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Defect-induced Torques in Axially Strained Orthotropic Composite Belts and Plates

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Abstract - *Longitudinally reinforced flexible rubber plates and belts with vulcanized steel cords form a highly orthotropic composite. During fabrication, cords can buckle or move out-of-plane within the rubber matrix due to thermal and mechanical effects. Displaced cords within the cured composite will not carry full load when placed under axial tension. Belts with distorted cord planes mistrack due to variation of the physical centre-line of tension. Analysis of the mistracking problem requires measurement of variations in cord-plane flatness, followed by a moment analysis to calculate the torque imbalance due to misaligned cords. A model is described that uses cord alignment data to compute the torque imbalance relative to physical centre-lines. Using an inverse approach, analysis of a mistracking signature from a moving belt, band or plate can indicate the extent of built-in defects along the plates. The model has application to transform off-centre belt motion into an assessable defect level. The research has application to quantifying the limits of manufacturing quality in relation to existing Standards.*

Keywords: Steel cord reinforced rubber belts, tensile member distortion, tensioned plates and belts, fabrication-induced torques

1.0 INTRODUCTION

Corded composites form a particular class of engineering material designed to exhibit properties that lend themselves to specific mechanical applications. One such material is hot vulcanized rubber conveyor belting containing fabric or steel cords for longitudinal strength. These materials are used worldwide and form the backbone of the industrialized bulk material handling world. However, manufacturing defects within these composite materials can severely limit their application for intended use.

Identifying operational problems with steel cord belt materials is not difficult due to their widespread application. Belt life is usually governed by bending fatigue, the existence of defective or partially displaced cord plane, splice adhesion and impact damage. Slow deterioration and fatigue of steel cord reinforcement at embedded rip detecting loops, brand marks and cord plane defects (displaced cords) in flat rubber belts has been identified as a major operational problem over many years [1,2].

Belts containing cord plane defects do not track straight, causing edge damage and rips. The nature of belt tracking problems in steel cord belts is linked to manufacturing quality and cord load sharing [3].

Steel cord reinforced rubber belts have been installed in mines since the 1960's. Manufacturing involves a discontinuous hot vulcanization pressing process. Steel cords aligned in the length-wise direction between rubber sheets were vulcanized to form connected plates, with an aspect ratio between 3:1 and 10:1. Once the composite rubber plate is cured at vulcanizing temperatures near 150˚C, any slightly displaced steel cord is "locked-in" and so will not carry axial load, resulting in fatigue due to bending over pulleys. The origin of the displacement stems from thermal expansion in relation to the pre-strain cord tension set at manufacture [4].

In manufacture, the cord or cable plane is controlled by a comb to equally separate cables. An applied strain or tension is added to each cord. The pre-tension in the free cables is usually set somewhere near 10% of working load. The placement of top and bottom uncured rubber covers may result in lateral and vertical cable movement. The uncured sandwich is then introduced into a fixed-length hot vulcanization platen, approximately 10 m long, where curing and bonding to zinc coated cables occurs.

When a cord is vertically displaced during the plate building process, even slightly, its length increase is sufficient for that cable to carry no tensile strain when the vulcanized composite is cured. The ratio of Young's moduli of steel to rubber is about 4000 : 1 [5], and so the bonded rubber will have little influence on the strength in a direction orthogonal to the cords. In other words, the composite is highly orthotropic. If the pre-tensile strain is inadequately calculated, the cords may undergo compression and buckle inside the vulcanized plate. In this process, any deformation remains after the mass cures.

Overall, cords in pre-strained composites cords displace for two basic reasons:

a) Irregular rubber cover material dimensions, cover joins and embedded sensors,

b) Thermal expansion of under-tensioned cables, causing buckling and cable twisting.

A major issue with plates and belt materials containing vertical cord plane irregularities is bending fatigue and cord failure over time. If a cord is only slightly displaced over a 1 m length, it will undergo compression-tension cycles when bending on pulleys. Note that a 1 mm displacement of a cord equates to approximately 0.1 mm cord-length contraction in a 300 mm buckle, based on a simple laboratory measurement.

The method used to quantify the extent of cord plane defects in steel cord belts is to conduct measurements of the cord plane alignment at selected locations of maximum sideways movement when running. Methods describing the testing procedure have been published elsewhere [1, 6]. Once cord-plane displacement data is obtained, the equivalent torque can be calculated and applied to predict the running offset of the belt centre-line, using the model outlined in this paper.

Control of the vertical alignment of the steel cord reinforcement still remains a problem today, even though International Standards exist to address the issues encountered in manufacture [7]. Quality control in the manufacture of corded pre-strained composites is complicated by use of a variety of cord diameters and spacing.

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Later in Section 4.0, the level of pre-strain required to prevent thermally-induced cord buckling is discussed. Standards only address the statistical variances in the quality of cord-plane, and do not address ways to minimize defective zones outside the Standards.

In mining belts, stress-related catastrophic failure at cord-plane defects is due to lowered safety factors. Edge damage due to mistracking also leads to costly failures. Both stem from cord plane load-sharing defects and non-neutral cord torques, respectively. The analysis of composite plates and belts containing irregular cord alignment is described in a way that is tractable for practical evaluation of defect levels in belts and plates.

2.0 CORD LOAD-SHARING MODEL

2.1 BACKGROUND

A typical steel-cord reinforced rubber plate segment is shown in Figure 1. The rubber cover was removed where the defect was detected by a NDT magnetic probe [6]. As shown, a section of the cord plane was found to be significantly vertically distorted.

Figure 2 illustrates a diagram of a corded composite cross-section in which some cords are displaced vertically and laterally. A non-destructive test (NDT) using a magnetic probe produces a signal shown at the bottom of the figure, which is described in detail elsewhere [5,6,9]. The signal indicates those cords that are out of plane or laterally displaced, and can be used to calculate a new torque-neutral center-line in the plate under axial tension.

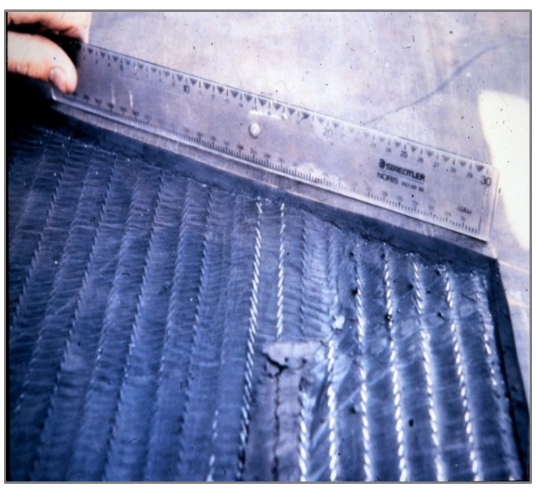

Figure 1: Example showing a cord plane defect in an orthotropic plate

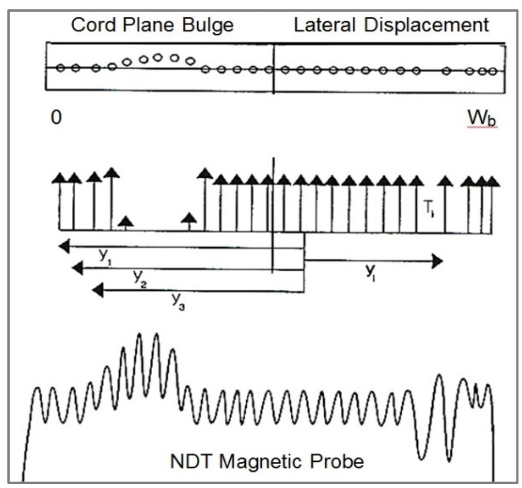

Figure 2: Diagram of unit loads and torques relative to new centre-line

Typically, steel cord belts can be up to 3m wide with a plate length is usually 9 m with a double-cure overlap zone of about 0.3 m. Over 60 pressings may result in rolls over 600 m long. Spliced rolls can form a conveyor length in excess of 10 km. Any cord-plane defect raises average cord load, and dynamic loads can cause the belt to break at sites of displaced cords [8].

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2.2 THE MODEL

The model considers a lengthwise corded composite plate or belt with *n* parallel cords in the axial *x*-direction, in which cords are embedded and bonded within a cured elastomeric matrix. A total axial force $F = F(x)$ at position *x* along the belt is applied to the plate width containing the cords. The plate width $w = Wb$. For long belt-like plates, the force *F* may change along the length of the belt due to rolling losses and friction.

A torque-neutral center-line will exist at some part of the plate's cross-section, defined as $Y'(x)$. If all cords carry equal load and no defect exists in the alignment of the cord plane, then $Y'(x) = Wb/2$, i.e., the plate's centre. In a general case, the average load carried by each axially strained cord i : { i = 0, 1, 2, ….(n - 1) } at each cross-section $Y'(x)$ along the plate's cord axis *x* is ;

$$F_i(x) = F(x)/(n), \text{ or} \tag{1}$$

$$F_i(x) = F(x)/(n - m)\, , \tag{2}$$

where m cords do not carry load due to an out-of-plane condition, such as a buckle or other cord-plane defect. In all cases, the applied axial force *F(x)* is constant and defined by the summation of individual cord loads ;

$$F(x) = \sum_{i=0}^{(n-1)} F_i\,(x) \tag{3}$$

Defining the left-hand edge cord at "0" of the y-axis, and the far right-hand cord n at width *Wb*, each cord has a position $y_i(x) = i\,Wb/(n-1)$. In the manufactured composite, not all cords may carry equal load and therefore allowance is made to accommodate variances in the loading of each cord. Irrespective, Eq. (3) always holds true.

Clearly, the simple model used to determine the torque-neutral centre-line is complicated by partial load-sharing of displaced tensile members. In the case of steel cords inside a rubber plate or belt, any slight out-of-plane cord buckle would result in no cord load at the buckle site. At best there may be some partial or non-zero loading.

Consider Figure 2. Moments $(F \times y)$ summed across the plate at cross-section x from y = 0 to width *Wb* , produce a torque-neutral center-line at $Y'(x)$;

$$Y'(x) = Wb\left[\sum_{i=0}^{(n-1)} \delta_i(x)\ F_i(x) \times\ y_i\,(x)\ \right]/\ (n-1)\sum_{i=0}^{(n-1)} F_i\,(x) \tag{4}$$

where δ_i is the Kronecker Delta switching the cord strain on or off when a cable in the cord plane is even slightly displaced, i.e. $\delta_i\,.\,F_i = 0$ or $\delta_i\,.\,F_i = 1$, for zero strain and positive full strain, respectively. If the strain in a cord is not 0 or 1, but some fractional amount k_i, then Eq. (4) is modified to ;

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$$Y'(x) = \frac{Wb}{(n-1)} \left[\sum_{i=0}^{(n-1)} k_i(x)\ F_i(x) \times\ y_i\,(x) \right] / \sum_{i=0}^{(n-1)} F_i\,(x) \qquad (5)$$

A value for k_i can exist as a fractional value if the cord strain is positive relative to the average strain in all cords. For the example shown in Figure 2, the piece of steel cord reinforced rubber belting with a defective cord plane was removed at a location of abnormal run-out detected by NDT probes [5, 6]. The fact that $Y'(x)$ would not be located at $Wb/2$ for this sample results from a center-line offset or torque that shifts a moving belt composite in the horizontal plane (termed mis-tracking). Research is continuing on the "Inverse Problem"; an algorithm that computes k_i values from a cord plane displacement measurement probe (from Figure 2) at a given applied axial load F.

3.0 APPLICATION OF ANALYSIS

A torque imbalance is inferred from Figure 2, due to irregular load-sharing of the applied tensile strain. The physical plate center-line or neutral axis (also referred to as a centerline-of- tension) moves to a new center-line location to balance torques within the composite. Figure 3 shows a stylized diagram of the strain distributions at defects undergoing bending. The curves reflect the influence of shear between cords in the bonded composite. In this case the values of k_i are used to compute the new central axis at this cross-section of the plate.

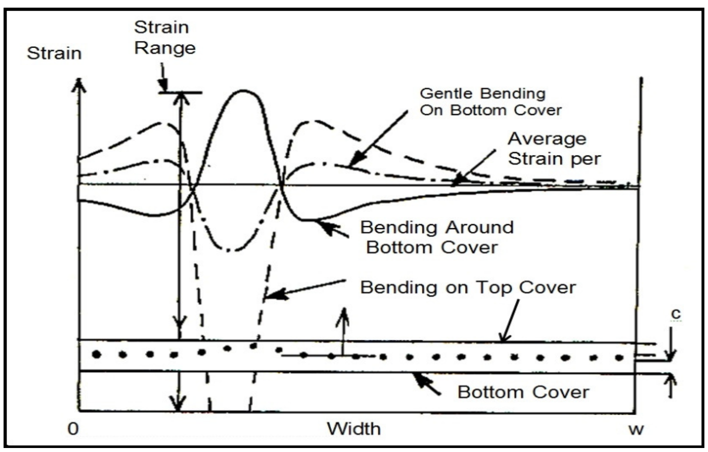

Figure 3: Cord strains due to bending the composite with cord plane defects

Using the example from Figure 2, with n = 27, values required in Eq. (4) to compute the torque-neutral center-line are listed in Tables 1a and 1b. In the example, displaced cords are considered to have an arc length that is longer than straight cords and therefore do not take load. One could ascribe a k value (0 < k < 1) for slightly displaced cords such as cords 4, 25, 26 and 27 in the example, however in terms of worst-case prediction of the new center-line, any displaced cord is considered non-load sharing.

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From Figure 2, 6 of the 27 cords are vertically displaced and are not considered to be strained, i.e., cords 4, 5, 6, 7, 8 and 9, for which $k = 0$ and $\delta = 0$. From Equ. (2), the load in each viable load-sharing cord is a = F / 21. The moment-arm for each cord uses the relation $y(i) = i \cdot Wb/(26) = i\, p$. The over-strain in each cord resulting from a loss of strain in m = 6 cords is, Fi = a = 1.286 F.

The tables below show the computations for cord i = 0 to i = 26, with results split between Tables 1a and 1b. In Tables 1a and 1b, let v = ap and the plate width containing 27 cords is Wb = 0.5 m. Note that slight moment-arm variations for related to cords 23 to 26 are not added in the model, but can be accommodated by adjusting y in the tables below.

Table 1a: Computed values for Equ (4) for i = 0 to 14

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14
i	0	1	2	3	4	5	6	7	8	9	10	11	12	13
δ	1	1	1	0	0	0	0	0	0	1	1	1	1	1
Fi	a	a	a	0	0	0	0	0	0	a	a	a	a	a
y(i)	0	p	2p	3p	4p	5p	6p	7p	8p	9p	10p	11p	12p	13p
Fi.y	0	v	2v	0	0	0	0	0	0	9v	10v	11v	12v	13v

Table 1b: Computed values for Equ (4) for i = 15 to 26

n	15	16	17	18	19	20	21	22	23	24	25	26	27
i	14	15	16	17	18	19	20	21	22	23	24	25	26
δ	1	1	1	1	1	1	1	1	1	1	1	1	1
Fi	a	a	a	a	a	a	a	a	a	a	a	a	a
y_i	14p	15p	16p	17p	18p	19p	20p	21p	22p	23p	24p	25p	26p
Fi.y	14v	15v	16v	17v	18v	19v	20v	21v	22v	23v	24v	25v	26v

Applying computed values from Table 1a and 1b in Equ (4) generates the following results :

ΣFy = 317 v ΣFi = 21 a Y' = ΣF.y/ΣF = 15.095 p

Y' = 15.095 x Wb/26 = 0.58 Wb
Y' = 29 cm from the left edge (width = 50 cm).

The new Center-Line Y' = 4 cm past physical center-line, to the right side. In a belt with this set of non-loaded cords, the belt will track 4 cm to the left side.

For real world comparisons, the results are scalable. A 1 m wide belt with a defect distribution identical to that shown in Figure 2 would mistrack at this defect location by 8 cm, if the belt contained 12 displaced cords at the same geometrical location as the example. Even though the physical centre-line of tension has moved right by 80 mm, the belt's

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guiding rollers may be biased for additional steerage, in which case the total sideways deviation or mistracking could be magnified towards 160 mm.

4.0 FIELD EXAMPLES AND TESTING

In one example, a steel cord composite belt used in the mining industry exhibited tracking problems to the extent that product would spill off the carrying side at certain locations. The belt was scanned by a magnetic sensing probe described above. The cord plane on one side was found defective in a 3 m long zone from (a) to (c) on Figure 4. Figure 4 shows the scan results and the cross-section of the sample derived from calibrated distance measurements. Cords displaced on the left edge resulted in a torque offset of 110 mm at cross-section (c).

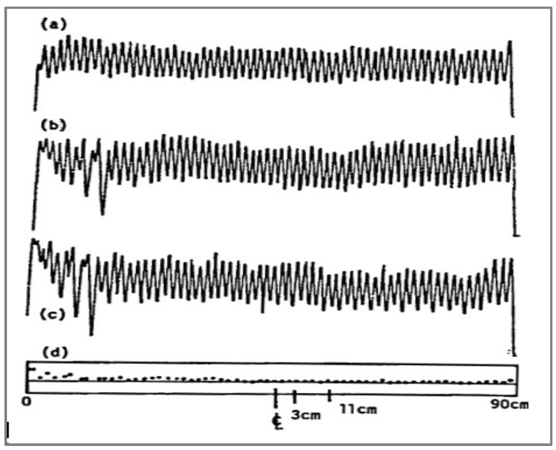

Figure 4: Probe scans at 3 locations along a composite steel cord / rubber belt sample with cord plane defects, showing the computed centre-lines for (b) and (c) tests

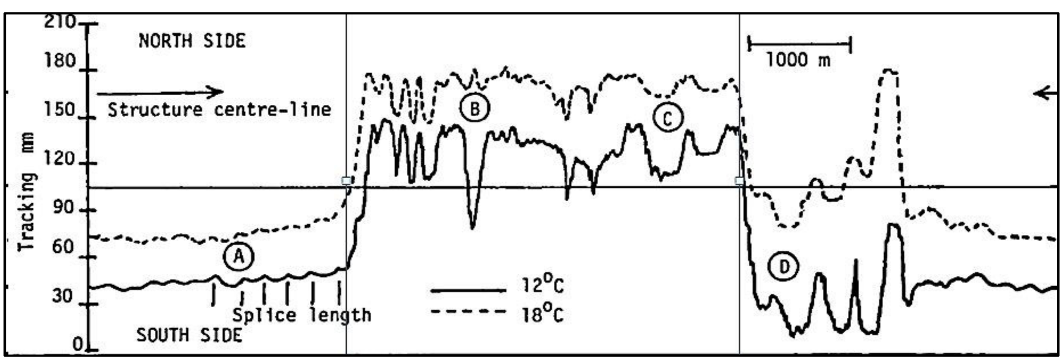

Figure 5: Tracking signature of a composite belt, showing sideways runout similar to those calculated in Section 3 [3]

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Although the graphs in Figure 4 show only a small region of defects within the entire belt, similar variations can be inferred for other locations of defects based on a sideways runout test. Figure 5 shows a tracking measurement of the edge of a long belt. Large offsets measured in regions A and D were due to incorrectly manufactured rolls.

Tracking deviations of the cord plane measured in Figure 4 occur in zone D of Figure 5. Deviations in regions B and C were repeatable for each revolution but with some variation due to daytime temperature effects. Variations in center-line torque at regions B and C were typical of those attributed to cord plane variations. Side travel deviations of + / - 70 mm are indicative of cord alignment problems similar to those calculated in Section 3.

Measurement shows that belt side travel is temperature dependent. In region A of Figure 5, the running deviations are not significant, indicating that the cord alignment is uniform along these rolls of belting. As temperature rises during the day, the tracking shifts about 30 mm towards a mean running position. The measurement shows that the center-line of torque shifts slightly as the belt composite warms, which would indicate that the cord plane alignment is uniform with a slight misalignment towards the edge. Uniformity of cord alignment is not the case in regions B, C and D.

Regarding temperate effects, the thermal coefficient of expansion Φ of a steel cable is approximately $\Phi = 1.14 \times 10^{-5}$ m/C. Within a 10 m platen during vulcanization, a 130° C temperature increase will result in a cable elongation of 14.82 mm or 0.148% of the cable length. A cord pre-strain of at least 0.15% of the plate length (10 m in this case) is needed to prevent thermally induced buckling in the press.

The pre-strain can be calculated from the modulus. A steel cable has a modulus E = 118,000 MPa. An applied stress is required to pre-strain the cable to compensate for thermal expansion, $\sigma = 0.00148 \times E = 175$ MPa, as a minimum. The calculation is cord diameter dependent. Table 2 shows the calculated minimum cord tension T_i required to prevent buckling in manufacture. Most manufactures of these composites have poor control of the thermal expansion parameter during manufacture [3].

Table 2: Required minimum pre-tension T_i in a cable just to prevent thermal buckling during vulcanizing

Cord Diameter (mm)	T_i (N)
3.5	968
5.0	1,960
8.0	4,794
12.0	10,474

Measurements of tracking variations as a function of temperature, like those shown in Figure 5, strongly indicate that center-line torques change in the material as it warms. Most likely, edge zone cords are losing strain due to thermal rises. However, any zone in the composite where there are existing defects could be adversely affected by temperature rises. For all conditions, Equ (3) must be satisfied, indicating that any off-center torque induced in the composite may be exaggerated by temperature changes due to competing effects of pre-strain and thermal expansion of cords.

5.0 STANDARDS AND DISCUSSION

Engineering Standards used in the manufacture of composite steel cord belting have been established over many years to specify tolerances and structure allowances. Standards such as AS 1333 and DIN 22131 broadly state that belts should run with a maximum deviation of +/- 5% of belt width when operated on aligned rollers. However, if cord plane defects are induced during fabrication, there is no way to predict how the composite belt will run when subjected to axial tensile loading or temperatures variations.

The inverse problem of inferring the extent of cord load sharing variations from tracking measurements is possible based on the above research. A deviation of 10 cm in a running belt center-line will imply a built-in torque that stems from misalignment of between 10 and 20 cords, to varying degrees. Running deviations will be modified by thermal variations particularly with wider belts containing edge-zone cord plane defects. Wider belts with edge zone defects experience increased effects of variations in torque center-line and will usually mis-track towards steel structure and cause edge damage.

With regard to vertical cord tolerances in manufacture, most Standards state that not more than 5% of the cords shall deviate by more than + / - 1 mm. Field tests over many years shows that this requirement is not always achieved. The Standards provide no way to predict the effect of cord misalignment on the operational performance of the composite belt.

Further research is necessary to improve the fabrication of composite steel cord plates and belts. One area open to research would involve improving the control of pre-strain in cords during manufacture. Another basic fabrication requirement should incorporate allowances for thermal expansion of the cords during the vulcanization process. Since belts are made in in 10 m lengths, each press length is considered a stand-alone composite plate.

Measurements have shown that corded composite plates and belts are prone to internal torques induced by cord misalignment. Measurements also allow a non-destructive method for estimating the degree of “at-fault” cords as a way of proving manufacturing quality. The latter has implications for warranty replacements and contract administration where defective materials have caused significant downtime due to interupted operation.

6.0 CONCLUSIONS

Steel cord reinforced elastomeric composites are subject to variations in the cord plane that affects strain distribution within the material. High modulus cords that are slightly displaced in axially-tensioned orthotropic plates and belts do not carry proper load, inducing torques that place the centre-line of tension away from the physical center of the plate or belt. The paper investigates solutions to an old problem that has eluded belt manufacturers to date, namely the manufacture of steel cord belts with a flat and stable cord plane, producing a belt with straight running characteristics.
Research has shown that the mistracking of long steel cord belts is related to the load sharing of each cord inside the rubber belt. Furthermore, a long steel cord belt is an assembly of connected plates with continuous orthotropic properties, separated by press lengths that reset conditions governing cord thermal expansion and loss of pre-tension within the rubber-steel cord composite plate during vulcanization.

A mechanical model of the off-centre torques generated by cord plane defects that do not carry load is used to predict belt side travel. Measurement of the side-travel running of a belt can therefore be analyzed in terms of equivalent defect existence, using the inverse method. Examples used in the paper provide a typical starting point for computing the defect-induced torques in running belts that mistrack. More importantly, the extent of the non-loaded cords can be inferred from a tracking measurement. This data is used to determine whether a belt material is within manufacturing Standards for cord plane quality.

The model provides a method for end users to independently determine the root-cause of belt mistracking problems. Current Standards linking the operation of a moving composite belt to its internally induced torques from defects does not exist. The research has shown that there is a practical need to improve the fabrication quality of corded plates and belts.

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