	408
70%	260	191 c	1021 c	1081	754 c	9048 c	320 ab	416
90%	256	225 d	1365 d	1365	896 d	10752 d	363 b	487
LSD[g] (P = 0.05)		18	78		57	684	61	

[a] Target plunger load as fraction of maximum allowed by baler manufacturer. Pre-cutter was not used in this experiment (see table 1).
[b] Maximum measured tension averaged across all replicate bales (eq. 1) or absolute maximum measured across all bales of that plunger load.
[c] Average tension across all six twines at equilibrium when bale is on the ground.
[d] Estimated total restraining force from twice the sum of tension in all six twines at equilibrium when bale is on the ground.
[e] Maximum measured tension pulse averaged across all replicate bales (eq. 2) or absolute maximum tension pulse amplitude.
[f] See table 1 for moisture content and number of replicate bales.
[g] Least significant difference. Means in the same column followed by different letters are significantly different at 5% significance level.

with plunger load (table 4) although differences were not always significant (tables 2 and 3). The average twine tension during the first 60 s the bale rested on the ground was 30% to 35% less than the maximum tension observed during bale formation.

Once the bale was on the ground, twine tension followed a classical decay model for a biological material (Peleg, 1980) due to stress relaxation in the bale. In a switchgrass bale (fig. 6), stress relaxation reduced tension from the initial value by 20% within 30 min. In a mixed grass bale (fig. 6), stress relaxation continued for days after baling and twine tension was 40% less than the initial value within 24 h. Lifting and moving bales with a conventional three-tine spear increased twine tension by as much as 30% relative to the initial value (data not presented). Dynamic loading of the bale due to rough field conditions increased tension by as much as 250 N when moving bales with a tractor-loader or skidsteer loader. However, the maximum tension measured when moving bales was typically less than the maximum tension measured during baling.

The capstan principle suggests that when an element is wrapped partially around a cylinder the static friction force increases exponentially with the angle of wrap (Levin, 1991). Because bales are primarily expanding in the longitudinal direction, the top strand tension would be analogous to the capstan load force and would likely be greater than the tension on the face strand which is analogous to the capstan hold tension. The top strand tension was approximately 40% greater than the face strand tension (table 5). The maximum tension and the amplitude of the tension pulses were also greater on the top strands than on the face strands. The presence of the knots and the greater strand tension on the top of the bale help explain why twine typically fails on the top of the bale rather than on the bale face.

Discussion

A three-phase viscoelastic process has been suggested for bale flakes undergoing compression: void reduction, followed by elastic and plastic deformation, and then stress relaxation (Nona et al., 2014). Increasing bale density is achieved by more resistance to flow through the bale chamber, resulting in greater plunger load and bale face pressure. Greater resistance is created by more chamber wall convergence and a longer bale chamber (Afzalinia and Roberge, 2012). Higher bale face pressure will likely cause more stems to plastically deform and yield while other stems will likely have more elastic deformation. While both results will increase bale density, high-density bales may have more release of stored elastic energy when the bale starts to exit the chamber and the twine must restrain these resilient forces. However, more plastic deformation from high face pressure plus additional stress relaxation due to longer residence time in an extended bale chamber may offset some of the impact of greater resilient forces. Average twine tension during the first 60 s the bales rested on the ground was greatest in crops with large, stiff stems where greater resilient forces could be expected due to greater stored elastic energy in the compressed stems.

Tension in the top strands of the twines approached 60% of specified knot strength only for a short duration as the bale exited the chamber. Twine tension then declined to levels much less than the specified knot strength. Therefore, design changes or strategies that reduce tension during the critical

Table 3. Twine tension for crops baled in the summer or fall.

Plunger Load[a]	Average Flakes per Bale	Bale Length (cm)	Bale Density (kg DM·m^{-3})	Twine Tension (N): On Baler: Average Maximum[b]	Twine Tension (N): On Baler: Absolute Maximum[b]	Twine Tension (N): Resting on the Ground: Average Maximum[c]	Twine Tension (N): Resting on the Ground: Restraining[d]	Amplitude of Twine Tension Pulse (N): Average Maximum[e]	Amplitude of Twine Tension Pulse (N): Absolute Maximum[e]
Alfalfa[f] – without pre-cutter									
30%	39	216	180 a	832 a	1,026	484 a	5,808 a	257 a	316
45%	45	216	201 b	865 a	990	501 ab	6,012 ab	329 b	380
60%	46	218	220 c	948 ab	1,122	599 b	7,188 b	309 ab	367
75%	52	216	249 d	1,173 b	1,296	735 c	8,820 c	298 ab	401
LSD[g] (P = 0.05)			13	258		111	1332	63	
Wheat Straw[f] – without pre-cutter									
60%	35	216	168 a	1,142ab	1,182	731 a	8,772 a	235 a	274
75%	39	222	178 b	1,126a	1,225	763 ab	9,156 ab	238 a	280
90%	45	218	196 c	1,205b	1,284	813 b	9,756 b	247 a	305
LSD[g] (P = 0.05)			8	77		77	928	31	
Wheat Straw[f] – with pre-cutter									
60%	32	232	171 a	1,081 a	1,177	748 a	8,976 a	274 a	348
75%	33	234	191 b	1,202 ab	1,280	769 a	9,228 a	328 a	429
90%	36	230	224 c	1,332 b	1,363	794 a	9,528 a	340 a	388
LSD[g] (P = 0.05)			13	172		57	678	102	
Corn Stover[f] – without pre-cutter									
60%	N/A	212	188 a	1,097 a	1,168	613 a	7,356 a	304 a	383
75%	N/A	218	198 ab	1,288 b	1,355	668 ab	8,016 ab	366 a	448
90%	N/A	224	214 b	1,456 c	1,468	740 b	8,880 b	387 a	526
LSD[g] (P = 0.05)			18	80		116	1,392	91	
Switchgrass[f] – without pre-cutter									
60%	37	216	195 a	1,336 a	1,567	761 a	9,132 a	287 a	350
75%	41	222	208 b	1,514 a	1,580	859 a	10,308 a	290 a	350
90%	46	220	217 c	1,422 a	1,525	896 a	10,752 a	260 a	300
LSD[g] (P = 0.05)			7	298		101	1,212	53	
Switchgrass[f] – with pre-cutter									
60%	27	222	198 a	1,185 a	1,236	698 a	8,380 a	248 a	298
75%	28	216	218 b	1,605 b	1,747	862 b	10,346 b	301 b	360
90%	32	222	225 b	1,502 b	1,575	918 b	11,010 b	259 ab	337
LSD[g] (P = 0.05)			7	211		142	1,704	50	
Native Grasses[f] – without pre-cutter									
60%	36	220	195 a	1,318 a	1,448	756 a	9,068 a	286 a	342
75%	43	224	208 b	1,287 a	1,430	770 a	9,241 a	345 a	413
90%	46	224	224 c	1,464 a	1,656	890 a	10,680 a	297 a	380
LSD[g] (P = 0.05)			12	314		197	2,368	60	
Native Grasses[f] – with pre-cutter									
60%	36	220	198 a	1,138 a	1,349	632 a	7,587 a	261 a	333
75%	36	218	213 b	1,256 a	1,360	745 ab	8,936 ab	298 b	385
90%	42	220	228 c	1,292 a	1,444	821 b	9,849 b	287 ab	330
LSD[g] (P = 0.05)			8	265		155	1,856	30	
Fescue[f] – without pre-cutter									
45%	36	216	187 a	911 a	928	709 a	8,505 a	231 a	255
60%	38	222	199 b	1,060 a	1,164	697 a	8,367 a	310 a	378
75%	38	216	208 c	1,049 a	1,088	716 a	8,587 a	322 a	380
90%	42	222	223 d	1,121 a	1,354	740 a	8,878 a	322 a	497
LSD[g] (P = 0.05)			7	222		103	1241	105	

[a] Target plunger load as fraction of maximum allowed by manufacturer.
[b] Maximum measured tension averaged across all replicate bales or absolute maximum measured across all bales of that plunger load.
[c] Average tension across all six twines at equilibrium when bale is on the ground.
[d] Estimated total restraining force from twice the sum of tension in all six twines at equilibrium when bale is on the ground.
[e] Absolute maximum tension pulse amplitude or maximum measured tension pulse averaged across all replicate bales.
[f] See table 1 for moisture content and number of replicate bales.
[g] Least square difference. Means in the same column followed by different letters are significantly different at 95% confidence.

period when the bale exits the chamber should be investigated. Twine tension was typically greater on the outer left twine and outer right twine, so using twine with lower knot strength on the remaining twines could reduce baling variable costs.

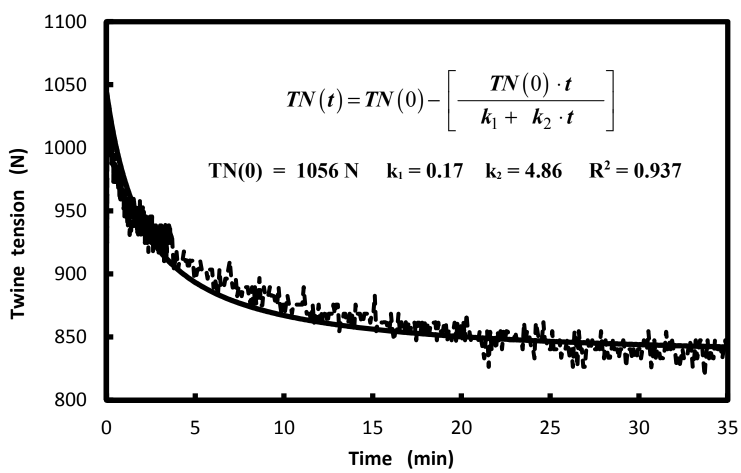
Table 4. Slope and intercept for linear models of bale density, and tension when bale is resting on the ground, and restraining force.

	Bale Density[a] (kg DM·m^{-3})			Tension when Bale Resting on Ground[b] (N)			Restraining Force[c] (N)		
	Slope	Intercept	R^2	Slope	Intercept	R^2	Slope	Intercept	R^2
Alfalfa	150	136	0.989	3.79	-236	0.933	44.7	-2504	0.938
Fescue	77	152	0.991	1.09	495	0.740	15.5	5441	0.847
Reed canarygrass	139	87	0.997	4.32	101	0.971	32.1	3763	0.677
Corn stover	89	133	0.988	4.96	-321	0.998	57.2	-3356	0.999
Sorghum	142	95	0.996	4.56	-120	0.999	33.8	1865	0.811
Wheat straw									
without pre-cutter	92	112	0.968	3.22	185	0.951	16.4	-5901	0.901
with pre-cutter	176	63	0.977	1.33	501	0.895	11.1	6709	0.306
Native grasses									
without pre-cutter	95	138	0.997	5.01	-240	0.864	52.6	-1307	0.803
with pre-cutter	100	138	0.999	4.67	-247	0.996	57.0	-3150	0.997
Switchgrass									
Spring – without pre-cutter	107	103	0.989	5.51	-103	0.946	61.2	-905	0.971
Fall – without pre-cutter	74	151	0.994	6.25	-452	0.978	74.1	-5252	0.969
Fall – with pre-cutter	89	147	0.918	8.47	-983	0.999	101.0	-11681	0.999

[a] Bale density (kg DM·m^{-3}) as a function of plunger load.
For example, bale density = 150 × plunger load + 136, where plunger load is the fraction of the maximum plunger load allowed by the baler manufacturer expressed as a decimal.

[b] Average tension (N) during the first 60 s the bale rested on the ground as a function of bale density (kg DM·m^{-3}).
For example, tension = 3.79 × bale density - 236.

[c] Restraining force (N) as linear function of bale density (kg DM·m^{-3}).
For example, restraining force = 44.7 × bale density - 2504.



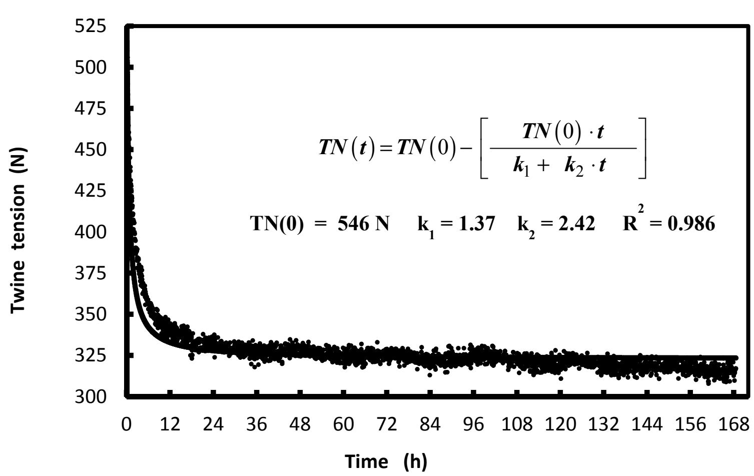


Figure 6. Decay of twine tension averaged across all twines for a switchgrass bale (top: density 177 kg DM·m^{-3}) and a mixed grass bale (bottom: density 165 kg DM·m^{-3}). Relaxation decay modeled after Peleg (1980) where TN = tension (N) and t = time (min (top) or h (bottom)).

Table 5. Top and face strand tension for wheat straw and corn stover bales.

		Wheat Straw[a]		Corn Stover[a]	
		Avg.	SEM[b]	Avg.	SEM[b]
Bale details					
Length	(cm)	236	2	220	2
Density	(kg DM·m^{-3})	202	2	208	4
Ratio of top strand to face strand tension					
On baler[c]		1.46	0.01	1.57	0.16
Resting on the ground[c]		1.39	0.08	1.24	0.11
Average maximum tension[d]	(N)				
Top strand		974	32	1263	127
Face strand		651	15	682	27
Absolute maximum tension[e]	(N)				
Top strand		1080		1666	
Face strand		700		743	
Average maximum pulse amplitude[f]	(N)				
Top strand		327	10	389	19
Face strand		147	6	141	29
Absolute maximum pulse amplitude[g]	(N)				
Top strand		340		445	
Face strand		162		190	

[a] Average bale moisture content was 9.5% and 16.0% for wheat straw and corn stover, respectively.
[b] Standard error of the mean.
[c] Ratio of top to face tension averaged either while bale was on bale chute or resting on the ground.
[d] Maximum tension or tension pulse averaged across all four replicate bales.
[e] Absolute maximum tension measured across all four replicate bales.
[f] Maximum tension pulse amplitude measured on each bale averaged across all four replicate bales (see eq. 2).
[g] Absolute maximum tension pulse amplitude measured across all twines and replicate bales. No statistical analysis was possible because this was a single value for each strand.

CONCLUSIONS

A method was developed and successfully implemented to measure twine tension during creation of high-density bales of several common hay and biomass crops. Measured tension was typically less than the recommended knot strength for high-density balers, so further investigation of the root cause of twine knot failure could lead to new knot strength recommendations for high-density large-square balers which could lead to reduced baling costs.

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APPENDIX A

Assumptions:

1. The twine is a fixed-length loop and does not change length during bale expansion.
2. As the twine just becomes taut, it forms a right angle at all corners (dashed lines, fig. A1).
3. As the bale expands and the resilient forces increase, the twine penetrates uniformly on all four corners.
4. At each corner, twine will penetrate equally on top and face of the bale.

As the twine just becomes taut the initial twine perimeter (P_i) is (left half of bale only):

$$P_i = 2\cdot\left(\frac{1}{2}L\right)+H \qquad \text{(A1)}$$

After the twine penetrates the bale corners, the perimeter (P_e) of the twine becomes:

$$P_e = 2\cdot\left(\frac{1}{2}L+\frac{1}{2}\Delta L - x\right)+2\left(x\cdot\sqrt{2}\right)+H-2x \qquad \text{(A2)}$$

Since the twine is a fixed-length loop, P_i must equal P_e:

$$2\cdot\left(\frac{1}{2}L\right)+H= \\ 2\cdot\left(\frac{1}{2}L+\frac{1}{2}\Delta L-x\right)+2\left(x\cdot\sqrt{2}\right)+H-2x \tag{A3}$$

$$\Delta L=4x-2\left(x\cdot\sqrt{2}\right)=2x\left(2-\sqrt{2}\right) \tag{A4}$$

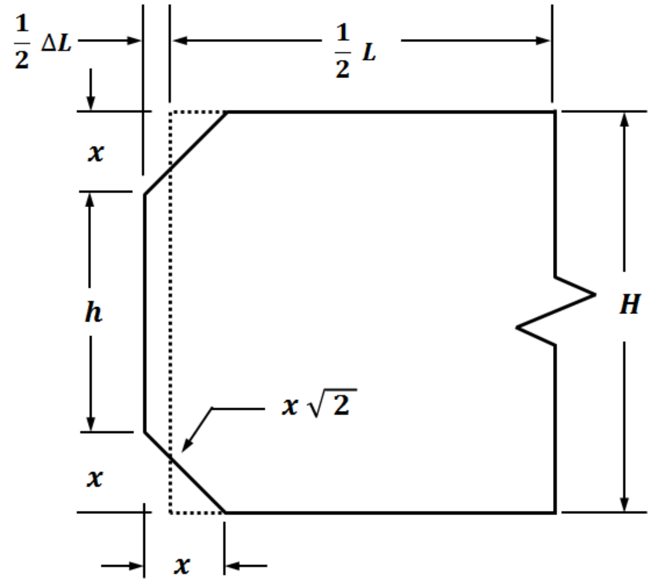

Figure A1. Side view of bale showing schematic representation of bale elongation as twine penetrates the bale corners.