BOWTIE BEAMS: NOVEL ENGINEERED STRUCTURAL BEAMS FROM SOUTHERN PINE LUMBER[1]

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Abstract. The intersection of decreasing resources and increasing population and its associated demands creates a need to develop alternative products to solid sawn lumber. This research used a modified form of sawn southern pine (SP) lumber in which cants were sawn into symmetrical double-trapezoidal shapes and glued together to form a bowtie beam. The result was a cross-sectional shape that was widest at the beam flanges and narrowest at the neutral axis. Cants were cut from logs and sawn into trapezoids, nondestructively tested, glued into the bowtie beams, and nondestructively and destructively tested to determine mechanical values as per ASTM D4761. The objectives of this study were to manufacture composite bowtie beams and to conduct nondestructive and destructive testing on the beams. Overall, the bowtie beams compared favorably with strength properties of No. 2 SP lumber of roughly equivalent size to the bowtie beams. The bowtie beam shows promise as an engineered product because a minimal amount of capital and technology is needed to process small-diameter trees into this value-added product.

Keywords: Southern pine, lumber, composite beam, structural beam, wood utilization, laminated wood, novel composite beam.

INTRODUCTION

New and innovative uses for small-diameter trees are needed to meet silvicultural and ecological goals of modern forests (Patterson et al 2002). In contrast to the forests of large, old growth trees of the past, forest inventories today have vast quantities of small-diameter trees (Kennedy 1995). Adding to this inventory is the increased harvest from plantation forests (Siry 2001) that frequently use short rotations to satisfy financial requirements of investors (Zobel 1984). Harvesting

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small-diameter trees is often limited by the economics of hauling material and other factors such as the declining pulp market have resulted in poor demand for thinnings (Patterson et al 2002).

To stay competitive, the forest products industry needs to produce products from a wide variety of woody resources (Hsu 1997). Engineered composites are one such product because they add value and extend the forest resource by using small-diameter trees efficiently (Youngs and Hammett 2001). Engineered lumber is particularly useful in beams in which the ratio of length to breadth and depth is relatively high (Brown et al 1952). One such engineered beam is the wooden I-beam, in which shear forces and moment capacity are provided by the web and flanges, respectively (Leichti et al 1990).

Patterson and Xie (1998) demonstrated an innovative value-added use of small-diameter yellow-poplar, red maple, and red oak trees. In the study, an 89 × 89-mm "inside-out" beam was produced by removing the corners from a green cant produced from a small-diameter tree, quartering the cant, turning the quarters inside out, and gluing the product together. The "hole" in the center of the beam allowed for faster drying as well as higher preservative retention when treated with creosote. No significant differences occurred between solid and inside-out beams for both modulus of elasticity (MOE) and modulus of rupture (MOR). Patterson et al (2002) demonstrated that the product could be economically produced. This research used a modified form of sawn southern pine (SP) lumber in which cants were sawn into symmetrical double-trapezoidal shapes and glued together on the neutral axis to form a bowtie beam. The result was a cross-section that was widest at the extreme fibers (beam edges or flanges) and narrowest at the center line or neutral axis. Essentially, this technique provides a means to produce deeper beams from small-diameter trees with a relatively small amount of capital investment. Cants were cut from logs and sawn into trapezoids, nondestructively tested, glued into the bowtie beams, and nondestructively and destructively tested to determine mechanical values as per ASTM (2005). Objectives of this research were to 1) manufacture composite bowtie beams using SP logs; and 2) conduct nondestructive and destructive testing on the beams to measure their performance.

MATERIALS AND METHODS

Material Preparation

Twelve loblolly pine (*Pinus taeda*) butt logs, diameters 23-41 cm at breast height, were acquired from Mississippi State's John Starr Memorial Forest. Rectangular cants sized in multiples of 86 × 112 mm were cut from the logs on a Wood-Mizer (Indianapolis, IN) band mill. The rectangular cants were then resawn into two similar trapezoids on a vertical band saw with a 15° tilted platen from horizontal. The 15° angle was developed based on intuition and calculation. Essentially, it sought to develop two matching trapezoidal sections from a solid lumber 3 × 4 cant that would provide a wide enough glue line for adequate adhesion and keep the maximum flange width less than 51 mm with the idea that this could be better optimized to fit within the dimension lumber category. The trapezoids were then resawn in an effort to make each one symmetrical about its central axis (Fig 1). Waste in this process was limited to the resaw kerf and the small triangular portions that were removed during conversion from similar trapezoids to symmetrical trapezoids. Following final resawing, the trapezoids were stacked on stickers and air-dried to approximately 9% moisture content (MC). After reaching target MC, the trapezoids were trimmed to a finished length of 3.7 m and marked with indelible ink for tracking and sorting purposes. In all, 45 trapezoids were produced.

Nondestructive Test of Trapezoids

Nondestructive evaluation is often an effective way to sort logs and lumber by stiffness (Carter et al 2006). Each trapezoid was nondestructively evaluated through vibrational stiffness analysis (Metriguard [Pullman, WA] Model 340 E-computer) and acoustic velocity (Director HM200 [Fiber-gen, Christchurch, New Zealand]). Acoustic velocity can measure wood properties

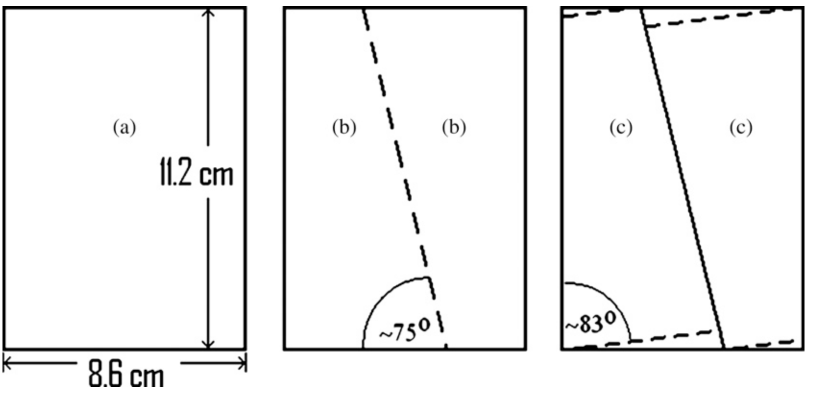

Figure 1. Three processing steps from solid rectangular cant (A), to similar trapezoids (B), to symmetrical trapezoids (C).

because of the relation between propagation velocity of longitudinal ultrasound waves and wood elastic properties (Sandoz 1999). Carter et al (2005) stated that the relationship between MOE and acoustic velocity is

$$\textit{dynamic modulus of elasticity} = \frac{\textit{density}}{\textit{acceleration due to gravity}}\textit{velocity}^2 \qquad (1)$$

For vibrational stiffness analysis, the machine assumes a complete rectangular section, thus it was not anticipated that the E-computer would produce completely accurate stiffness measurements for the trapezoidal sections. It was however hypothesized that the results would be relatively consistent and thus they could be used for sorting of trapezoids, for comparing with acoustic velocity, and with final mechanical properties as per destructive mechanical testing. The trapezoids were sorted by stiffness and arranged in matched pairs and designated for manufacture of composite bowtie beams. Because of the odd number of trapezoids, the trapezoid with the highest E-computer rating was not used and was not included in the results. No visual grading to identify stress-decreasing characteristics was done on any trapezoid.

Manufacturing Bowtie Beams

Immediately prior to gluing, each trapezoid was jointed along its glue edge. Approximately 85 g of commercial polyvinyl acetate (PVA) adhesive was applied to each jointed edge. PVA adhesive was chosen based on its cost, easy clean-up, strong performance in interior applications, and ability to cure at ambient temperature conditions. Pressure was applied to the trapezoids through a series of C-clamps spaced at approximately 610-mm intervals. Each clamped beam remained under pressure for 24 h at ambient conditions to ensure proper resin adhesion. Final dimensions after pressing averaged 3.7 m long, approximately 195 mm deep, 51 mm wide at the flanges, and 30 mm wide at the neutral axis. Overall, 22 beams were produced with an average specific gravity of 0.53 (S_9) (Fig 2).

Nondestructive Testing of Bowtie Beams

The bowtie beams were again nondestructively tested with both the E-computer and acoustic

Figure 2. The completed 22 bowtie beams.

velocity. The sole difference from the trapezoid testing was that two acoustic velocity readings were taken from each bowtie beam—one from each of its trapezoids. The average of the two readings was used as a predictor value of mechanical properties of each bowtie beam.

Destructive Testing

To account for MOR and MOE differences in rectangular vs bowtie beams, each beam was measured at the flange edge (b_f), neutral axis (b_n), and beam depth (h), each in two locations (Fig 3). From there, the base width of each triangle (b_t) was calculated from maximum beam width (b_f) minus minimum beam width at the neutral axis (b_n) divided by two. The measurements were averaged and used in computing moment of inertia of the bowtie section (I_{bowtie}).

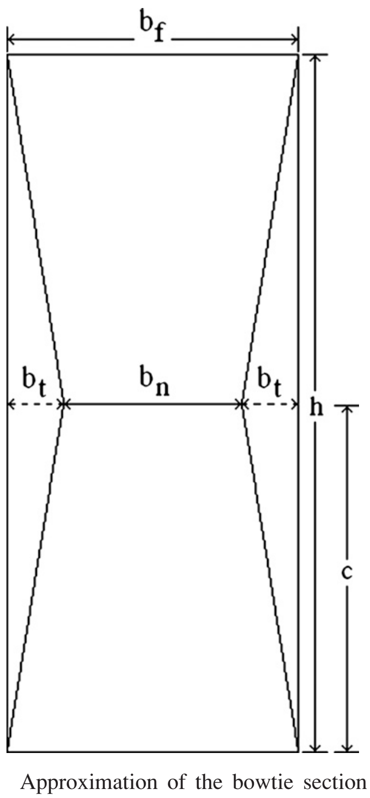

Figure 3. Approximation of the bowtie section used for mechanical property calculation.

To calculate this, moment of inertia of a full rectangular section ($I_{rectangle}$) was calculated using beam depth (h) and maximum width (b_f). Next, moments of inertia of the triangular sections ($I_{triangle}$), about the neutral axis that were removed, were calculated using triangle depth (c) and base width of each triangle (b_t). Finally, moment of inertia of the missing wood was subtracted from moment of inertia of the full rectangular section to determine moment of inertia of the bowtie section. Moment of inertia of the missing wood was equivalent to four times the moment of inertia of the triangular section.

The beams were destructively tested in third-point loading (load heads positioned one-third of the span distance from the reactions) according to ASTM (2005) on an Instron (Norwood, MA) universal testing machine. Span-to-depth ratio was approximately 17 to 1 (3.2-m span). Rate of loading was 38 mm per min, which would result in beam failure at approximately 2 min. MOE was measured at the load heads, and values were calculated and adjusted based on the proportion difference between the section modulus of the virtual rectangular beam, as programmed in the testing machine software for each beam, and the section modulus of the actual bowtie beam. MOR was calculated from maximum load, test span, and section modulus.

Strength and stiffness of the bowtie beams were compared with the 38 × 178-mm SP lumber values that are roughly equivalent in depth and maximum width as shown in the National Design Specifications (AFPA 2005). To facilitate more accurate comparison with lumber, several adjustments to the bowtie beams were made according to ASTM (2007, 2010) and Evans et al (2001). MOE of each beam was adjusted from 9-15% MC ($MOE_{15\%}$) and then to third-point uniform loading ($MOE_{uniform}$). MOR of each beam was adjusted from 9-15% MC ($MOR_{15\%}$) according to ASTM (2007). To calculate F_b, the height of each piece was adjusted to 15% MC, then $MOR_{15\%}$ was adjusted to a characteristic size of 38 × 184 mm and length of 3.66 m, and divided by a

2.1 safety factor according to ASTM (2007) and Evans et al (2001).

Statistical Analysis

Statistical analysis was performed in SAS 9.2 to calculate mean, median, standard deviation, and coefficient of variation for all tested variables using the proc univariate procedure. Typically, the design values of lumber are calculated using nonparametric statistics according to ASTM (2010). However, the sample size here was too small for a nonparametric analysis at 75% confidence, therefore the lowest value was used as the nonparametric value. Additionally, the Shapiro-Wilk test for normality was conducted to determine if using the normal parametric tolerance limit (PTL) at the 5th percentile at 75% confidence was appropriate per ASTM (2010). Simple linear regression analysis comparing nondestructive and destructive test values were also done in SAS 9.2 using the proc reg procedure.

RESULTS AND DISCUSSION

Nondestructive Trapezoid and Bowtie Beam Results

For the trapezoids, stiffness values as determined by the E-computer ranged from 10.27-22.25 GPa with an average value of 15.69 GPa (Table 1). Again, these values are based on rectangular sections of approximately the same area, therefore the primary utility value of these results is for relative sorting among the trapezoids. Acoustic velocity ranged from 4561-5970 m/s with an average value of 5289 m/s. The stiffness calculated from acoustic velocity and density explained 75% of the variation in stiffness from the E-computer for the trapezoids (p value = < 0.0001).

Table 1. Nondestructive evaluation of matched trapezoids and bowtie beams.

	E-computer (GPa)			Acoustic velocity (m/s)		
Beam	Trapezoid A	Trapezoid B	Beam	Trapezoid A	Trapezoid B	Beam
1	12.68	13.02	15.30	5110	5140	5250
2	10.27	10.68	9.58	4561	4940	4705
3	15.09	15.30	15.30	5380	5371	5450
4	15.71	16.40	14.47	5280	5420	5490
5	17.71	17.91	16.67	5380	5590	5520
6	11.58	12.68	10.61	4940	4830	4940
7	15.71	15.71	13.78	5430	5040	5310
8	14.33	14.47	14.81	5330	4970	5180
9	15.50	15.71	14.88	5620	5520	5620
10	18.05	18.74	16.26	5830	5520	5660
11	19.36	19.50	17.46	5660	5380	5550
12	16.67	16.67	16.47	4870	5450	5210
13	16.95	17.5	14.40	5350	5250	5310
14	14.19	14.26	14.19	5250	5010	5195
15	21.57	22.25	18.95	5590	5970	5800
16	19.84	20.88	17.50	5250	5660	5522
17	13.71	13.92	10.75	4770	5210	5010
18	14.54	14.61	14.51	5490	5040	5280
19	14.95	14.95	14.47	5420	5490	5550
20	13.64	13.64	10.82	4770	5250	5140
21	16.54	16.60	14.40	5420	5450	5550
22	13.16	13.37	12.95	5450	5070	5350
Mean	15.69		14.48	5289		5345
Median	15.4		14.49	5360		5330
Standard deviation	2.72		2.40	298		260
Coefficient of variation	17%		17%	6%		5%

Table 2. Measurements, destructive evaluation, and conversion to standard conditions of lumber for bowtie beams.

Beam	b_f (mm)	b_n (mm)	b_t (mm)	h (mm)	$h_{15\%}$ (mm)	I_{bowtie} (cm^4)	Maximum load (kg)	MOR (MPa)	$MOR_{15\%}$	F_b (MPa)	MOE program (38 × 184 mm) (GPa)	MOE bowtie (GPa)	$MOE_{15\%}$ (GPa)	$MOE_{uniform}$ (GPa)
1	48.5	29.1	9.7	193.9	196.5	2653.3	3814.6	72.9	62.0	29.5	20.8	15.5	14.2	14.5
2	51.6	30.7	10.4	195.2	197.8	2873.1	1015.2	18.0	17.8	8.5	13.0	8.9	8.2	8.4
3	51.2	29.7	10.7	191.0	193.6	2660.6	3210.9	60.3	51.8	24.6	21.4	15.9	14.6	14.9
4	51.2	28.8	11.2	196.9	199.5	2898.2	1779.2	31.6	28.7	13.7	19.6	13.4	12.2	12.5
5	49.0	28.7	10.2	196.9	199.5	2793.2	4042.0	74.5	63.3	30.3	20.7	14.7	13.4	13.7
6	51.3	29.5	10.9	196.9	199.5	2914.3	2273.5	40.2	35.6	17.0	16.7	11.4	10.4	10.6
7	50.8	30.6	10.1	193.3	195.9	2753.5	2523.2	46.3	40.6	19.3	16.5	11.9	10.9	11.1
8	51.3	30.1	10.6	194.9	197.6	2840.3	3839.9	68.9	58.8	28.1	29.8	20.8	19.0	19.5
9	48.6	28.7	10.0	195.2	197.8	2705.8	3454.4	65.2	55.8	26.6	20.4	15.0	13.7	14.0
10	48.5	28.7	9.9	197.0	199.6	2774.4	4049.7	75.2	63.9	30.6	24.7	17.6	16.1	16.5
11	55.0	33.4	10.8	192.3	194.9	2937.9	3849.2	65.9	56.4	26.8	23.7	16.0	14.6	15.0
12	53.2	32.6	10.3	193.9	196.5	2921.6	2428.5	42.2	37.2	17.7	22.4	15.2	13.9	14.2
13	50.8	29.7	10.5	195.2	197.8	2821.9	3413.4	61.8	53.0	25.3	19.4	13.7	12.5	12.8
14	50.9	29.3	10.8	194.9	197.6	2810.9	3387.2	61.4	52.8	25.2	17.1	12.1	11.0	11.3
15	50.4	31.1	9.7	191.8	194.3	2679.5	4387.8	82.1	69.5	33.0	26.1	19.3	17.7	18.1
16	52.8	34.3	9.3	196.9	199.5	3063.7	4386.5	73.7	62.7	30.0	23.0	14.9	13.6	13.9
17	54.5	29.7	12.4	193.4	196.0	2912.1	1842.5	32.0	29.0	13.8	16.5	11.2	10.2	10.5
18	49.7	27.8	10.9	194.9	197.6	2728.6	3440.0	64.3	55.1	26.3	19.6	14.2	13.0	13.3
19	51.7	29.6	11.0	194.6	197.2	2833.4	3201.7	57.5	49.6	23.6	18.3	12.8	11.7	12.0
20	54.7	30.5	12.1	193.5	196.2	2940.8	1342.3	23.1	21.9	10.4	15.5	10.5	9.6	9.8
21	48.9	29.0	10.0	196.9	199.5	2791.2	2403.0	44.3	39.0	18.6	17.4	12.3	11.3	11.5
22	48.4	28.3	10.0	195.7	198.3	2709.1	2663.7	50.3	43.8	20.9	16.5	12.1	11.0	11.3
Mean	51.0	30.0	10.5	194.8	197.4	2819.0	3034.0	55.1	47.7	22.7	20.0	14.1	12.9	13.2
Median	51.1	29.7	10.5	194.9	197.6	2816.4	3299.1	60.9	52.3	24.9	19.6	14.0	12.8	13.1
Standard deviation	2.0	1.6	0.7	1.8	1.8	106.9	975.3	18.1	14.6	7.0	3.9	2.8	2.6	2.7
Coefficient of variation	4%	6%	7%	1%	1%	4%	32%	33%	31%	31%	20%	20%	20%	20%

b_f, beam at the flange edge; b_n, neutral axis; b_t, base width of each triangle; h, beam depth; I_{bowtie}, moment of inertia of the bowtie section; MOR, modulus of rupture; MOE, modulus of elasticity.

For the bowtie beams, MOE values from the E-computer ranged from 9.58-18.95 GPa with an average value of 14.48 GPa. Acoustic velocity ranged from 4705-5800 m/s with an average value of 5345 m/s. For all but two beams, acoustic velocity for each trapezoid was the same. This may suggest that after adhesion, the beams were acting as a single composite section, but matching up similar trapezoids probably assisted in this. The stiffness calculated from acoustic velocity and density explained 83% of the variation in the stiffness from the E-computer for the trapezoids (p value $= < 0.0001$).

Destructive Test Results

All but two beams failed in gross tension on the tensile face. Two beams appeared to fail as the result of warped trapezoids, which caused failure initiation at the glue line resulting in a horizontal shear failure. Perhaps in these two beams, glue did not achieve adequate adhesion because of the warped trapezoids. Average $MOE_{uniform}$ was 14.2 GPa, and average $MOR_{15\%}$ was 47.6 MPa (Table 2). The nonparametric F_b strength value was found to be 8.4 MPa, but because of the limited number of samples, the value was at less than 75% confidence compared with how F_b values of lumber are derived (ASTM 2010). The Shapiro-Wilk test for normality failed to reject the null hypothesis (p value $= 0.2351$) such that there was not enough evidence to suggest that the data are not normal. The calculated PTL 5th percentile at 75% confidence was 9.1 MPa, slightly higher than the nonparametric value. Because the nonparametric value was more conservative, it was more appropriate for comparing bowtie beams with dimension lumber. In comparison with design strength values of 38 × 184-mm SP lumber, it was found that the nonparametric bowtie strength values were similar to Number 2 (8.3 MPa) grade lumber (AFPA 2005). The tested MOE from the bowtie beams compared favorably with the Select Structural (13.1 GPa) grade (AFPA 2005). The wide difference between MOR and MOE results was probably caused by the lack of visual grading. If a commercial manufacturer were to create beams using this process, it would be critical to segment the beams into different grades not only to capture more value, but also to eliminate variation. If some form of visual grading were done on the boards, it is more likely the MOR results would better match the MOE results with regard to grade comparisons. The variation found in the properties also shows that more samples are needed to determine the allowable properties for grades of structural lumber per ASTM (2010). However, this study was undertaken as more of a proof of concept and less of an attempt to produce design values for the commercial market.

MOE from the E-computer explained 61% of the variation in the tested MOE in the bowtie beams (Table 3). The MOE calculated from acoustic velocity and density explained 52% of the variation in tested MOE in the bowtie beams. The MOE from the E-computer explained 67% of the variation in MOR in the bowtie beams. The MOE calculated from acoustic velocity and density explained 47% of the variation in MOR in the bowtie beams. Tested MOE explained 60% of the variation in MOR in the bowtie beams. It was particularly interesting that the E-computer MOE explained more variation in MOR than the tested MOE. Overall, the E-computer slightly

Table 3. Regression statistics for bowtie beams.

Variable A	Variable B	p value	R^2
MOE from E-computer	MOE from acoustic velocity and density	<0.0001	0.83
MOE from E-computer	MOR	<0.0001	0.67
MOE from E-computer	MOE	<0.0001	0.61
MOE	MOR	<0.0001	0.60
MOE from acoustic velocity and density	MOE	0.0002	0.52
MOE from acoustic velocity and density	MOR	0.004	0.47

MOE, modulus of elasticity; MOR, modulus of rupture.

better predicted MOE and MOR during destructive testing than did acoustic velocity and density prediction.

CONCLUSIONS

Using small trees to produce high-performance products that possess competitive advantages compared with solid sawn lumber would help use resources more wisely. The bowtie beam shows promise as an engineered product because a minimal amount of capital and technology is needed to process small-diameter trees into this value-added product. Also, the bowtie weighs less than traditional beams. The weight savings are concentrated toward the neutral axis of the beam and decrease toward the tension and compression faces. It is possible that the shape of the bowtie beam could be further optimized, and it is also recommended that the size be decreased to better fit with dimension lumber sizes. Also, much testing is needed before this product could be produced commercially. However, because the concept appears to have merit, one could expand it to a full study with the intent of developing allowable properties. Furthermore, because ASTM (2007) was developed for dimension lumber, further research is needed to determine how the adjustments used here corresponded to bowtie beams.

Although the material tested in this study came from mature trees, there are potential dimensional stability concerns that would be encountered if the product was manufactured from trees containing a high percentage of juvenile wood. Some possible solutions to this problem would be to dry the solid cants to the target moisture content prior to cutting the trapezoids and gluing into the bowtie beam. The trapezoids could be glued when green into the bowtie beams using a waterproof adhesive. Also, the profile of the material could be machined through a feed-through moulder, which may tighten the tolerances of the product, which is essential for achieving a uniform surface for gluing. A combination of these process changes may yield more uniform beams. Additionally, a potential advantage of the bowtie beams could be the decrease of warp in service because of the opposing shrinkage and swelling forces that the two different pieces would have on the overall beam. MOE of bowtie beams produced from juvenile wood would probably be much less than MOE found in this study.

Future testing on bowtie beams could also include different wood species, such as hardwoods and beetle-killed trees from the western US and Canada along with different types of adhesives that potentially could improve the process. Other improvements would be to visually grade each trapezoid prior to assembly to identify defects that could negatively impact the structural capabilities of the product. Another improvement to the beams would be to orientate knots and other strength-decreasing defects on the inside of the glued line on the neutral axis of the beam. This would probably improve strength properties of the beams because the strength-decreasing defects would be closer to the area with no longitudinal stresses and subsequently more clear wood would be placed on the tension and compression faces. However, further research would be needed to determine if the knots had a detrimental effect on the glue bond.

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