Chapter 6

STEEL CORD SPLICE DESIGN AND FABRICATION TECHNIQUES

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Historical methods of designing steel cord belt splices are compared with modern finite element modeling (FEM) methods. Dependence of the belt strength rating on the splice dynamic fatigue strengths is reviewed. A number of splice schematics are examined, using simple spring theory and FEM methods. Steel cord wire rope design is discussed. The importance of the insulation gum rubber properties and their splice dimensional factors and tolerances are analyzed. Splice fatigue life analysis procedure is reviewed. This may be used to predict splice life or time of failure, depending on how the conveyor belt is operated.

INTRODUCTION

The steel cord splice dynamic strength rating and design should dictate the belt's strength rating and construction. The splice dynamic strength is defined as its structural capacity when subjected to repeated loading cycles. Unfortunately, most design engineers and manufacturers do not adhere to this tenet. We hope that sufficient insight is presented in this paper to make this premise axiomatic in future design standards. Research in Europe has already provided compelling evidence of the fundamental nature of this concept (Lorani, 1962) (Hager, 1974) (Flebbe, 1988) (Hager and von der Wroge, 1991).

Responsible engineering and research must include the quest for safer and more reliable recommendations when this pathway is evident. The research presented herein is based upon this philosophy and has the added benefit of significant cost efficiency. Resolution of the splice strength attributes has allowed us to focus on the means to improve its economy and explore the most effective methods to expand its capabilities.

Common myths are briefly noted. Through comprehensive investigation they have been proven false.

Basic splice patterns are examined for peak cable and rubber stresses. Stress variations of up to 60% are noted for the same splice length and pattern group. Usually, the published standard splice is the weakest.

A brief comment is given on splice reinforcement and its benefits.

A significant gain from this research is the development of a splice life prediction method. In testing, the algorithm has proved to be very accurate.

Conveyor Dynamics, Inc. has developed a comprehensive finite element model (FEM) which incorporates the belt's rubber and steel cord stress-strain behavior. Photoelastic experimentation, special dynamic testing jigs, and full scale splice testing have been conducted to verify the theory and its results as presented here. Some of these concepts were first introduced in an article published by Nordell, Qiu and Sethi, 1991.

This material is not exhaustive. Material properties, adhesive bond of cable to rubber and cohesive strengths within rubber, belt manufacturing methods, field vulcanizing methods, field repair, and bad craftsmanship are beyond the scope of this paper.

HISTORICAL SPLICE DESIGN METHODS

Splice patterns are designated according to their number of steps and step arrangement. They are made up of eight fundamental features:

1. cable dia. (d) - effective diameter from manufacturers
2. cable pitch (p) - distance between cable centers in the belt
3. gap (g) - closest distance between points of tangency of cables in splice; also the rubber spacer thickness between cables in the splice
4. cable bend zone (b) - length cables are joggled from their pitch in belt to be oriented along new axes representing the position of cables in the splice
5. splice length (L) - total length of cables passing including cable bend zone and end clearance. For this paper, "L" excludes bend zones.
6. step (s) - splice length in proportion to each cable with butted ends excluding cable bend zone
7. butt end (e) - end clearance between cables oriented on the same axis but coming from opposite belt ends
8. insulation stock or core gum - splice rubber material that has molecular properties enabling it to adhere to (bond) the cable and to the top and bottom rubber cover stock; there are two types: 1) spacer rubber placed in the gap between cables (i.e., gap, bend zones, and butt end clearance), and 2) sheet of rubber placed above and below cable and cover stock.

The standard one and two-step splice designs are used to illustrate the seven major dimensional controls of the splice shown in Figure 1. The illustrations are taken at a section along the horizontal plane through the steel cord centerline.

Figure 1a depicts a single step splice with two labeled rubber zones which are connected along the full length of each cable, noted by cable #1. The two rubber zones are illustrated as two solid blocks. They are shown under load and deformed to illustrate the rubber zone loaded in shear by the pull of opposing cables in the splice.

Figure 1b depicts a two-step splice, showing four labeled rubber zones which show the shear action in the rubber of the opposing cables in the splice. The cables on the left hand side are designated No. 1 and No. 2 to indicate the length of each step.

Additional steps are required when the proposed cable pitch, cable diameter and rubber spacing between cables, leads to an interference among their dimensions, or does not allow sufficient rubber between cables.

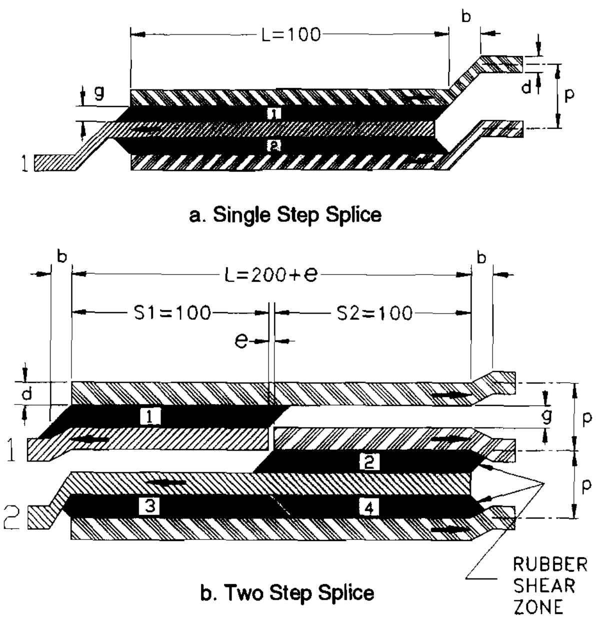


Figure 1: One & Two Step Splice Dimensional Arrangements

Rubber Spacing Between Cables

Sufficient rubber spacing or gap between cables is required to carry the shear forces of opposing cables. A set of rules govern the selection of the rubber gap which is compatible with the cable diameter. Additional rules are then combined to select the cable pitch in the belt, and number of steps which also produced the required belt strength, and which lead to an optimized belt construction and cost. These rules differ among researchers, published industrial norms and belting manufacturers.

Figure 2 illustrates proposed rubber gap distances plotted with respect to belt strength for a number of leading belt manufacturers (M1, M2 and M3) and the industrial German standard DIN 22131. There does not seem to be a consensus among these adherents. The values appear to fluctuate about a mean value of g = 2.5 mm, regardless of belt strength.

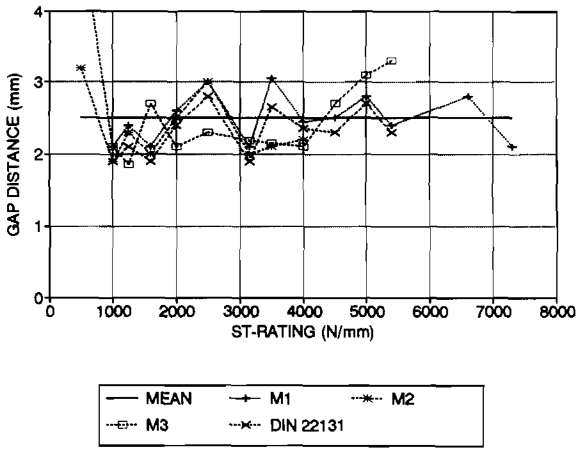


Figure 2: Rubber Gap vs. Belt Breaking Strength

From our research (Nordell, Qiu and Sethi, 1991), and that of others (Flebbe, 1988) (Kakuda, 1983) (Yokohama, 1973) (Lorani, 1962), the pullout strength, or adhesion resistance, of the cable imbedded in rubber increases with an increase in the rubber spacing between cables. The pullout strength continues to increase with larger rubber spacing between cables until the spacing is about equal to the cable diameter. The pullout strength improvement with increased rubber gap, as shown in Figure 3, and which is reflected in its splice strength, is of such significance that it can be said that the belt designs based upon the criteria of Figure 2 would not be optimal.

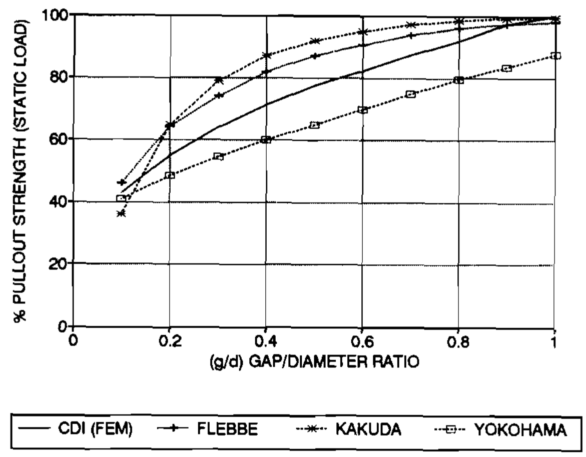


Figure 3: Pullout Strength vs. Rubber Gap Ratio (g/d) (Approximate Splice Efficiency vs. Rubber Gap)

Figure 4 illustrates the potential splice pullout strength as a function of the belt breaking strength, for a fixed rubber spacing between cables of 2.5 mm. The graph also shows the DIN 22131 (German Industrial Standard, 1988) recommendation for the number of splice steps. This graph is of special interest in that it shows that high belt strength and multiple splice steps are penalized by the fixed rubber spacing. They are not designed to their potential when engineered according to the DIN standard.

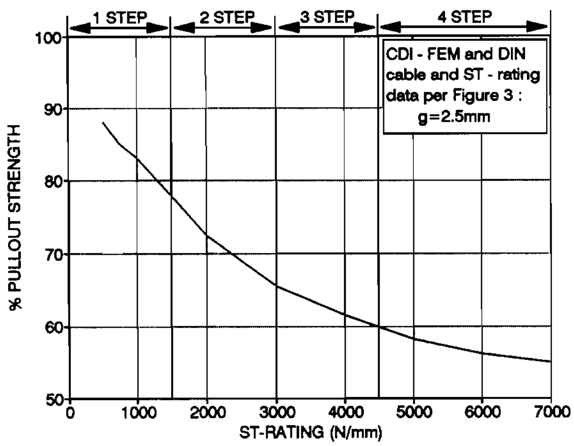


Figure 4: % Pullout Strength versus Belt Breaking Strength (ST)

A larger rubber spacing (gap) is required at higher strength. The increased rubber spacing is generated by either using a larger cable diameter or by increasing the number of splice steps. The larger diameter may require more insulation gum between cables and a large pulley side belt cover stock for the larger diameter. The idea of using a larger rubber spacing must be balanced with the notion of a more complex splice and/or a possible economic penalty. There may be an economic penalty if the belt cable diameter and pitch are increased too much. The gain in strength must be weighed against the cost of additional rubber to fill the voids between cables in the splice, and increased pulley cover rubber required. Figure 5 shows a possible improved pullout strength versus belt strength. This is achieved using a new set of rules which govern the design of the splice and belt. This demonstrates that far greater splice strength is achievable with increased spacing, and, conversely, reduced splice strength will result with poorly aligned cables in the splice. The results vary with cable diameter.

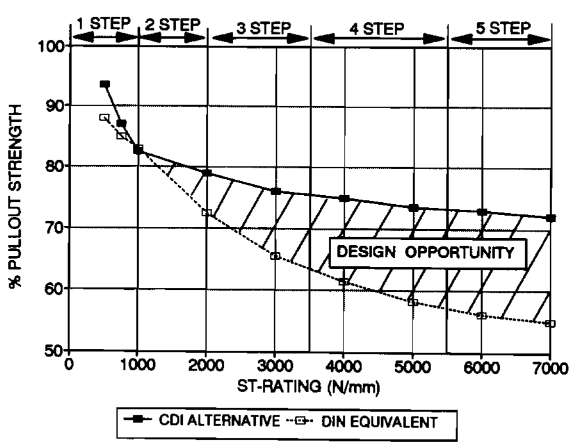


Figure 5: % Pullout Strength versus Belt Breaking Strength at Variable Rubber Gap vs. DIN

The pullout strength experimental measurements are usually made with an H-block arrangement as illustrated in Figure 6. A central cable is pulled out of the block from between adjoining cables. The force required to pull out the cable is measured for varying rubber gap dimensions. Unfortunately, this design cannot provide consistent and repeatable measurements due to the manner in which the rubber fails and the way in which the block is prepared. Many tests are required to generate an accurate trend dependent on the rubber spacing and the cable diameter, rubber properties, temperature, the rate at which the force is applied, and the procedures used to prepare the block.

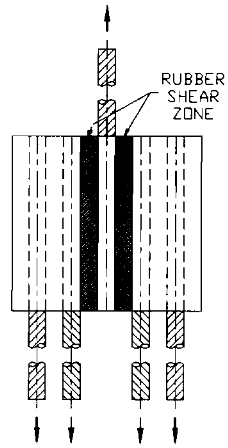


Figure 6: Typical H-Block Pullout Test Assembly

Splice Step Length

In theory, each cable is embedded into the splice with sufficient length to equal or exceed the breaking strength of the cable. The cable to rubber bonding strength therefore sets the length of the splice step. With present day bonding methods, the step length equals or exceeds the cable breaking strength when:

$$L = 100\,(d) + 25, \text{ where L and d are in millimeters} \quad (1)$$

This length is based on static loads plus a reserve factor for dynamic cyclic loads and cable elongation. Cable elongation adds additional stress on the splice which is discussed later. Manufacturers have attempted to shorten the step length (L) by taking advantage of the disparity between the accepted published norms and the potentials realized in Figure 5. This appears to be a false economy, as will be discussed later.

Historically, splice strength has been determined by measuring the total amount of rubber in shear, for a given splice step, cable diameter and rubber spacing between cables in the splice. Using a set of examples, for one through four step splices, the often used concepts will be demonstrated.

We will demonstrate, that there are significant differences among splice patterns and how they load cables in the splice, by counting the total amount of rubber in shear. Some simplifying assumptions must be made. The rubber gap (g) is fixed as per the DIN average, the forces on the cables entering the splice are equal, the cable diameter (d) and splice step length (s) are held constant, and the cables do not stretch. The total amount of rubber in shear is then equal to the number of shear panels attached to each cable for each step length in one repeat pattern in the splice. From this, an average stress per panel is calculated:

$$\overline{\sigma} = \frac{\text{Force}}{\text{Area}} = \frac{\text{No. Cables in one repeat pattern}}{\text{No. Shear Panels in one repeat pattern}} \quad (2)$$

The force acting on each cable in the splice is then calculated by adding up the number of rubber shear panels which are attached:

$$F_i = \overline{\sigma} \times \text{No. Shear panels } (i)$$
$$\text{where } i = \text{the designated cable } (1, 2, 3\text{...etc.}) \quad (3)$$

The different splice patterns are designated by a set of numbers assigned to each cable on their left hand sides shown in Figures 7-10. The numbers denote the length each cable is embedded in proportion to the maximum step length it engages for one repeating pattern. Table 1 summarizes the splice capacity in terms of relative rubber stress and cable force.

Table 1: Splice Step pattern vs. Rubber & Cable Force

Steps in Splice	Splice Pattern Designa-tion (F_i)	No. Shear Zones per Pattern (PR)	Average Rubber Stress $\sigma=\Sigma F_i/PR$	Cable Force(F_i) minimum maximum
1	1	2	0.500	1.000 1.000
2	12	4	0.500	0.500 1.500
3	123 DIN Std	6	0.500	0.500 2.000
	132	6	0.500	0.500 1.500
	213	8	0.375	1.125 1.875
	12333	18	0.278	0.278 1.667
4	1234 DIN Std	8	0.500	0.500 2.500
	1342	8	0.500	0.500 1.500
	3142	12	0.333	0.667 1.667

From the table, the relative rubber stress and cable forces are compared within each splice group (i.e., 1, 2, 3 and 4 step).

In the 2-step pattern, one cable is loaded to 50% of the nominal cable force while the other is loaded to 150% of the nominal force.

In the 3-step pattern, the DIN 123 standard has the highest cable force (200%). The 132 pattern has the lowest cable force (150%). The 213 pattern has the lowest average rubber stress, 0.375 versus DIN 123 pattern value of 0.500 (33% more).

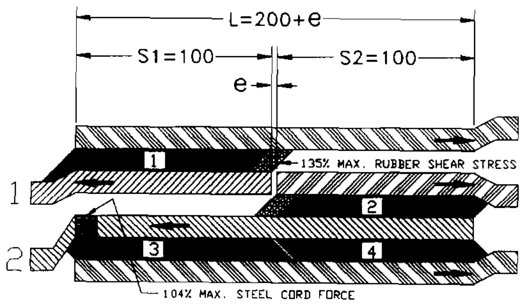
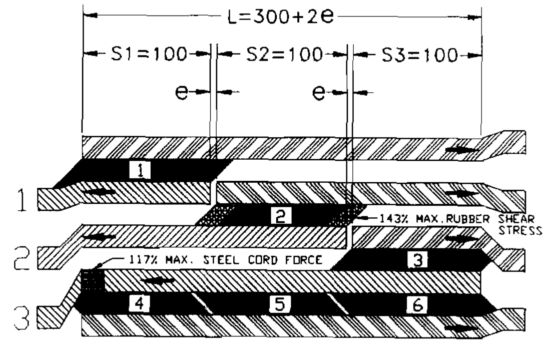
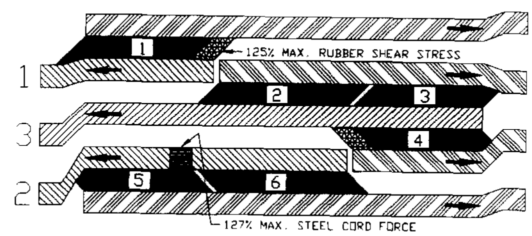


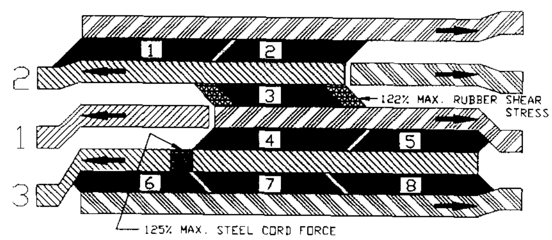
Figure 7: Two Step Pattern Showing Peak Stresses in Rubber and Steel Cord From FEM Analysis



a. 3-Step 123 DIN Standard Pattern w/ Peak Stresses



b. 3-Step 132 Pattern w/ Peak Stresses



c. 3-Step 213 Pattern w/ peak Stresses

Figure 8: Three Step Splice Patterns Most Commonly Used, Showing Peak Stresses in Rubber & Steel Cord From FEM Analysis

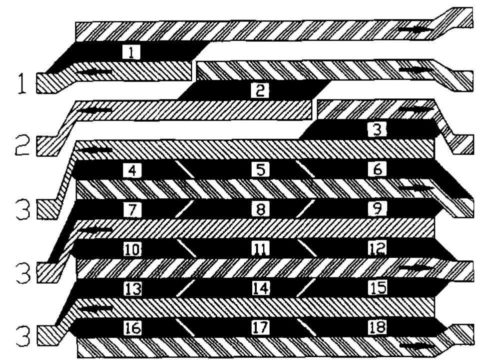
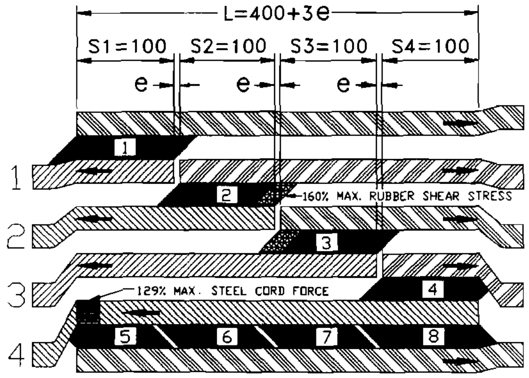
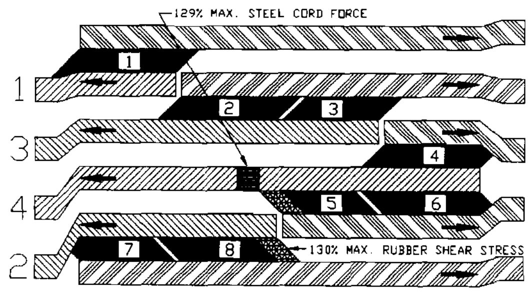


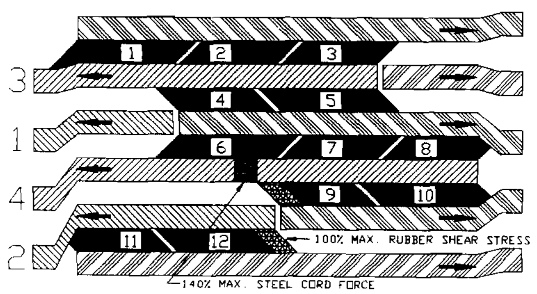
Figure 9 Special 3-Step 12333 Splice Pattern



a. 4-Step DIN Standard 1234 Pattern



b. 4-Step Palabora and Prosper Haniel 1342 Pattern



c. 4-Step 3142 Pattern

Figure 10: 4-Step Patterns Showing Peak Stresses in Steel Cord & Rubber Using FEM Analysis

A special 3-step pattern, designated 12333 is presented in Figure 9. This pattern was proposed for a long overland installation. It appears to have the benefit of many rubber shear zones (18) in comparison with the cable loading (5). Thus, it would be expected to have good rubber stress properties. Also, the cable loading appears to be better than that of the 213 pattern. Using FEM methods, and by laboratory destructive testing, this was proven not to be true. The splice had a significantly reduced structural capacity, which cannot be determined by the historical methods.

The DIN 1234 standard splice has the highest cable force for the 4-step splice. The 1342 has the lowest maximum cable force. The 3142 sequence has superior rubber stress.

The DIN pattern is inferior on both peak cable force and maximum rubber stress for the three and four step splice sequences. As the number of steps increases, the DIN method becomes more inferior.

Refer to the FEM analysis section of this paper for a summary on the true ranking of these splice systems.

The illustrations of the splice patterns given in table 1 are presented in Figure 7 (2-step), Figure 8 (3-step), Figure 9 (special 3-step), and Figure 10 (4-step). Each pattern is shown to have the same step length to demonstrate comparisons among splices and patterns within splices. The special notes presented on these figures: maximum rubber stress and steel cord force do not apply to this historical perspective. These values were derived from FEM methods as will be discussed later.

SPLICE DESIGN USING DYNAMIC EFFICIENCY

Modern splice design methods depart from the past methods, previously mentioned, by using first principles in the development of the stress-strain distribution within rubber and steel cords. The modern methods demonstrate that many of the past assumptions about splice integrity are inaccurate and need to be revised. The rubber stresses are generally much higher, are in localized regions, and have specific regions where the stresses peak. Cable construction can enhance or degrade the splice strength due to its flexibility. Highly flexible cables can increase the rubber shear stress, thereby limiting the step length. The importance of proper rubber gap dimensioning and cable impregnation, as previously noted, offers benefits in a number of areas. The section on Myths and Axioms itemizes many of these considerations.

A significant number of proponents now demand using dynamic splice cyclic loading theory and testing to quantify steel cord splice performance. A great amount of academic research has been carried out at the University of Hannover at their Institut für Fördertechnik und Bergwerksmaschinen (IFH) to support the use of splice endurance stress criteria in rubber and steel cords (Oehmen, 1977) (Flebbe, 1979) (Hager & von der Wroge, 1991).

The splice endurance or fatigue limiting stress, in the rubber and in the cable, is the most significant of the four major factors that set the design criteria for the belt's strength ratings. The other three factors include: 1) steady-state running tensions; 2) starting and stopping elastic transient (dynamic) tensions; and 3) elongation and degradation conditions which must be considered as added tensions, in part, due to expected future loss of structural capacity. The belt strength rating is given in terms of its breaking strength (ST) per unit of width (kN/mm).

Safety Factor vs. Service factor

Figure 11 illustrates the respective contributions of the four major structural design criteria. The values of each category are given as a percentage of the cable breaking force. The graph represents an interpretation of the German Standard DIN 22101 (German Industrial Standard, 1982) section on the selection of the belt's "Nominal Rupture Force" at infinite life. This standard sets out the concept of a splice fatigue strength and the above noted additional three factors. It also refers to three of the four criteria (splice endurance, elongation and dynamic loads) as "Safety Factors." The term Safety Factor (SF) is misleading. Figure 11 shows, on the graph's right hand side, the SF values associated with the four criteria. Their cumulative effect yields the commonly accepted SF = 6.7:1.

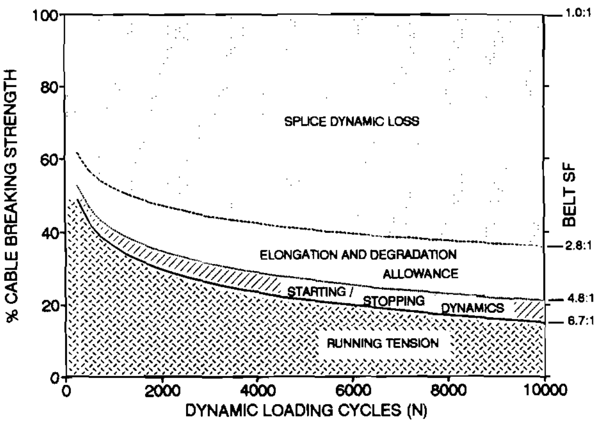


Figure 11: Belt Strength Endurance Curve in Cable Breaking Strength vs. Load Cycles Four Major Fatigue Categories

A Safety factor of 6.7:1 represents the multiple of the *running force*. We know there are three other fatigue categories that are additive to the running loads. We also know from destructive testing that the splice dynamic capacity (efficiency) does not exceed 65% of the belt's breaking strength and often is, with larger step patterns, closer to 36%. At 36% efficiency, the 64% fatigue allowance represents 4.3 times the running force. If each of the four criteria is necessary for the integrity of the conveyor, then the Safety Factor is unity. It is misleading to represent the "Normal Rupture Force" as a *safety factor*. This implies the belt is designed with a strength equal to 6.7 times the necessary load to account for unknown conditions.

Today we know that belt splice efficiency can be increased to 50-60%, allowing the safety factor to be reduced to SF = 4.5-5.0. We can determine, from first principles, virtually all of the major factors.

Users become concerned when they are told the safety factor is being reduced, when, in fact, the belt may be stronger and safer with an efficient modern design. Therefore, the term "Safety Factor" is suggested to be replaced with the more accurate term, "Service Factor."

Four Fatigue Categories

1. Running Forces can be resolved to a far greater accuracy (±8%) than the published standards (Nordell, 1991). The power equations are now based on viscoelastic analysis. The belt's cover rubber is supported by idler rolls which indent the belt's surface as shown in Figure 12. The main rolling resistance is generated by the viscous damping loss unique to the rubber compound.

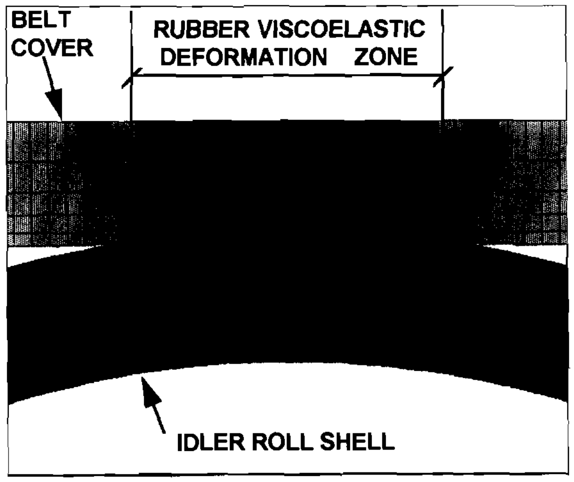


Figure 12: Viscoelastic Deformation of Belt Cover by Idler Indention Leading to Improved Power Equation

2. Starting and Stopping Dynamic Forces are quantified to a high degree of accuracy (±10%) using elastic transient mathematical models (Funke, 1974) (Nordell and Ciozda, 1984) (Nordell, 1989).

3. Elongation and Degradation Forces are noted in DIN 22101 as "additional elongations." A special note is added in the DIN Standard (German Industrial Standard, 1982) on *elongation and starting and stopping* — "The mathematical relationship between the additional stresses is not known at this time." Many of these forces can be established today. To insure structural capacity for a long term installation, the following categories are considered together with their respective forces. The requirements are presented as a percentage of the running tension:

Description of Forces	Percentage of Running Force
Splice construction errors (5% of splice strength)	22
Aging of belt core gum in 10 years	15
Bending stress over pulleys (varies with design)	10
Troughing transition at high tension zone	10
Vertical curve at high tension location	10
Belt alignment	10
Load sharing differential on multiple drives	10
Core rubber damage due to impact (large rock)	10
Surface buildup or lagging anomalies on pulley	10
Cable damage in 10 years (large rock; ice)	5
Belt cover wear and discontinuities	5
Proximity of pulleys to each other	*
Belt fabrication errors (alignment, lap joints, et al.)	*
Fixed and high hysteresis take-up action	*
Total (without vertical curves and load sharing)	97

* value cannot now be determined

This number compares favorably with DIN 22101 for the combined factors "$r_0 + r_1$" (German Industrial Standard, 1982). For most designs, the vertical curve peak stress will not occur simultaneously with the other conditions.

The reduction values have been taken from our internal design criteria of special conditions and field experience, and then compared with the DIN standard. Computation of the DIN Standard will yield an elongation and degradation force equal to 1.01 times the running load, which is close to our criterion. As shown by the Description of Forces, the criteria is dependent upon the installation and its operating procedures, and therefore the value will vary.

4. Splice Endurance — The splice core rubber and steel cable each have endurance limits, which depend on the applied loads or stress levels. The endurance level of rubber is highly compound dependent. As previously noted, the cable static pullout strength does not give a good indication of the rubber's dynamic strength (Hager, 1974). The dynamic strength depends more on the rubber's stress fracture and crack propagation properties, and on its viscoelastic properties (properties like carbon black and filler particle size, distribution and shape; rubber molecule cross-link density, etc.). The rubber's cyclic tear resistance becomes more of an appropriate indicator.

Measurement of the splice endurance limits has been successfully quantified at the University of Hannover (IFH) (Flebbe, 1984) (Hager, 1987) (Hager and von der Wroge, 1991). The University has developed a splice endurance measurement (destructive testing) machine, shown in Figure 13. The procedure for endurance testing has been developed into DIN 22110 (German Standard, 1991).

Caution must be exercised in the use of the Hannover endurance test results. The machine produces stresses in the rubber and cable which do not replicate actual operating procedures. One cyclic load consists of increasing the force on the belt (splice) from 6% of its breaking strength to a test target strength. One load cycle is applied in a series of incremental steps (usually 16-18) over a 50 second time base The target strength is fixed for each test. A test is completed when failure in the rubber or cables can be observed. The machine produces very meaningful relative measurements among splice patterns within one belt design or among manufacturers using the same splice design. The results have been used to tune the FEM models. Hannover warns against direct use or extrapolation of the results. The machine does introduces added stress to the rubber through the repeated bending of the cable around the pulleys. The splice bending stiffness causes the overall loop modulus to change twice per rotational cycle and up to 36 times per load cycle. We have observed an increase of approximately 7% load fluctuation per pulley at our target test strength.

The endurance threshold continues to be reduced with added load cycles as is noted later in this paper.

The cable fatigue threshold (infinite life) is about 25% of its breaking strength.

The rubber fatigue threshold is not known. The rubber appears to degrade with any load fluctuations.

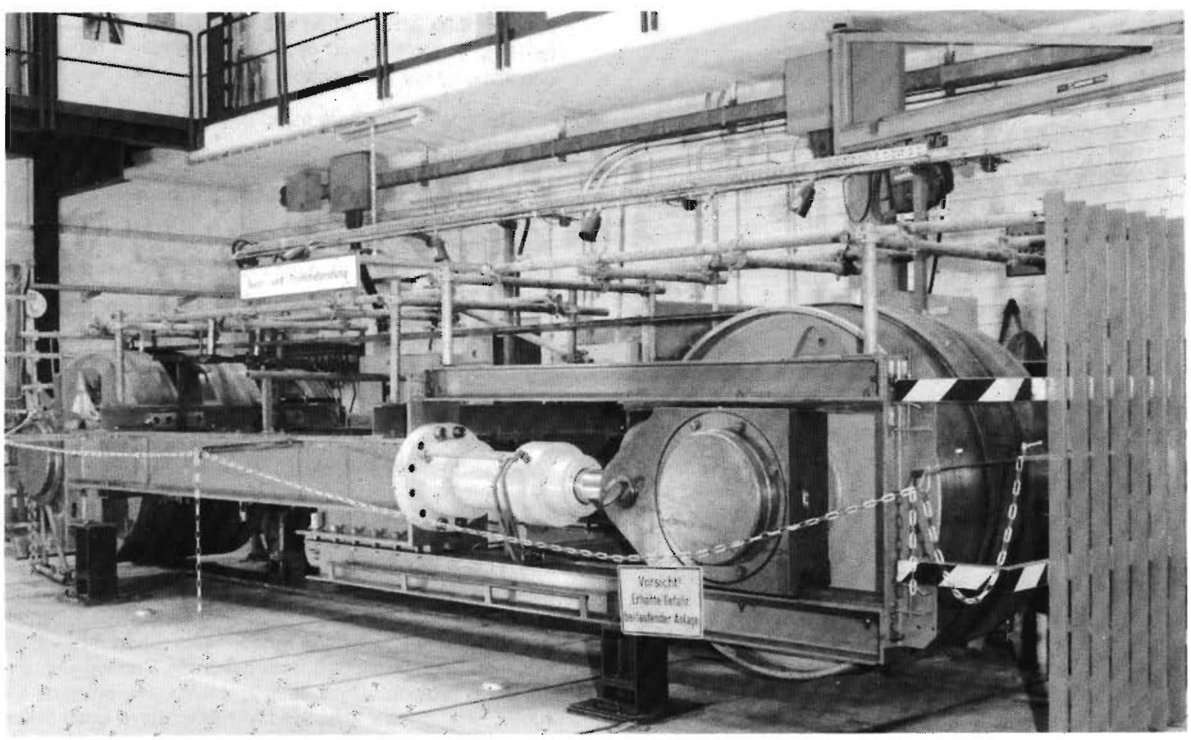


Figure 13: The Dynamic Splice Testing Machine at the University of Hannover Institut für Fördertechnik und Bergwerksmaschinen

FINITE ELEMENT MODELING OF STEEL CORD SPLICE

Conveyor Dynamics, Inc. completed development of a splice finite element method (FEM) in 1991. The work was made possible through a joint agreement with Fluor Daniel Wright. The purpose was to develop an analytical tool for researching the many splice pattern alternatives and possible reinforcing techniques. Our focus was guided by:

a) The general lack of technical support, outside of Germany, offered in steel cord belt design;
b) A need for methods to scale the size of high capacity systems;
c) A need to provide safer systems;
d) A need to improve insight and precision incumbent on the system designer;
e) To explore economic opportunities evident in Figures 5 and 11.

FEM Verification

The splice FEM model has been verified by a number of testing procedures. These include:

a) Measurement and prediction of rubber surface strains by comparing H-block photoelastic measurements with theory, as shown in Figures 14 and 15;
b) Development and testing of a special jig to test and quantify rubber failure under dynamic loading conditions similar to those of an actual splice;
c) Full scale destructive testing and photoelastic measurements of working splices.

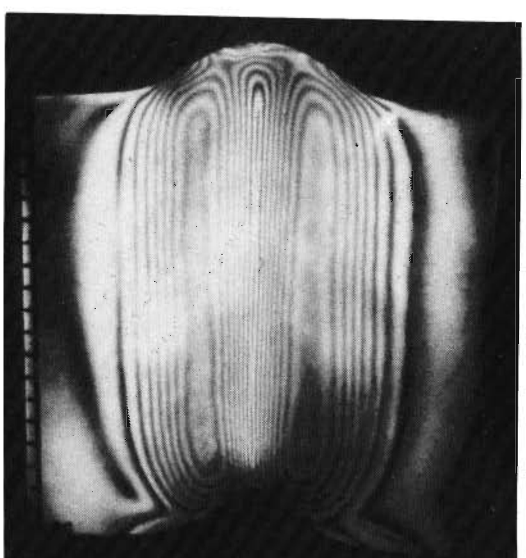


Figure 14: Standard H-Block Photoelastic Testing Surface Strain Measurements, per Figure 6

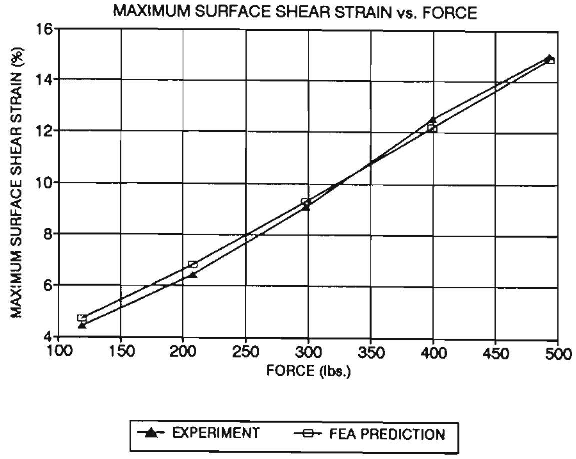


Figure 15: Standard H-Block Photoelastic Measurements and FEM Prediction

1. Rubber Testing: Conveyor Dynamics, Inc. has developed a special proprietary jig that mimics the dynamic action of rubber failure with the steel cord in the splice. The CDI jig was tested using a number of rubber gaps in the splice. A rubber fatigue failure curve was then developed. The information was compared with the 1991 doctoral research work of H. von der Wroge. Dr. von der Wroge studied all destructive testing conducted at Hannover University where the splice survived a minimum of 10,000 load cycles (the Hannover criterion for approximating infinite life). He found that the surviving splices had a rubber shear stress of 2.20 MPa (±15%). The CDI jig produced 2.19 MPa (±10%), at 10,000 load cycles, regardless of rubber gap, quantified by our FEM model.

The special jig offers many advantages which allow the economical study of:

a) testing alternative rubber compounds to quantify fatigue behavior;
b) reinforcing techniques to improve splice efficiency
c) compatibility of manufacturers' core rubbers with splice kit materials;
d) influence of installation sensitivities (i.e. contamination, solvents and cements, degradation of splice through aging, recurring, etc.).

The rubber fatigue failure curves (stress vs. load cycles) are very similar to the Hannover splice results for a belt that achieves 36% splice efficiency, shown in Figure 11.

2. Steel Cable Testing: The steel cable wire construction has been modeled (Nordell, Qiu and Sethi, 1991) using classical mechanics. The elongation, torsion and bending deformation stress behaviors have been determined. The cable elongation, torsion and bending coupling action with the rubber has been tested and modeled through support from Syncrude Canada Ltd. on a separate project. Bare cables, cables impregnated with rubber, and cables imbedded in rubber have been tested. These tests have verified the classical analysis development. The cable was then made into a special element for modeling with rubber in the commercial FEM program ANSYS V5.0 (Swanson, 1992). Further modeling of the belt in bending, by Syncrude, with varying belt constructions and temperature conditions have corroborated the theoretical model.

Studies of bend over sheave testing have been researched to establish the fatigue criterion for the cables (Drucker and Tachau, 1945) (Battelle, 1974).

3. Splice Testing: Conveyor Dynamics, Inc. has been associated with the design of a number of significant high capacity and overland systems where modern splice and belt engineering techniques were mandatory, such as Palabora's 300 m high lift belt rated at ST-6600 N/mm (1988), the Hamersley Iron Ltd. Channar 20 km overland rated at ST-3000 N/mm with a belt service factor of SF = 5:1 (1989), and the SASOL 22 km overland with a belt rating of ST-3150 N/mm (1991). The high capital cost of these installations warrants proper assessment of the splice to minimize any risk to their long term operation. These belt splices were destructively tested at the Hannover Institute (IFH). Multiple splice patterns were tested with differing step sequences, step numbers, and rubber spacing variations.

One noteworthy test was conducted on 12 and 12333 splice patterns at Hannover in 1990. The belt design was supplied by others. The 12333 pattern was recommended by others. The splice length was equal for both designs. The belt was identical. The FEM analysis indicated the 12333 step splice should not last more than 1400 load cycles in the Hannover dynamic testing machine shown in Figure 13. CDI recommended an alternative two step pattern which should have infinite life (>10,000 load cycles). A number of belts were tested. The splice load was set at 42% of the breaking strength. The FEM and fatigue model predicted the 12333 pattern should fail at less than 1436 cycles. The best 12333 splice lasted for 1316 load cycles. The model predicted the alternative two step pattern should last more than 27,000 load cycles. This pattern was pulled off the machine without rupture after 11,613 load cycles (i.e. greater than Hannover's criterion of 10,000 load cycles).

4. Splice Length: Sufficient cable must be embedded in rubber to transfer the forces of each cable from one belt section to the next. The length must be sufficient to drop the peak stresses in the rubber below the fatigue life failure criteria. As the length of cable embedment is increased, the peak rubber stress drops, but the cable elongates, causing an increased rubber stress at the cable passing its opposing cable end. This effect is illustrated in Figure 16. The graph shows that with a rigid cable, the shear stress remains constant over the engagement length. An elastic cable, which elongates with load, produces significantly higher rubber stresses at the ends of each step length. Cables with impregnated rubber typically have a 30% higher elastic modulus, which produces a similar benefit in reduction of cable elongation in the splice.

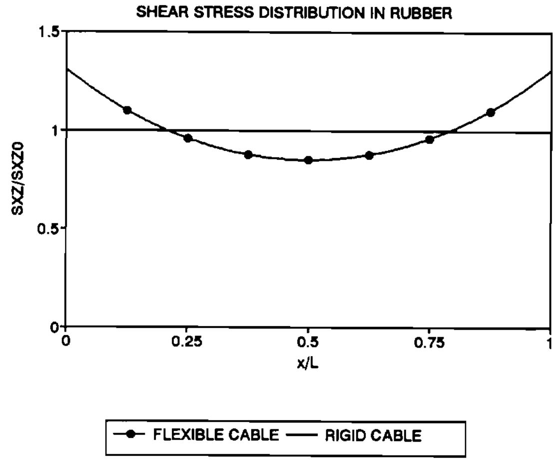


Figure 16: Rubber Stress versus Splice Step Length (SXZ/SXZ0 denotes ratio of peak rubber stress of flexible cable to rigid cable) (x/L denotes ratio of length across the step)

Figure 17 illustrates that as the splice step length is increased, the rubber shear stress falls. Eventually, the cable elongation becomes predominant, and no further reduction is possible. As the force is increased on the cable, the helical path of the wires and strands within the cable are pulled into alignment with the cable axes. This tends to increase the elastic modulus.

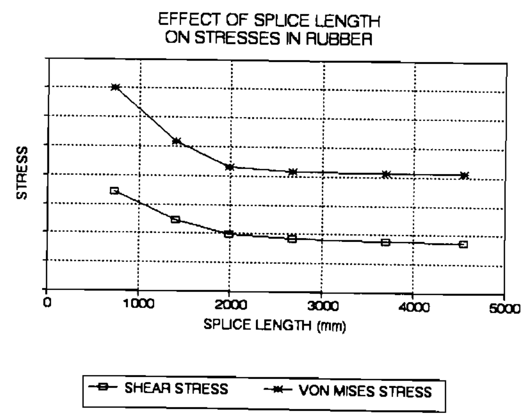


Figure 17: Rubber Stress versus Splice Step Length

Reduction of the splice length may be possible and/or necessary to allow adaptation of existing belts and splice vulcanizers. It should not be the goal on an original installation. The splice installation normally constitutes from 15-20% of the belt cost. More economy can be gained in improving the splice strength and reducing the belt rating than by any incremental savings in splice length.

FEM Comparison with Historical Analysis

A comparison of historical methods and the FEM model shows significant differences in magnitude and location of peak stresses. To illustrate the differences a known ST-5000 N/mm belt design and splice length was used.

Seven splice patterns were studied. They are listed in Table 2. These patterns are also given in Table 1, and correspond to Figures 7, 8 and 10. Our purpose in this presentation is to illustrate the diversity of performance for *one* belt design. The four step 3142 pattern had the lowest peak rubber stress. Figure 8c shows the location of the peak rubber stress and maximum cable force. All other splices' rubber stresses are referenced to this value. The cable force is referenced to the nominal force in the belt.

If the belt was designed with a service rating of SF = 6.7:1, then the nominal cable force times the peak force would be (36% x 1.4 = 0.50%) loaded to 50% of the cable's breaking strength. This would be an acceptable load. Therefore, we would conclude the 3142 pattern is superior to all other patterns for this belt design. The DIN 4-step 1234 pattern has a 60% higher rubber stress than the 3142 pattern.

Altering the belt design and optimizing the splice design, we would recommend ST-4200 N/mm over the present design, using the same cable size and construction. This alternative belt would have a stronger splice and be more economical.

These concepts are presented as considerations in the splice design and belt construction recommendation. They do not necessarily reflect the recommendation for all installations. Heavy impact resistance, ice buildup, etc. are among other factors which may alter the recommendation.

Table 2: ST-5000 N/mm Belt
Splice Performance Comparisons

Steps in Splice	Splice Pattern	% of Peak Rubber Stresses	% of Cable Force
2	12	135	104
3	123 DIN Std	143	117
	132	125	127
	213	122	125
4	1234 DIN Std	160	129
	1342	130	129
	3142	100	140

Table 3 illustrates the comparative performance of two and three step splices we tested on the Hannover machine, and that are noted in the section: Finite Element Modeling, 3. Splice Testing. The three step pattern has 58% higher rubber stress and 10% higher cable force.

Table 3: 2-Step & 3-Step Splice Performance Comparison

Steps in Splice	Splice Pattern	% of Peak Rubber Stresses	% of Cable Force
2	12	100	114
3	12333	158	125

LIFE PREDICTION

The splice life is dependent on the histogram of load cycles for each level of stress. This can be equated with tons per hour (stress) and number of load cycles (time). The time-tonnage history can yield knowledge about the length of the life of a splice or if the belt can sustain a higher capacity. This is an important design criterion in the selection of the belt design.

Using the Palmgren-Miner cycle-ratio summation theory (often called "Miner's Rule"), the splice life prediction was made on the 2-step and 3-step (12333) patterns given in the "Splice Testing" section of this paper (Palmgren, 1924) (Miner, 1945).

This concept is illustrated in Figure 18. The cumulative load damage curve represents the damage to the splice. By sampling the motor kW versus time history over a standard day's normal operation, and knowing the splice kit characteristic properties (fatigue failure curve) and splice stress distribution (by FEM), the following can be determined:

a) expected failure rate per day
b) expected failure rate per shift
c) expected time of failure
d) potential for increasing tonnage (programming catch-up on stockpile)
e) residual strength in splice beyond design capacity
f) substandard splice design and its production limitations
g) benefits of going to an alternative splice design.

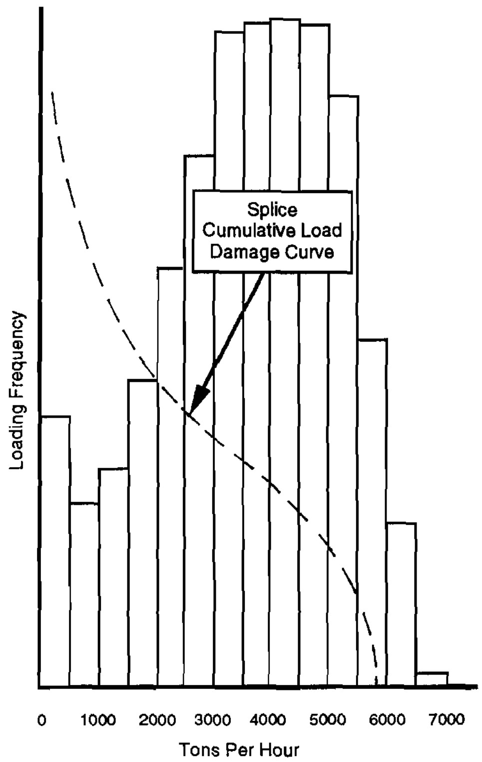


Figure 18: Splice Loading Histogram
Frequency vs. Tonnage per Hour
Illustrating Cumulative Load damage in
Equivalent Tons per Hour

SPLICE FABRICATION TECHNIQUES

This presentation gives strong arguments for increasing the core rubber gap to improve splice dynamic strength characteristics. The analysis assumes optimal conditions. Field assembly of the splice will not produce the optimal design. The differences are dependent on the belt design, splice design, and on the fabricator. A belt rating of ST-3150 and greater (g/d > 0.235) with a rubber spacing of ± 2 mm will be extremely sensitive to installation tolerances. A specific cable diameter and gap cannot be recommended, isolated from the many variables that go beyond the scope of this paper. Each belt manufacturer has on hand, or is familiar with, the design of specific cables that meet their quality control standards and design methods. The arguments presented in this paper suggest that many design techniques need revision. The strongest argument presented here is that the belt selection should be predicated on the splice design. The client often receives a quality belt, but its capacity is diminished by the poor selection of the cable size and pitch.

Rubber Gap

The rubber gap should be increased over the DIN standards both to improve the splice strength and to reduce the influence of bad cable spacing during installation. Stripping of the cables usually produces variation in residual core gum thickness that when installed causes bulges and waves in cables and rubber spacing. Often the splicing contractor block-hammers the cables to bring them into alignment. The gap tolerance is far more critical at 2 mm than at 3 or 4 mm. As a rule, the gap should not vary by more than 20%. This is very difficult to quantify with many of today's procedures. X-ray photographs are the only good measure of the pattern arrangement. An ultrasonic sensor can detect the cover thickness. This should only be necessary if there is suspicion of vulcanizer performance or splice contractor error.

Rema Tip-Top and ContiTech in Germany have each developed molds to lay the cable pattern.

Rema Tip-Top commercially markets a splice cable stripping machine that leaves a consistent core gum rubber film thickness of 0.5-1.0 mm.

Using these two methods, no solvent or cement tack is required. The cable spacing is virtually guaranteed. These advances are beginning to find their way into the marketplace.

Butt End Clearance

The cable butt ends should be four cable diameters apart plus about 15 mm allowance for cutting errors. When cable butt ends are brought into close proximity, a high tensile stress is developed in the rubber between cables as they tend to pull apart. The high rubber tensile stress combined with high local shear forces can create a premature point of failure in the rubber (Nordell, 1991).

Step Length Variations

The step length should be uniform between steps and within steps. The splice contractor is not aware that certain rubber shear panels are critical, as shown in Figures 7, 8 and 10. The worst panel is usually the short panel. The short shear panel lengths should be held within 5% of the splice design pattern dimensions. The long shear panel lengths should be within 10%.

Pattern Arrangement

Errors in the pattern arrangement are serious. They are also more critical near the edge than in the center.

The belt should be designed with an odd cable count. An even cable count means the contractor produces a splice design that may be asymmetrically installed.

The belt center, at the splice, should never be located from the edge dimensions. The rubber spacing to the first outer cable may not be held to the appropriate tolerance. The proper tracking of the belt is more reliable with alignment to the center cable. If an error in rubber edge spacing exists within the belt, at the splice end, it should be trimmed symmetrically to provide good edge cable and guide alignment during vulcanizing.

Cable Bend Zone

The cable bend zone should be long enough to keep excessive fatigue bending stresses from developing in the cables or from initiation of rubber failure at the cable end in the bend zone. We recommend a bend zone length of fifteen times the cable diameter plus 50 mm. This becomes of greater concern with lower belt SF values.

The cables should be kept out of the bend zone. We recommend a clearance equal to the butt end clearance.

Cover Insulation Stock

The cover layer above and below the cable provides the means to adhere the wear covers to the cables. This layer must be thick enough to fill all void zones and still have sufficient thickness to act as the bond of wear cover to cable. Poor cable alignment can cause local voids which nullify this purpose. Proper specification of this stock thickness is critical with larger cable diameters.

COMMON MYTHS ABOUT STEEL CORD SPLICE DESIGN

Users and engineers often make decisions based on misunderstanding of steel cord splice engineering. Some of the more common misconceptions are:

- Splice strength can equal belt strength (100% efficient)
- The "Belt Safety Factor" term defines belt safety
- Rubber static strength equals dynamic strength
- A longer splice is a stronger splice
- Splice standards and belt manufacturing standards equal the best splice
- More rubber in shear equals a stronger splice
- A higher belt strength rating equals a stronger belt
- More steel in cord cross section makes a stronger cable
- All belt manufacturers make equally strong belts and splices
- All belts and splice rubbers are compatible
- All methods of stripping rubber from cable are equal
- Center and edge carry equal loads and at equal stress
- Anybody can build a good splice

AXIOMS OF STEEL CORD SPLICE DESIGN

- The splice governs the design of the belt !
- More rubber between cables decreases rubber stress
- Less rubber between cables decreases steel cord stress
- More pulleys decrease splice life
- Proximity of pulleys can reduce splice life
- Small pulleys can reduce splice life
- An odd number of cables is highly preferable to an even number, to identify center and to provide splice symmetry
- Align the belt from the center cable at the splice, not from the edge
- Cleaning solutions and tack cement decrease splice life
- Misaligned cables decrease splice life
- Edge stresses are higher than center stresses
- Rubber impregnated cables increase splice fatigue strength and steel cord fatigue strength
- Rubber impregnated cables dam moisture migration through the cable's interior, thereby increasing cable resistance against corrosion
- There is an optimal pattern for each splice group
- Belt loading history dictates splice life (not design loads or peak loads)
- The splice is the weakest section, with usually less than half rated strength (a splice cannot be made stronger than the belt)
- Splice crews need retraining to be shown the consequences of manufacturing defects
- Fixed take-ups reduce splice life
- Splice endurance strength equals fatigue capacity, not pullout capacity
- Dirt and moisture, added during the splice preparation, reduce strength — test the splice area and air condition it.

CONCLUSIONS

This paper presents a recommendation to change the design philosophy on steel cord belt and splicing methods. A great opportunity exists to improve the belt's reliability, safety, and economy. Owners and the engineering society need to become more involved in developing a set of standards that meet the industry's agenda and which transcend the dicta of the manufacturers.

There are new classes of splice designs which offer significant levels of improvement over today's standards and which exceed the performance of the splices presented here.

Scaling up to the next generation of belt ratings, ST-8000 to ST-10000, is now viable. We believe the performance of these belts will substantially exceed present expectations. The performance can now be more easily quantified.

With proper belt and splice designs, the belt service factor can be safely lowered to SF = 4.5:1 for belt strength ratings up to ST-2000 N/mm, SF = 5.0:1 for belts up to ST-6000 N/mm, and SF = 5.5:1 up to ST-8000 N/mm.

Today splices can be built which will exceed 70% efficiency in the lower strength range. This is almost double the accepted industrial standard. With proper installation controls, the higher efficiencies will result in substantial savings.

Prediction of splice life and performance is now possible. Industrial support is required to gather sufficient operating data to set the new standards for splice design.

Splice research is now centered around selected reinforcing techniques. Reinforcing has raised the splice dynamic efficiency by up to 20%. Higher levels are anticipated.

Extensions of this research will make more projects economically viable, will enhance operating safety, and will improve plant reliability. These efforts will benefit virtually all users of steel cord belting in the future.

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A special appreciation is extended to Syncrude Canada Ltd. for their involvement in conducting laboratory testing and in their supporting studies on the splice patterns of tomorrow.

The Hannover University belt splice research staff and facilities are vital to the dynamic testing of advanced splicing systems. We are truly thankful for their cooperation and guidance.

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