A PSEUDO 3D ANALYSIS OF THE INDENTATION ROLLING RESISTANCE PROBLEM

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1. INTRODUCTION

This paper presents a pseudo three dimensional analysis to predict the indentation rolling resistance of belt conveyors. Conventional methods used to analyse the indentation rolling resistance problem typically assume a bottom cover of uniform thickness bonded to a rigid substrate with no consideration of the carcass properties. This work aims to analyse the influence of the carcass construction and configuration for steel cord conveyor belts and predict the influence on the indentation rolling resistance.

Due to the presence of steel cords embedded in the conveyor belt, the pressure distribution at the interface between the belt and a conveyor idler roll is not uniform. To solve this problem, a static three dimensional finite element model was developed to determine the pressure distribution and reaction forces transmitted through the belt to the conveyor idler roll. The reaction loads are then used in a two dimensional viscoelastic finite element model to determine the indentation rolling resistance for the steel cord belt.

This paper investigates the influence of the conveyor belt carcass and bottom cover properties on the resulting stress distribution throughout the belt and consequently on the indentation rolling resistance. The influence of the steel cord diameter and pitch, applied load, bottom cover thickness and strain rate is investigated. A finite element method is detailed for the analysis of the stress distribution throughout the belt. A range of carcass configurations is investigated and experimental verification of the calculated stress distribution undertaken using a Tekscan™ pressure measurement system.

2. BACKGROUND

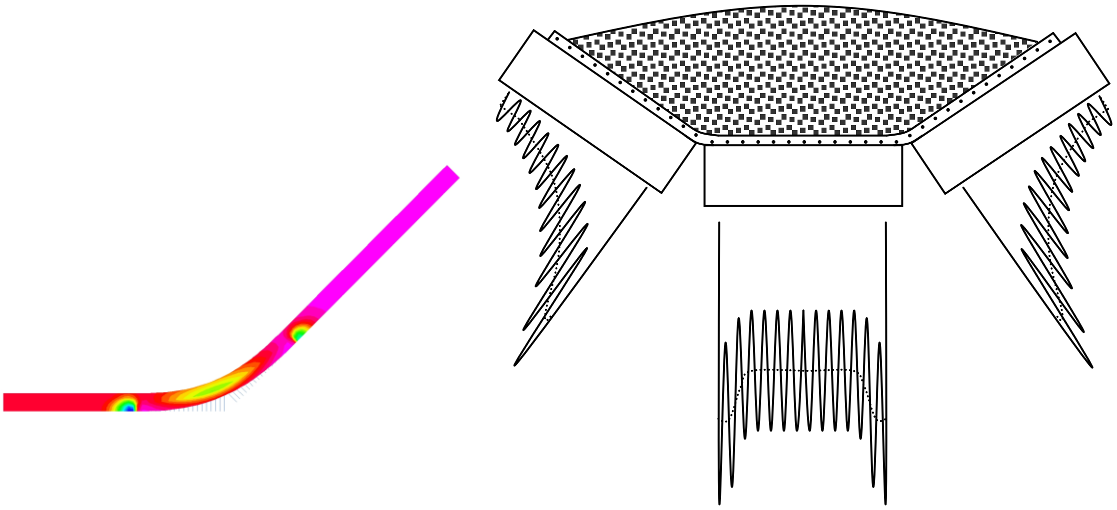
The indentation rolling resistance for a belt conveying system is influenced by a number of design parameters. These typically include the idler roll diameter, belt speed, normal load, bottom cover thickness and viscoelastic properties of the bottom cover compound. Generally, it is assumed that the bottom cover is subjected to a pressure distribution determined by the self-weight of the belt and the loading induced by the bulk solid being conveyed. A finite element analysis of the stresses within a loaded conveyor belt is shown in Fig. 1(a). This analysis highlights the stress distribution throughout a typical conveyor belt across the width of an idler set, and in particular the peak contact stresses around the idler junction. Similar contact pressures were calculated by Nordell [1] and measured by Grabner et al [2].

Clearly, due to the presence of the steel cables and the large difference between the elastic moduli of the rubber compounds and the cables, the contact pressure across the belt will fluctuate. The spacing, or pitch of the cables, determines the frequency of the pressure fluctuations, while the magnitude of the normal force and the cover thickness determines the amplitude. Fig. 1(b) shows pictorially the nature of the contact pressure at the belt and idler roll interface across the width of a loaded belt.

As previously noted, the influence of the fluctuating pressure distribution across the belt and idler roll interface will directly influence the magnitude of the indentation rolling resistance. Experimental evidence of the influence of the steel cords on the indentation rolling resistance was first reported by Hager and Hintz [3]. This work showed significant variations in indentation rolling resistance for a number of belts with varying carcass construction. The influence of the steel cord diameter was investigated and belts with larger diameter cords, having identical rubber compounds and cover thicknesses were found to have greater indentation rolling resistance.

König [4] presented a numerical analysis that modelled the carcass and bottom cover as two distinct layers. The viscoelastic finite element method analysed the carcass as a single layer of material that simulated the combined properties of the steel cords and insulation rubber.

Wheeler and Munzenberger [5] adopted a two part process to model the influence of the carcass on the indentation rolling resistance. The first involves calculating the stress distribution throughout the cross-section of the steel cord belt at the interface between the idler roll and the belt. Secondly, given the stress distribution, the indentation rolling resistance is then calculated by integrating across the width of the belt. The two part process involves the use of separate finite element methods leading to a pseudo three dimensional analysis. This paper details the numerical approach and specifically analyses the influence of the cable diameter and pitch, applied load, bottom cover thickness and strain rate on the stress distribution and consequently the indentation rolling resistance.



(a) FEA of conveyor belting under simulated loading **(b) Contact pressure at belt and idler roll interface**

Figure 1: Contact pressure distribution at conveyor belt and roll interface

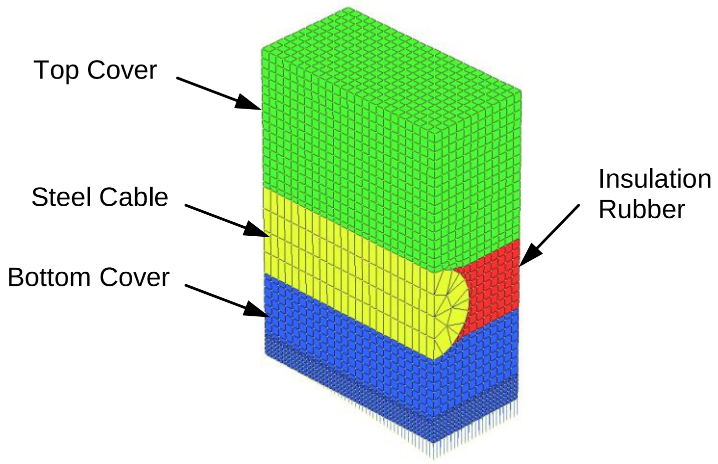
3. THEORETICAL ANALYSIS

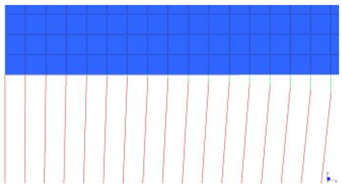
FINITE ELEMENT ANALYSIS

A static three dimensional finite element model was developed to determine the stress distribution and reaction forces transmitted through the belt to the conveyor idler roll. The reaction loads and an apparent bottom cover thickness can then be used in a conventional one dimensional analytical model, or as in the case presented, a two dimensional viscoelastic finite element model to determine the indentation rolling resistance.

The finite element analysis (FEA) models a section of steel cord conveyor belt with a width of half the cable pitch and long enough to ensure that the full contact path is modelled. For reasons of symmetry, the particular section of belt modelled started at the centreline of the cable and finished half way between the cables, and in the other direction, begins at the conveyor idler apex and models one side only.

Fig. 2 shows a typical model used within the analysis. The model incorporates the three different rubber compounds and the steel cable. The steel cable is modelled as a solid, since its only purpose is to transmit load it therefore does not need to accurately represent the properties of the steel cable.





(a) Finite element model components **(b) Belt - Idler roll contact model**

Figure 2: Finite element model

The model itself is composed entirely of eight node bricks and six node wedges. The model was restricted to using simple brick elements to avoid any issues relating to conservation of energy in the contact area that are associated with higher order elements.

A key element to the model is the modelling of the contact area. This area allows the bottom of the belt segment to be initially flat, and then allows it to gradually conform to the shape of a conveyor idler roll as the load is applied. In Fig. 2, the surface of the conveyor idler roll was suggested by the vertical "zero gap" elements on the bottom of the model. These elements were designed to have no strength when they have a length other than zero, and then to possess strength when they have zero length, thereby imitating contact in their location between the belt and the shell of the conveyor idler roll. The "zero gap" elements are forced to remain vertical by a "master slave" link connected in parallel to each one, and the bottom end of each "zero gap" element is held at the radius of the idler roll by a "pinned link" which connects it to what would be the centre of the roll. This arrangement is shown in Fig. 2(b).

The restraint, or boundary conditions used in the model were designed to best represent the actual loading situation whilst bearing in mind that symmetry has been used to simplify the model. Imagining an actual piece of belt resting on a conveyor idler roll, the sides of the segment are restrained from moving in the conveyor idler roll's axial direction, the surface normal to the roll's surface at its apex is restrained from movement across the roll, and the points representing the centre of the roll are fully fixed. A final boundary condition was applied to the fourth face of the belt model and is designed to imitate longitudinal strain in the belt before it is loaded. All other degrees of freedom are free to move.

Since the FEA model contains non-linear materials and a contact problem, the solution of the model was found using a non-linear solver. The main feature of the non-linear solver is the way in which the load is applied. For this model the load was gradually increased from zero to a full load of 5 kN/m in ten percent increments. The software further reduced each ten percent load increment into approximately 12 to 16 sub increments in order to meet convergence criteria. The total solution times for each individual model ranged from four to six hours.

INDENTATION ROLLING RESISTANCE

To accommodate for the fluctuating pressure distribution across the belt and idler roll interface, both the vertical reaction forces and an apparent, or non-uniform bottom cover thickness is considered. The vertical reaction forces across the width of the belt are directly obtainable from the FEA results, while the apparent bottom cover thickness is determined by the stress propagation through the bottom cover into the insulation rubber.

By way of an example, Fig. 3 shows an analysis of a section of conveyor belt under a simulated load of 5 kN/m in contact with a Ø152 mm idler roll. The simulated load refers to the applied load per unit length of the idler roll. The results for this particular belt construction indicate high stress regions occurring well into the insulation rubber. This will have the effect of increasing the apparent thickness of the bottom cover when calculating the indentation rolling resistance.

Given the vertical reaction forces across the width of the belt and the apparent bottom cover thickness, the indentation rolling resistance can be calculated by integrating across the width of the conveyor belt. For example, if the apparent bottom cover thickness is assumed to be approximated by a sine relationship (shown by the dashed line in Fig. 3) then the indentation rolling resistance increases by approximately 8% to 10% over a uniform thickness equal to the actual bottom cover. While the present analysis was undertaken using a two dimensional viscoelastic finite element method by Wheeler [6], similar results are also directly obtainable from one dimensional analytical methods.

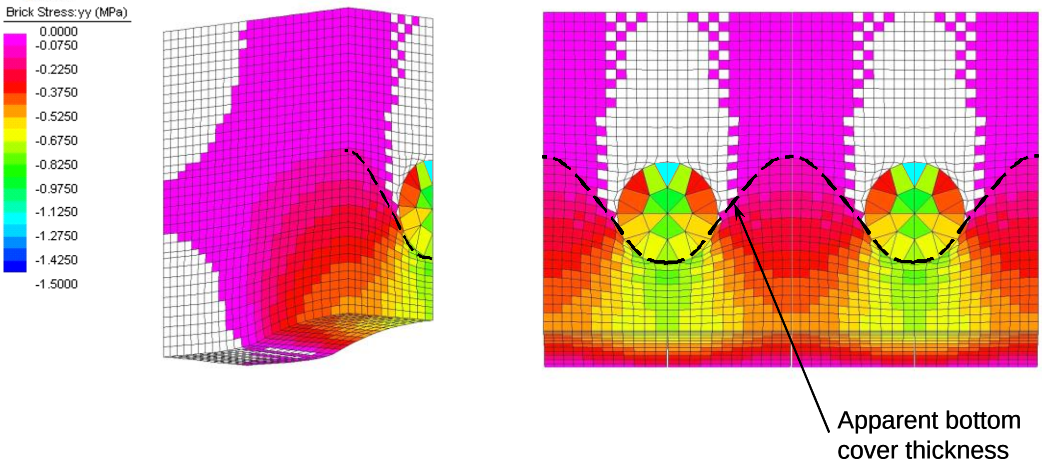
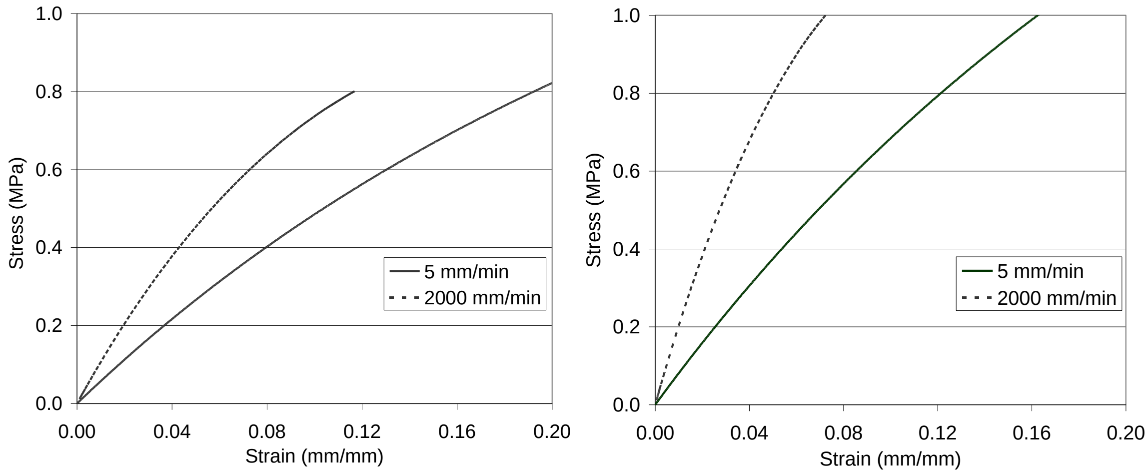


Figure 3: Typical stress distribution and assumed apparent bottom cover thickness for a steel cord conveyor belt.

4. RESULTS AND DISCUSSION

MATERIAL PROPERTY TESTING

The mechanical properties of the individual rubber layers are each tested experimentally. From these tests the constants for the Mooney-Rivlin model are derived and utilised by the FEA program. Fig. 4 shows typical experimental data for both a bottom cover rubber and insulation rubber compound at 25 ^{o}C. Additionally, testing was also undertaken at a number of strain rates, with 5 mm/min and 2000 mm/min shown for comparison in Fig. 4. The results highlight the strain rate dependency of the rubber compounds and the variation in mechanical properties of the two compounds for the different applications. Clearly, the belt speed will dictate the strain rate required, with typical belt speeds requiring time-temperature-superposition techniques to simulate higher strain rate tests.



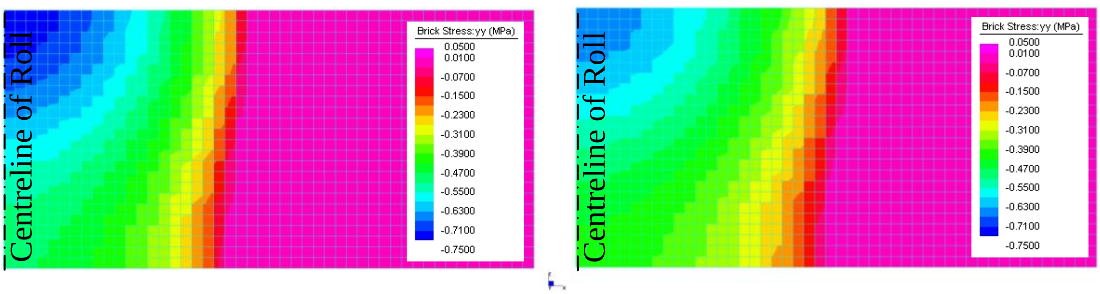
(a) Bottom cover rubber compound **(b) Insulation rubber compound**

Figure 4: Stress strain functions for bottom cover and insulation rubber compounds at different strain rates

FINITE ELEMENT ANALYSIS - STRESS DISTRIBUTION

Fig. 5 shows the results for the compression stress on the surface of the bottom cover for Ø127 mm and Ø178 mm idler rolls. The belt designation for this analysis was an ST1750, and had a top cover thickness of 8.3 mm, an insulation layer thickness of 4 mm, a steel cord diameter of 5.2 mm, bottom cover thickness of 5.3 mm and a cable pitch of 12 mm.

In each plot, the centreline of the roll is indicated with the highest stress (towards the top of each diagram) located beneath the steel cable. Each square represents one quarter of a millimetre. These results clearly show that the pressure distribution is not only influenced by the diameter of the idler roll, but the presence of the steel cables.



(a) Ø127 mm conveyor idler roll **(b) Ø178 mm conveyor idler roll**

Figure 5: Bottom cover surface stress for a simulated 5 kN/m load

Fig. 6 shows a plot of the pressure values along the centreline of the idler rolls, from the centre of the steel cable to the midpoint of the cable spacing for a number of idler roll diameters. The results demonstrate the influence of the idler roll diameter on the vertical stress distribution across the width of the belt. For the belt analysed, the stress fluctuates by approximately ± 20% from the mean pressure across the width of the belt.

While the influence of idler roll diameter on indentation rolling resistance is well established, the results shown in Figures 5 and 6 show the fundamental reason for this occurring. The finite element solution clearly shows a larger contact area and resulting lower stress levels for larger diameter rolls, resulting in an overall reduction in indentation rolling resistance.

Additionally, the influence of the steel cable is also evident, highlighting the need to consider its influence in calculating the indentation rolling resistance.

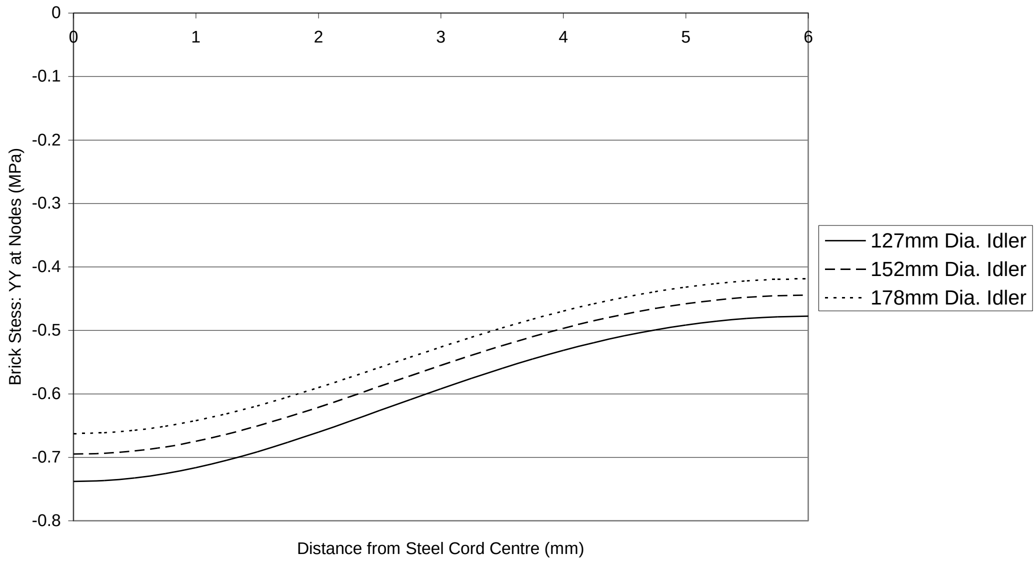
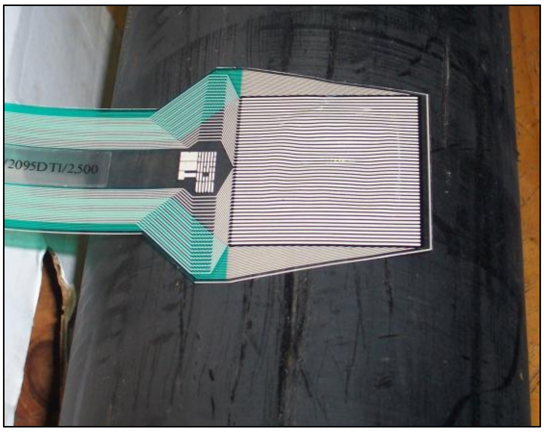


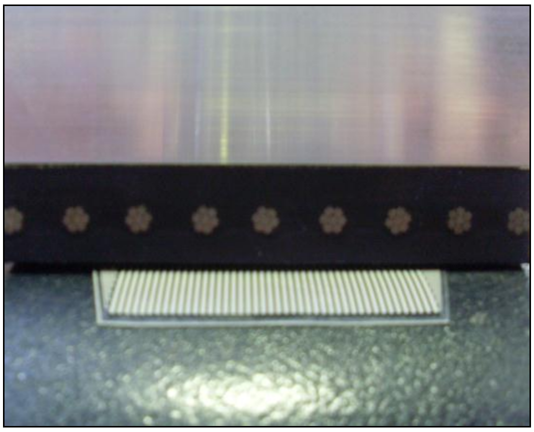
Figure 6: Belt pressure along roll centreline with respect to roll diameter for a 5 kN/m load

EXPERIMENTAL VERIFICATION

Surface pressure measurements were undertaken over a range of loads to validate the finite element analysis. Surface pressures were measured using a TekScan™ pressure measurement system. Each pressure pad consists of two thin, flexible polyester sheets which had electrodes deposited in a 50 mm square pattern. Tekscan's matrix-based systems provide an array of force sensitive cells known as sensels, that enable measurement of the pressure distribution between two surfaces.

Fig. 7 shows the experimental setup. The pressure sensor used for the analysis consisted of a matrix of pressure sensels each 1.27 mm x 1.27 mm. The sensor was placed between the idler roll and the belt surface and a steadily increasing load applied. The pressure acting on each sensel in the contact zone and therefore the contact width for each load was recorded.





(a) TekScan™ pressure pad **(b) Experimental setup**

Figure 7: Experimental pressure measurement

Fig. 8 demonstrates typical output from the testing program and shows the peak pressure along the centreline of the idler roll for a Ø127 mm roll under a simulated load of 5 kN/m. Good correlation between the FEA and the experimental results were found. The overall pressure levels are in good agreement, while the frequency of the peak pressures directly above the cables correlate well with the theoretical analysis. Tests were undertaken for a number of idler roll diameters for a range of loading conditions, with experimental results comparing favourably with the FEA predictions.

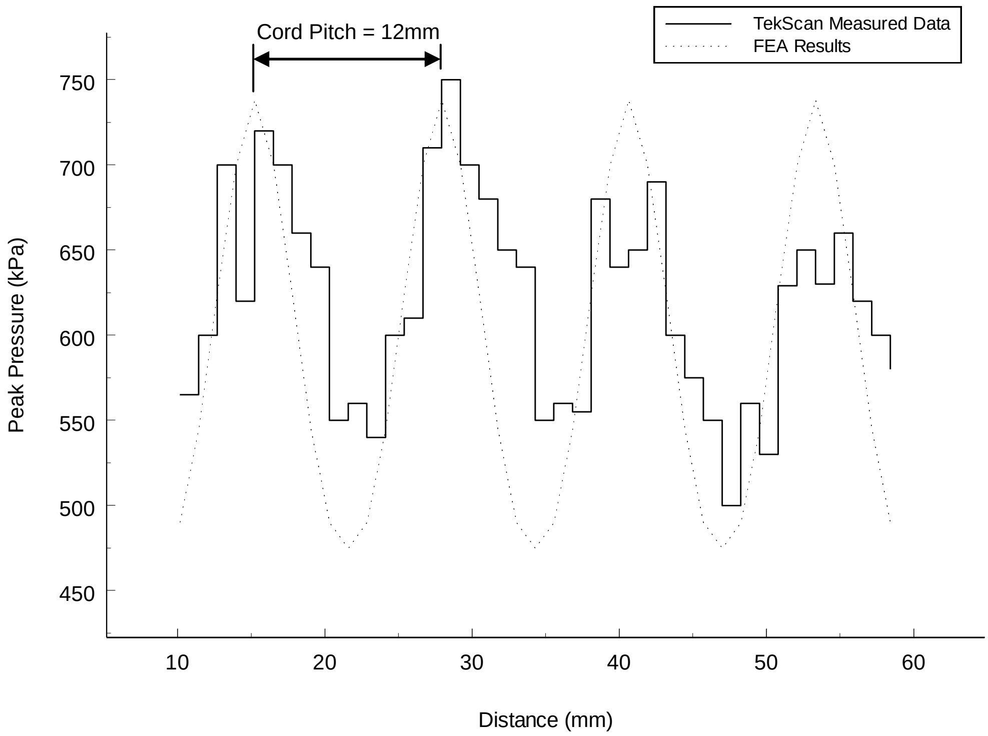
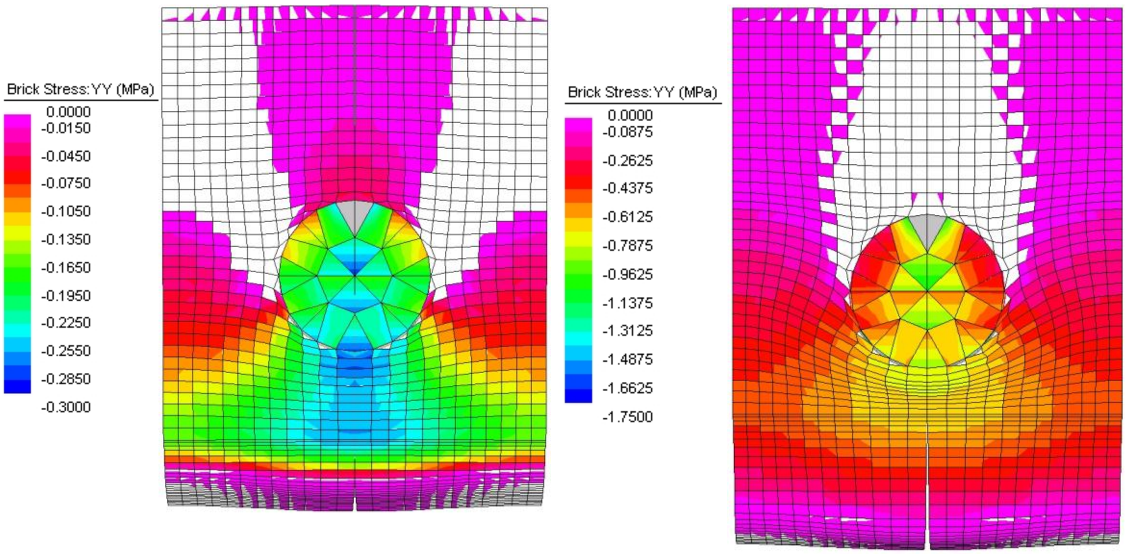


Figure 8: TekScan™ pressure measurement results for a Ø127 mm roll under a 5 kN/m load

APPLIED LOAD

The influence of the magnitude of the applied load on the induced stress distribution was also investigated. Fig. 9 shows the stress distribution for the ST1750 belt described earlier under a 1 kN/m and 5 kN/m simulated vertical load. While the stress levels differ according to the magnitude of the applied load, the overall distribution throughout the cross-section remains similar.

From an indentation rolling resistance perspective, the peak stress occurs beneath the cable and propagates well into the insulation layer during both loading conditions. As a result the use of the calculated vertical reaction forces and an apparent bottom cover thickness to calculate the indentation rolling resistance in both situations is warranted.



(a) 1 kN/m applied load **(b) 5 kN/m applied load**

Figure 9: Belt stress distribution – Ø152 mm idler roll under 1 kN/m and 5 kN/m applied loads

BOTTOM COVER THICKNESS, CABLE DIAMETER AND PITCH

To determine the influence of the bottom cover thickness, cable diameter and pitch a range of simulations were undertaken. Nominal cable diameters of 3.6 mm and 5.2 mm were modelled for a 5 kN/m simulated load acting on a Ø152 mm idler roll. The cable pitch and bottom cover thickness was varied and the pressure along the centreline of the idler roll (peak pressure) plotted in Fig. 10.

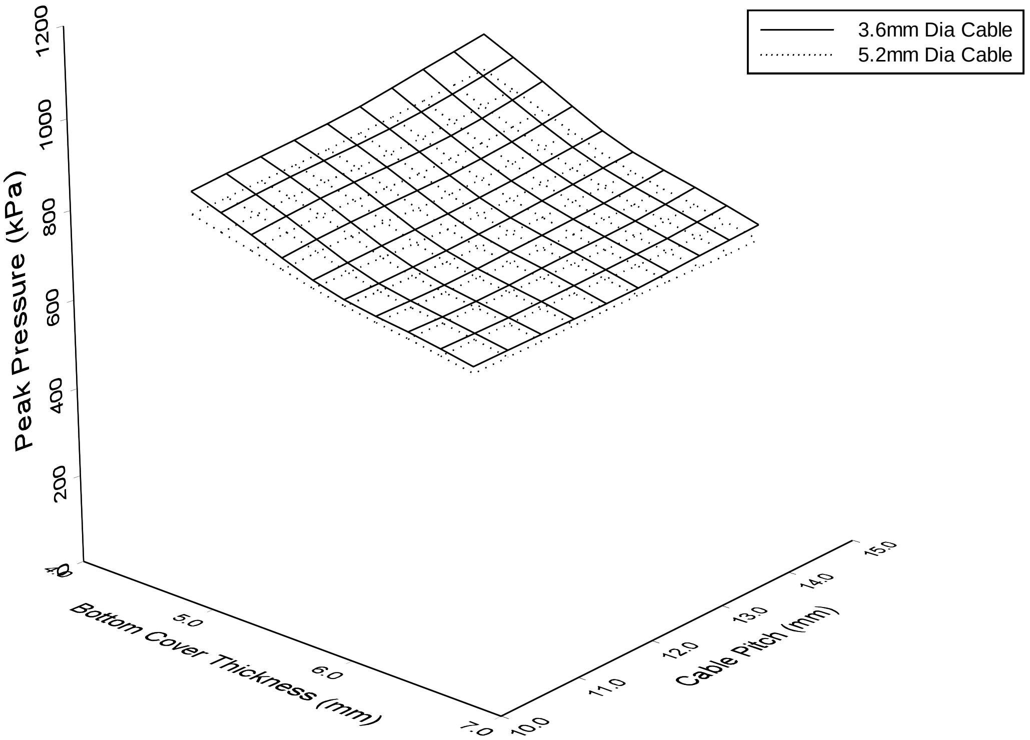


Figure 10: Peak pressure versus bottom cover thickness and cable pitch for a Ø152 mm idler roll under a 5 kN/m simulated load

For the configurations analysed the results indicate minimal change in the peak pressure with cable pitch. As expected, for the same load the smaller diameter cable shows a higher peak stress. Fig. 11 shows the results for a 14 mm cable pitch and highlights that the thickness of the bottom cover had a significant influence on the magnitude of the peak stress.

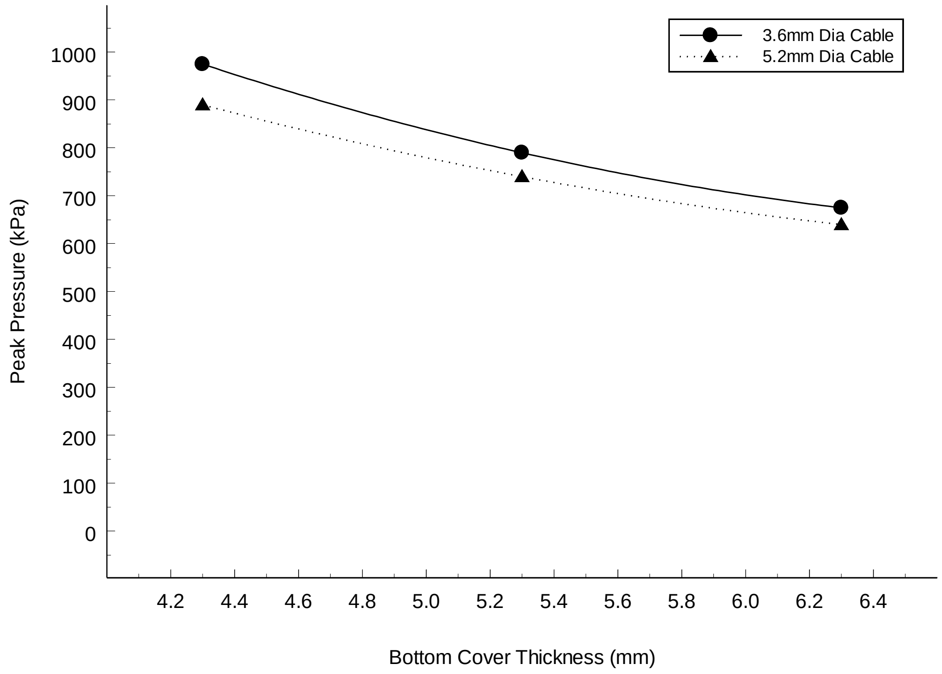
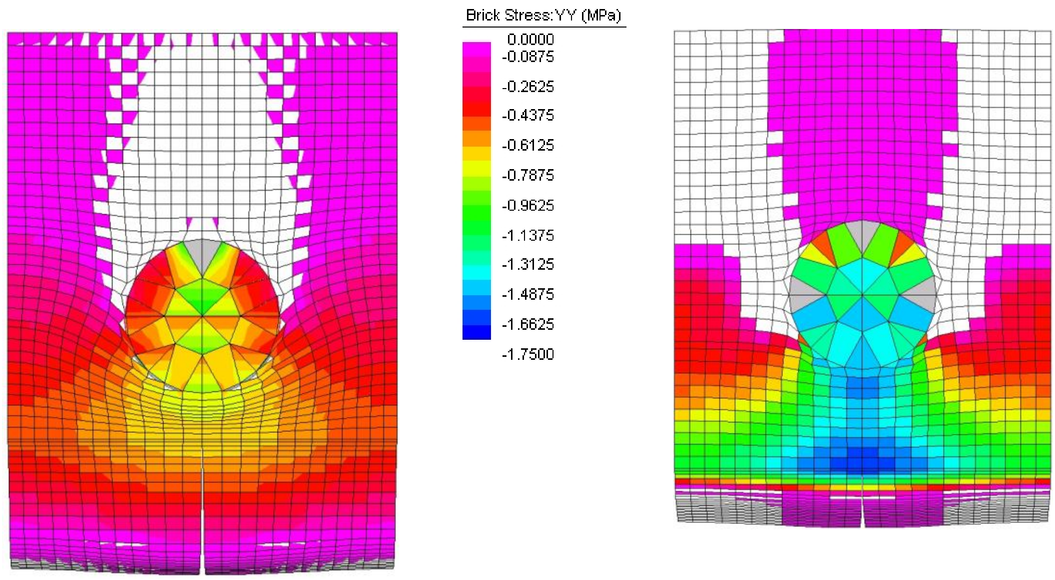


Figure 11: Peak pressure versus bottom cover thickness for a Ø152 mm idler roll under a 5 kN/m simulated load and a 14 mm cable pitch

STRAIN RATE

Rubber compounds used in the insulation layer and the top and bottom covers are viscoelastic materials, and thus exhibit both time and temperature dependent behaviour. Consequently, the rate of applied strain will influence the stress-strain relationship and therefore the stress distribution throughout the belt.

Clearly, from Fig. 4 the elastic moduli of the rubber samples are greater at higher strain rates and thus the belt acts stiffer. This results in less contact area between the belt and the idler roll, and therefore higher stress levels in the contact zone, as shown in Fig. 12. Of significance to this analysis is that the stress still propagates well into the insulation layer, highlighting the need to consider the properties and configuration of the belt carcass when calculating the indentation rolling resistance.



(a) 5 kN/m applied load – low strain rate **(b) 5 kN/m applied load – high strain rate**

Figure 12: Belt stress distribution – Ø152 mm idler roll under a 5 kN/m applied load for low and high strain rates.

INDENTATION ROLLING RESISTANCE

Given the results from the finite element analysis the influence on the indentation rolling resistance is best demonstrated by an example. Fig. 13 shows the variation in indentation rolling resistance versus bottom cover thickness for a Ø152 mm idler roll under a 5 kN/m load operating at a belt speed of 2 m/s. The indentation rolling resistance calculations were undertaken using a two dimensional finite element analysis (Wheeler [6]).

Variations from an assumed uniform bottom cover thickness range from 8% to 17% higher. Greater variations from the uniform bottom cover analysis occur for the larger diameter cables due to the increased thickness of the insulation layer. This trend fits well with the experimental data of Hager and Hintz [3]. Similarly, as the bottom cover thickness increases the variance decreases as the influence of the insulation layer reduces.

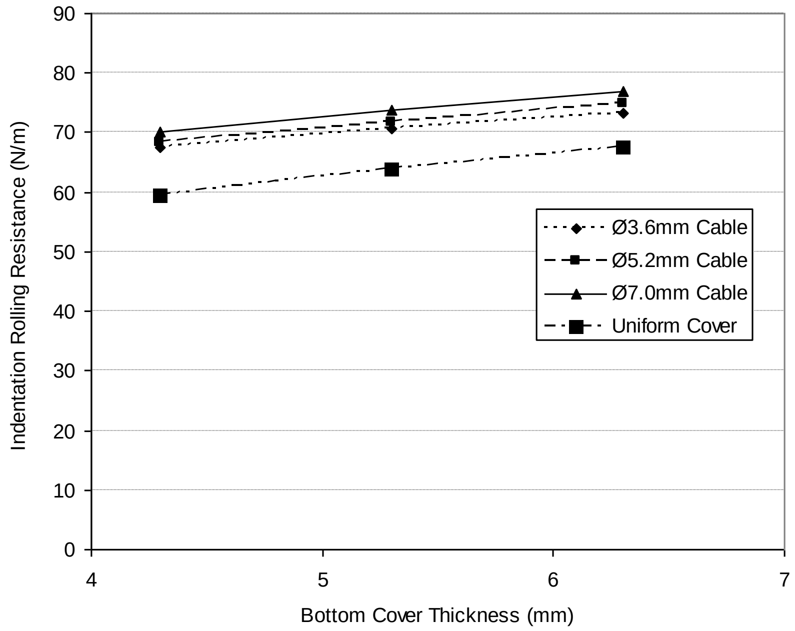


Figure 13: Indentation rolling resistance versus bottom cover thickness

5. CONCLUSION

This paper presents a theoretical approach to predict the influence of the carcass properties on the indentation rolling resistance of steel cord conveyor belts. The method adopted a two part process involving the use of separate finite element programs. Analysis of the stress distribution throughout the conveyor belt provides the reaction loads and an apparent increase in bottom cover thickness based on the stress propagation. This data is then used in a two dimensional viscoelastic finite element model to determine the indentation rolling resistance for the steel cord belt.

The research investigated the influence of the conveyor belt carcass and bottom cover properties on the resulting stress distribution throughout the belt and consequently on the indentation rolling resistance. The influence of the steel cable diameter and pitch, load, bottom cover thickness and strain rate was investigated. The results show the magnitude of the indentation rolling resistance will increase due to the presence of the steel cords and is predominantly influenced by the diameter of the cables. For the configurations analysed, smaller diameter cables showed higher peak stress levels for the same loading conditions, but lower indentation rolling resistance values due to a decrease in thickness of the insulation layer.

6. REFERENCES

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7. AUTHORS CV

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Mr Paul Munzenberger completed an apprenticeship as a Fitter Machinist in early 2001, and spent several years afterwards as a tradesman principally involved with maintenance and repair of “Cable Belt” and conventional trough conveyors, as well as a variety of other equipment associated with coal handling and preparation. He completed his Bachelors Degree in Mechanical Engineering at the University of Newcastle in 2007 with first class honours. He is currently studying part-time for a PhD in Mechanical Engineering in the field of belt conveying technology, while working as a Research Engineer for TUNRA Bulk Solids.

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