# CALCULATION OF THE STEEL CORD SPLICE FATIGUE LIFE BASED ON SPLICE AND CONVEYOR CONDITIONS

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## ABSTRACT

A belt safety factor of 6.7 or other rules of thumb value are typically used to select the steel cord belt rating for conveyors, large or small. The underlying assumption has been that the selected belt safety factor will provide infinite splice fatigue life. In practice, splice fatigue failures occur more often than anticipated. The loss from unplanned downtime due to splice failures on the main line and overland conveyors can be substantial.

This paper presents a methodology to calculate and predict the splice fatigue life of a given steel cord belt construction, based on the splice pattern, conveyor operating conditions (static/dynamic tensions, curves, transitions, turnovers, annual running hours, cycle times), and splice construction quality. The methodology is established using splice fatigue test result data, finite element analysis, and conveyor analysis. The results are corroborated with actual splice fatigue failure data from overland conveyors, showing that the calculated splice fatigue life can be shorter than the expected belt service life and lead to persistent splice fatigue failures. This methodology can be used to optimise the selection of the belt safety factor for a given conveyor application to achieve a target splice fatigue life, instead of making a blind assumption of infinite fatigue life using empirical safety factors.

## 1. INTRODUCTION

Belt conveyor transports bulk materials upon an endless loop of belt. The belt is manufactured in discrete sections with typical lengths around several hundred metres. Each section is wrapped around a reel like a roll of tape. The two ends of a belt on a reel are joined together by a process called splicing. The joint is called a splice. For a short conveyor, a single belt reel is sufficient and there is only one closing splice. For the world's longest single-flight belt conveyor in South Africa (1), the entire belt loop requires joining belts from 55 reels using 55 splices. Each reel has a 1000m long belt, probably a world record in itself.

Long-distance, high-tension belt conveyors commonly use steel cord belts. In steel cord belts, the steel cords from the opposing direction are not directly mechanically connected but bonded together through a special rubber called core gum or tie gum rubber. In the belt body, steel cords carry the belt tension while the core gum rubber functions as a bonding matrix; in the splice, the core gum rubber transmits the belt tensions by shear deformation, illustrated in Figure 1. Because steel cords are packed more tightly in the splice, the width of core gum rubber, called rubber gap, is normally 2mm to 4mm wide. The length of the rubber gap is called the step length in the splice, between 100x~150x steel cord diameter. This narrow strip of rubber transmits the entire tension of a steel cord and is highly stressed.

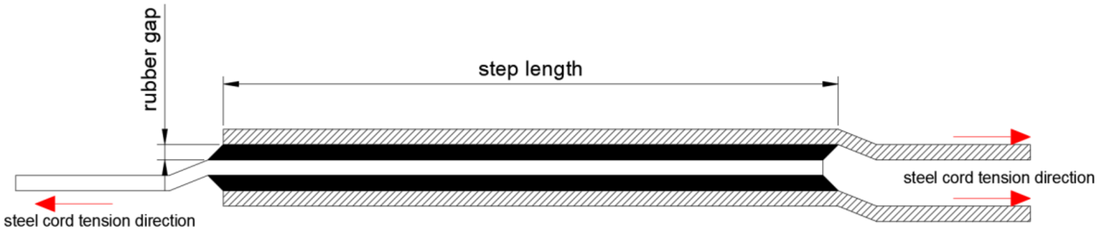

Figure 1, Steel cord tension transmitted by shearing of rubber (black areas)

Splice failure can occur in three ways: 1) failure at the bonding interface between the rubber and steel cords; 2) failure of the core gum rubber; 3) the failure of steel cords. The first two failures relating to the rubber are dominant. Steel cords in the belt body carry higher tension than cords in the splice. Steel cords in the splice have free ends, which allow some relief of tension and stress. Failure in steel cords does happen, but there is no reason for such failure to occur within the splice.

Both the bonding between the core gum rubber and steel cords, and the core gum rubber's fatigue limit, govern the fatigue life of a splice. Both are inversely proportional to the shear stress in the core gum rubber, i.e., higher shear stress reduces the fatigue life. Core gum rubber's chemical and physical properties determine the fatigue life at a given shear stress level, varying between different belt manufacturers due to their rubber technology. The shear stress is affected by the rubber gap, step length, and splice pattern, which are decided by the splice design (2). Figure 2 shows the shear stress distribution in the core gum rubber in a 2-step splice from finite element analysis.

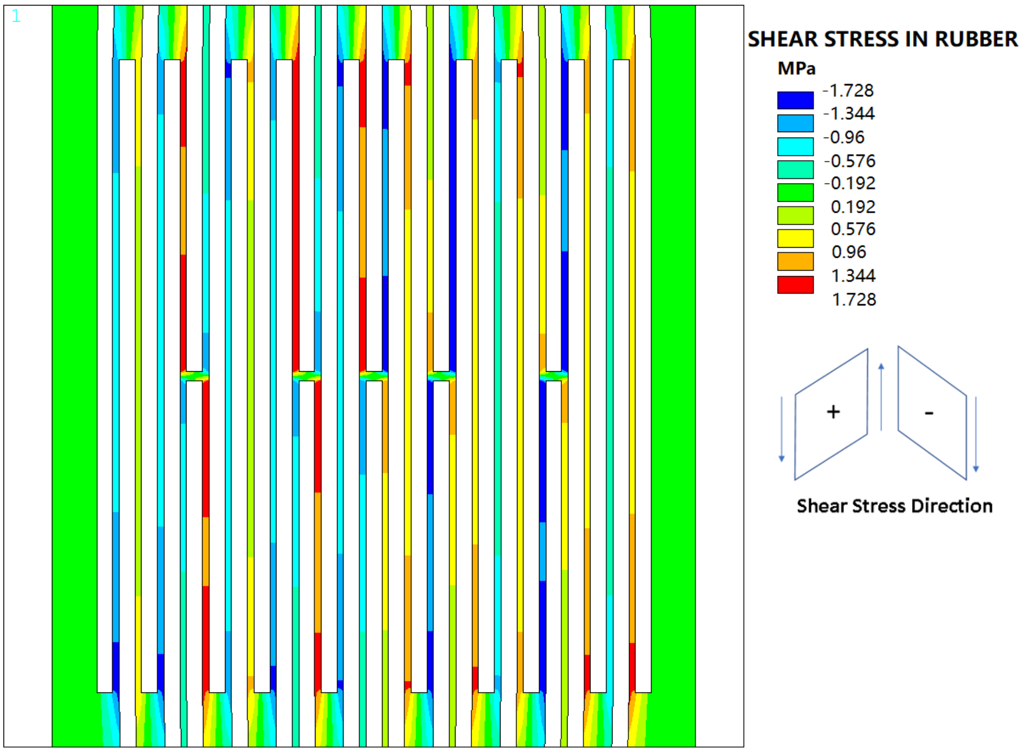

Figure 2, Finite Element Analysis of a 2-Step Splice (shear stress is directional, indicated by the positive and negative sign.)

The actual rubber gap is affected by the alignment of cords during splice construction. Figure 3 shows an X-ray image of a 4-step splice. It is apparent that the rubber gaps between steel cords are not uniform. Narrowed rubber gaps can significantly increase the rubber shear stress and decrease the splice fatigue life. To address this issue, sheets of core gum rubber with grooves preformed to fit steel cords defined by the splice design are used as an advanced splicing technology (3).

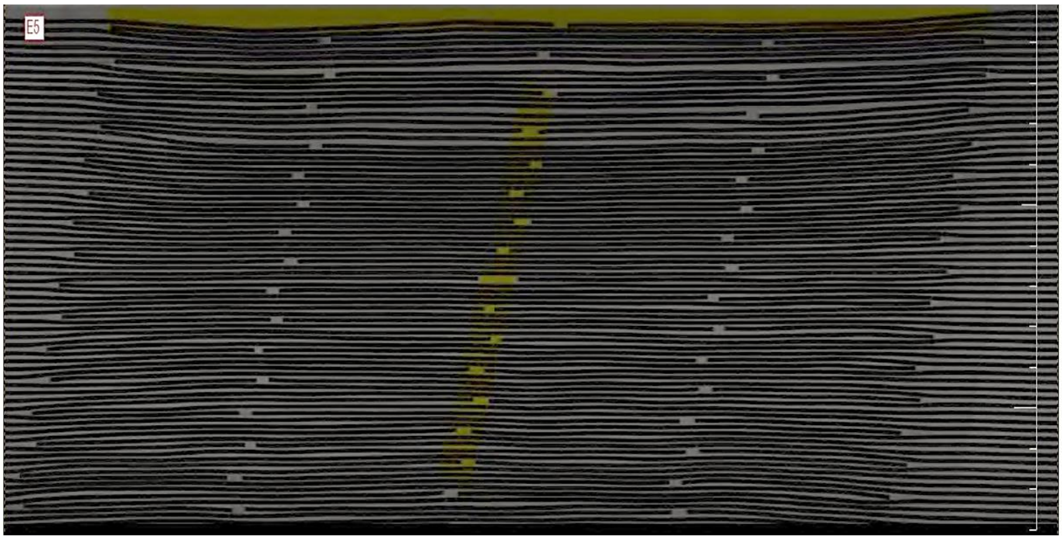

Figure 3, X-Ray of an actual 4-Step Splice, showing variations of rubber gap between cords

The core gum rubber's fatigue life can be quantified by two tests. The ISO7623 standard describes a static, single-cycle pull-out test of the ultimate bonding strength or the physical strength of core gum rubber, depending on whichever fails first (4). This static test can be adapted to a dynamic test using a cyclic load pattern to measure the fatigue strength of the core gum rubber. The dynamic test version is included in the Australian standard AS1334 Appendix K (5). A second, more extensive dynamic test is described in the German standard DIN22110-3 (6). It measures the fatigue strength of a splice in a belt loop that runs on a two-pulley configuration. The test conditions mimic some of the conveyor operating conditions. The dynamic splice efficiency is defined as the peak tension of the load cycles divided by the breaking strength of the belt, providing that the splice can survive 10,000 load cycles without failure.

When a belt is selected for a conveyor application, the Safety Factor (S.F.) is used to set the ratio between the belt's breaking tension to its working tension. Because the splice is the weakest link in the belt loop, the S.F. is really selecting the fatigue strength of the splice. The parent belt body's fatigue strength is quite higher than the splice under normal operating conditions. An important assumption is that the splice's fatigue life will be longer or even infinite compared to the required belt service life. In reality, conveyor belts do show splice fatigue failures. When such a problem occurs, the root-cause investigation is focused on the splice design, splice construction quality, and any abnormal conveyor operating conditions imposed.

Traditionally, a safety factor of 6.7 for steel cord belts is widely accepted as a design criterion. In the DIN22101 standard (7), S.F. comes from the following equation:

$$S.F. = \frac{S_0 S_1}{K_{t,rel}} \qquad 1$$

Where $S_0$ is a qualitative factor relating to the belt splice, and $S_1$ is a qualitative factor relating to the conveyor operating conditions. If $S_0S_1$ is 2.4 and $K_{t,rel}$ is 36%, then S.F. is 6.67. The definition and value range of $S_0$ and $S_1$ have evolved over the years. In the current version of DIN22101, the product of $S_0S_1$ has a value range between 1.5 to 2.28, with 1.87 as the normal value. There are multiple S.F. that can be applied to this equation. Current DIN22101 uses the belt edge S.F. in equation 1, which can be 15%~25% lower than the average S.F. due to the higher edge stress in belt transitions. $K_{t,rel}$ is the dynamic splice efficiency, which is more objective because it can be measured in the splice fatigue test mentioned above. $K_{t,rel}$ has been increasing with the advancement in rubber chemistry, belt manufacturing, and splicing quality control over the years. Nowadays, requiring $K_{t,rel}$ to be above 45% or 50% has been permeating through belt specification documents issued by end users like mining companies.

In this paper, the authors present a more refined and quantitative approach than Equation 1 to arrive at the S.F., along with a splice fatigue life calculation based on the splice design, conveyor operating conditions, and splice construction quality.

## 2. METHODOLOGY

First, a curve can be generated to establish the relation between the rubber shear stress to the rubber fatigue life (load cycles), where a lower rubber shear stress increases the load cycles and vice versa. Figure 4 shows an example of such a relation. The load cycles are measured by a fatigue test, which is either the dynamic version of the ISO7623 steel cord pull-out test or the larger splice fatigue test by the DIN22110-3 standard. The rubber shear stress comes from the finite element analysis of the fatigue tests. Performing finite element analysis on the belt splice is no trivial task, because the steel cords twist under tension and complicate the stress field. Another difficulty is that the available fatigue test data is clustered around the high-stress, low-cycle end of the curve, where the load cycles are between several thousand to less than fifty thousand for practical testing durations. Actual load cycles of a running belt may exceed one million on some short conveyors. Belts on long-distance conveyors have significantly longer cycle time and thus fewer load cycles. The difference in load cycles impacts the overall reliability of splices, but isn’t included in the conventional belt selection criteria using the S.F. Numerous overland conveyors have encountered rubber fatigue failures in splices. These projects provide valuable data points on the other end of the curve, where the shear stress is lower and the fatigue load cycles are higher than the test data. Combining both test and field data, the curve is ‘anchored’ on both ends to be more accurate. From this curve, the rubber shear stress in the splices of a running belt will give the corresponding fatigue load cycles, which can be further converted into fatigue life in operational hours or years.

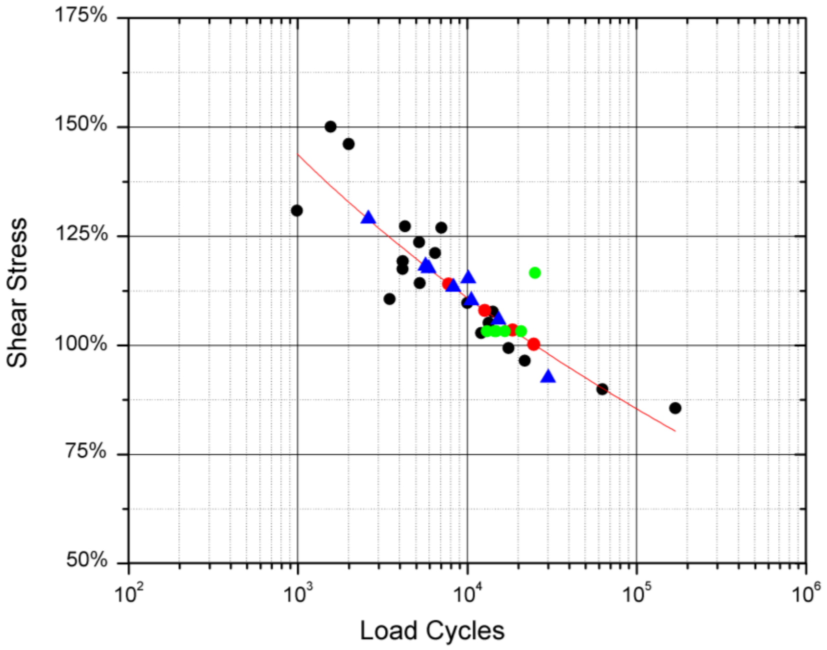

Figure 4, Shear Stress vs Expected Load Cycles for Splice Failure

The rubber shear stress in the splices of a running belt is analysed by finite element analysis (FEA). It is possible to generate curves from FEA to cover different splice designs, from single-step, two-step, three-step splices, etc., and include variables like step length, steel cord diameter, and rubber gap, so that the shear stress for a given splice design can be extracted from these curves without requiring FEA. The shear stress is further modified based on a set of factors based on the conveyor operating conditions and splice construction quality. One important point is that the shear stress value from FEA is relative. It is used to establish a link between the existing load cycle data to the predicted load cycles.

The conveyor operating conditions include dynamic tensions from the starting and stopping, belt transitions, turnovers, vertical curves, belt bending on pulleys, and pulley diameter variations due to material deposit or lagging wear. The conveyor operating conditions are input parameters into an excel spreadsheet, but they can also be directly exported from a conveyor analysis software to expedite the process.

The effects of the splice construction quality are covered by two input parameters. The first is the cord gap variation. I t represents the misalignment of steel cords in the splice during construction. For example, if the theoretical rubber gap is 3mm, some rubber gaps may be 4mm and some may be 2mm to maintain the overall splice width. Narrowed rubber gap increases the shear stress and reduces the fatigue life. Rubber gap variations impact the splice fatigue life more significantly for high-strength splices, where the theoretical rubber is quite narrow around 2mm to 2.5mm. A rubber gap variation of 1mm is much worse in such a splice than in a low-strength splice where the theoretical rubber gap is 3mm~4mm.

The second is the splice construction quality factor to represent factors like cleanness, cord preparation, control of pressure, and temperature in vulcanisation. t is a parameter between 10%, 20%, 30%, and 40%, from best to worst. It is a qualitative assessment based on the site condition, quality control, experience, and track record of the splice contractor. This factor is used similarly to the $S_1$ factor in DIN22101. Complete elimination of subjective assessment is not feasible at this point. But it can be retired to a more secondary role by introducing more objective, quantitative factors in the splice fatigue life analysis.

The steel cord itself has a fatigue life, which has been studied and tested (8). In conveyor belts, the fatigue life of steel cords is generally higher than that of core gum rubber. Most steel cord breakages in belts are due to accidents and external damage mechanisms including belt rips and large lump impacts. Some steel cord breakage events seem to be tension and/or bending-related and are more difficult to determine the root cause. Such breakage locations are observed to be random in the belt loop, not concentrating in splices. The analysis process discussed above yields a predicted fatigue life of an individual splice for a specific splice design, conveyor design and operating conditions. It can be interpreted as the expected or mean fatigue life from a statistical point of view. In this paper, it is assumed that the splice fatigue life follows a normal distribution, with a standard deviation at 20% of the expected fatigue life, shown in the following equation. More test data and analysis may refine or revise the probability distribution model in the future.

$$F(X) = \frac{1}{\sigma\sqrt{2\pi}} \int_0^X e^{-\frac{(x-M)^2}{2\sigma^2}} dx \qquad 2$$

Where *F(X)* is the cumulative probability of failure of an individual splice at X number of load cycles. *M* is the mean or expected load cycles where splice failure occurs. $\sigma$ is the standard deviation, currently estimated to be 20% of the mean or expected load cycles to failure.

A sample curve of F(X) is shown in the figure below, where M=250,000 load cycles and σ=50,000 load cycles.

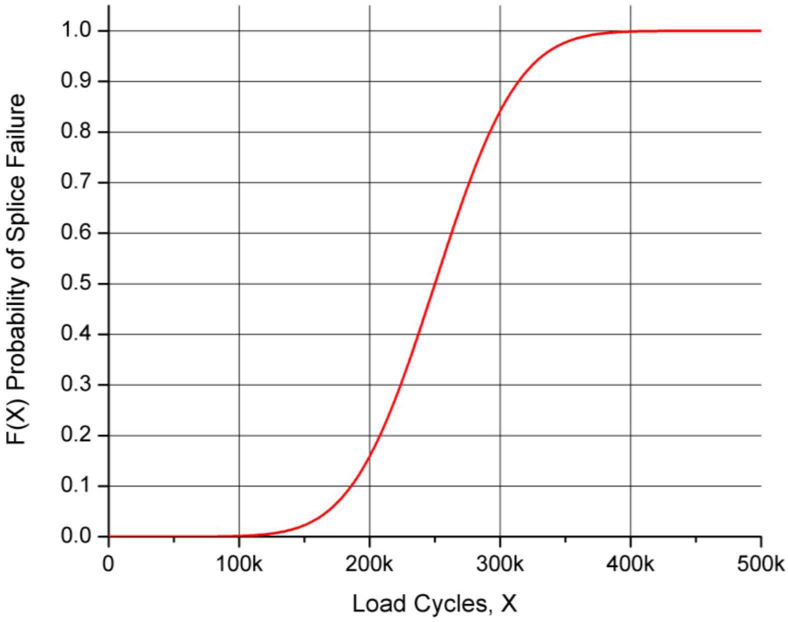

Figure 5, Cumulative Probability of Failure of an Individual Splice

Next, the probability of failure of multiple splices in a conveyor belt loop can be calculated. A growing number of splices increases the probability of a single splice failure in the belt loop because splices are connected in series. This effect is shown in the following figure, where the probability of a single splice failure in a belt loop vs. the number of splices is shown. Although a 3% probability of an individual splice failure seems low, having 50 such splices in a belt loop increases the probability of single splice failure to 78%! On the other hand, cutting the number of splices by half from 50 to 25 reduces the probability of failure from 78% to 53%. The relationship in Figure 6 stays true regardless of the individual splice's failure probability model.

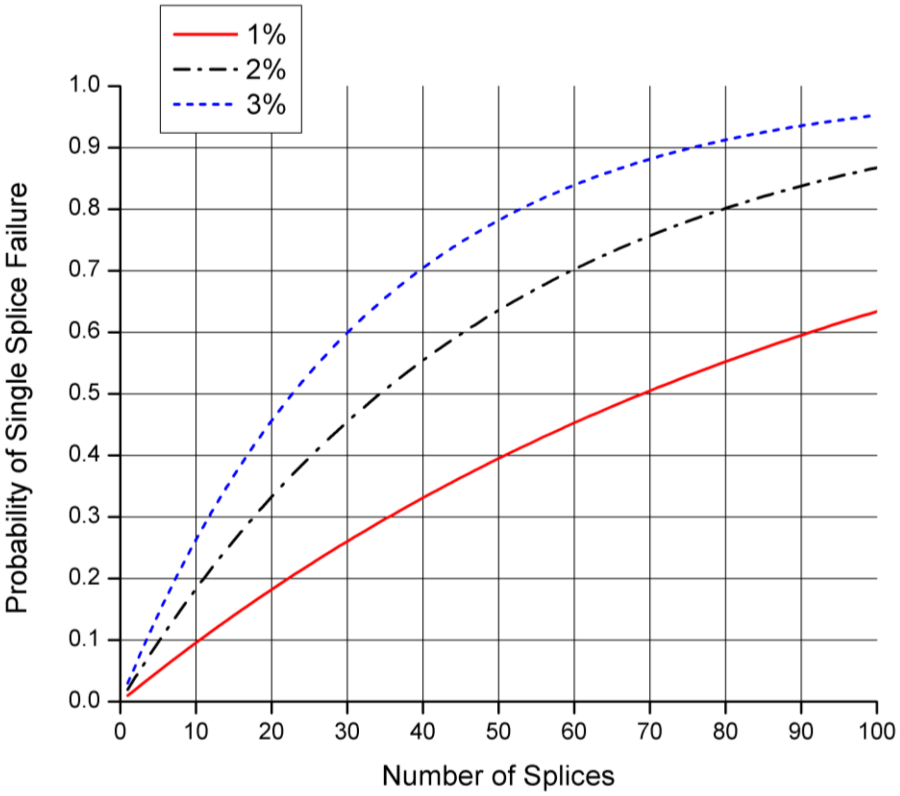

Figure 6, Probability of Single Splice Failure in a Belt Loop vs Number of Splices, with Three Curves showing 1%,2%, and 3% Probability of Failure of an Individual Splice

Similar to the L10 life commonly used in the bearing calculations, the 10% possibility of a splice failure in a belt loop can be expressed by the following equation:

$$L_{10}(X) = 1 - \left(1 - F(X)\right)^n = 0.1 \qquad 3$$

Where $L_{10}(X)$ is the 10% probability of a single splice failure in a belt loop at X load cycles.

Where $F(X)$ is defined by Equation 2.

n is the number of splices in the belt loop.

For example, if F(X)=1%, then the number of splices in a belt loop (*n*) should not exceed 10 to achieve the L10 at X load cycles for a belt loop. Equation 3 can help select an operational belt safety factor and the number of splices to meet the target L10 life or 90% reliability of all splices in a belt loop.

## 3. PROJECT EXAMPLES

Three project examples are shown as examples in

.  The first project is an overland conveyor for a cement plant in East Africa.  It is an incline conveyor with a high lift, requiring a ST4000 belt.  The belt experienced multiple events of cord pull-out in the splice during the first year of operation.  When steel cords pull out in the splice due to the loss of adhesion to core gum rubber, bulges or ‘bubbles’ and depressions will appear in the belt splice (Figure 7).  Although the belt has a relatively high running S.F. above 7:1, multiple factors are causing the splice problem.  During the rainy season, the material containing clay became sticky and caked to the surface of a bend pulley near the head drives.  The bend pulley circumference grew irregular.  When the belt moved over this bend pulley, the line speed across the belt width was uneven.  This disrupted the tension distribution in the belt and caused drive torque to fluctuate, which resulted in high local stress in the belt.  The splice design initially used a 3-step pattern with a relatively short step length, leading to a weak splice.  Improvements in maintenance cleared most of the material deposits on the bend pulley.  The 3-step splice was changed to a 4-step splice with a longer step length and wider gap between cords.  With these measures implemented, the splice problem was finally brought under control.

Figure 7, Project example 1“Bubble” in the splice due to cord pull-out

The second project is an overland conveyor in South America commissioned in 2012.  It travels over undulating terrain with a moderate overall lift.  A ST5000 belt is used to transport 6000 t/h copper ore from the mine to the processing plant.  Premature splice failure with major cord movement evidenced by depressions in the splice surface at the cord butt ends and cord ejection was reported regularly with a typical splice life of only 2.1 years being achieved.  During the subsequent root cause investigation, the splice fatigue analysis of the specific splice design under conveyor operating conditions showed an expected splice fatigue life of 1.8 years providing a good correlation.  The original splice design was a 4 step non-optimal pattern with a short step length requiring a very high quality and splice construction tolerance to achieve an acceptable fatigue life.  Improvements in the splice design were made to increase the fatigue life and reduce sensitivity to splice construction quality issues with an estimated 350% increase in splice fatigue life expected.

Figure 8, Project example 2, cord end depressions in splice are indicative of cord movement

The third project is a 20km long overland conveyor in Australia. Although the belt has a relatively low running safety factor around 5.6:1, the splice fatigue life analysis indicates a long fatigue life. There were no known splice fatigue failures throughout the belt's operational history.

|  | Project 1 East Africa | Project 2 South America | Project 3 Australia |
|---|---|---|---|
| Year Commissioned | 2014 | 2015 | 2007 |
| Conveyor Length(m) | 2465 | 6000 | 20035 |
| Elevation Change (m) | 420 | 222 | 68 |
| Capacity (T/H) | 1200 | 6000 | 2500 |
| Motor Power (kW) | 2700 | 7600 | 4250 |
| Belt Speed (m/s) | 5.6 | 6.5 | 7.5 |
| Belt Rating (N/mm) | 4000 | 5000 | 1500 |
| Belt Width (mm) | 1000 | 1372 | 1200 |
| Load Cycles per Year (thousand) | 24.5[1] | 10.8 | 8.09 |
| Static Belt Safety Factor at Full Load | 7.5 | 5.23 | 5.6 |
| Expected Splice Fatigue Life (Years)[2] | 2.7 | 4.1 | 26.3 |
| L10 Life of All Splices in Belt | 1.4 | 1.8 | 11.0 |
| Confirmed Splice Fatigue Failure | Yes, within the 1st-year operation | Yes, initial and after 2y operation | No |

Table 1, Example Projects with Splice Fatigue Analysis Results

[1] estimated based on 6000 hours/year operation time

[2] Predicted splice fatigue life and L10 life should be above 10 years to minimise the probability of splice failure.

## 4. CONCLUSION

This paper demonstrates a new approach to calculating a splice fatigue life for a specific conveyor design, splice design, construction quality and conveyor operating conditions. This enables the statistical splice fatigue life for an entire conveyor belt loop to be quantified which enables a more informed and tailored decision on the splice design and the belt safety factor for each application.

This is a step forward from the current practice of selecting a belt rating using a rule-of-thumb safety factor value. Existing splice problems can also be analysed by the same approach so that remedial changes can be evaluated.

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Dr. Yijun Zhang obtained his Ph.D in materials science and engineering from Michigan State University in 2006. He started working at Conveyor Dynamics Inc. since 2007 and currently is the Technical Director and a Member of the Board of Directors of CDI. He is a Licensed Professional Engineer in Washington State since 2011. Dr. Zhang has designed and audited multiple long-distance trough and pipe conveyors with combined length exceeding 100km and worked the belt design and analysis of ST10000 trough belt and ST4000 pipe belt.

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