ADVANCES IN PREDICTING THE INDENTATION ROLLING RESISTANCE OF CONVEYOR BELTS

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ABSTRACT

This paper describes improvements to the numerical modelling of the indentation rolling resistance (IRR) of conveyor belts as used in the bulk materials handling industry. The numerical modelling used is of the finite element analysis (FEA) type and includes linear viscoelastic properties. It is shown how the accuracy of the FEA results can be improved with a change in element type; use of the "apparent cover thickness"; and an improvement in model geometry. The effects of other incremental changes are also discussed. Comparisons are then made between changes and data derived through experiments on the IRR test facility at the University of Newcastle.

1. INTRODUCTION

Indentation rolling resistance (IRR) is a conveyor system friction caused by the viscoelastic properties of the rubber from which the conveyor belt is manufactured. The resistance is generated by an imbalance of belt to conveyor idler roll contact pressures on either side of the apex of the roll; and it has been shown by Hager and Hintz[1] and others to be the primary resistance in long overland conveyors. Currently, rapidly rising energy costs are forcing engineers to consider energy efficient designs and belt conveyors are no exception. Obviously, since IRR is a large – often the largest – resistance of a conveyor, it is a key area for consideration when looking for ways to reduce energy consumption.

There are two ways in which IRR of a conveyor belt may be investigated. Physical experiments can be carried out on conveyors similar to the one being designed; or on specialised machinery in the lab which examines a number of specific scenarios; or material properties can be measured using dynamic mechanical analysis (DMA) equipment and then entered into a mathematical model where any possible scenario can be solved by a computer. Several analytical models exist for predicting IRR performance; these include the work of Jonkers[2] and Spaans[3] as well as later work by Lodewijks[4], Rudolphi and Reicks[5] and Qui[6]. The mathematical model – and its improvements – which is considered in the following pages is of the finite element analysis (FEA) type. It is a continuation of the work originally published by Lynch[7] and adapted for use with conveyor belt IRR problems by Wheeler[8]. The work of Wheeler was modified by Munzenberger[9] so that it could be used in commercial FEA software. This greatly improved solution times, facilitated a much wider range of post processing operations after the solutions were computed, and allowed the model to be visualised. This last iteration of the IRR FEA model is briefly presented here again, and several improvements are described and their effects demonstrated.

2. FINITE ELEMENT ANALYSIS MODEL

Lynch[7] was the first to use a finite element analysis (FEA) model to investigate a rolling contact problem that incorporated a viscoelastic material. In this case, Lynch was investigating a system in which a viscoelastic material was drawn between two rollers whose centre distance was known before the rolling operation commenced. This prescribed distance greatly simplified the analysis process as it allowed the boundary conditions to be mostly set at the outset, and only required that a small number be modified during the calculation process. Additionally, Lynch was only interested in the required driving torque and axel loads for a given roller separation rather than finding the results for a prescribed load as is required when studying the indentation rolling resistance (IRR) of conveyor belt.

Wheeler[8] was the first to apply Lynch's FEA method to the study of IRR of conveyor belts. His method is very similar to that used by Lynch. However, in the context of the conveyor rolling contact problem, generally the load rather than the indention depth is known. Initially, to overcome the problem of not knowing the actual indentation depth in advance, Wheeler estimated a depth and calculated a torque and axle load from the resultant solution. If the load was not the one required, he then modified the indentation depth in the appropriate direction and recalculated the solution. This process was repeated until the calculated load agreed with the desired applied load to within a small tolerance.

Information yielded at the end of each iteration delivered the IRR for a range of indentation depths, and thus loads, beginning from very small depths and loads until a load just above that of the desired load was reached. This information produced a graph which showed the influence of vertical load on the IRR performance over a range of loads in the same manner that is provided by a set of physical IRR experiments.

Wheeler's IRR model provided reasonable results but the calculations are very slow and there is little in the way of post processing abilities, let alone any visualisation of the deformed model. A considerable mathematical understanding would be required to implement algorithms to speed up the calculations and the delivery of a range of post processing abilities would require hundreds of hours of programming. Fortunately, there are many commercial FEA packages available that have highly efficient solvers and provide very detailed post processing environments, that when used, would render extra hours of programming and study unnecessary. Unfortunately, while it is a simple matter to create a model of a piece of conveyor belt with appropriate boundary conditions and material properties in commercial software, it is quite another to implement a viscoelastic analysis of a piece of moving conveyor belt with the same program.

Munzenberger[9] found a solution to the problem of adapting a commercial software package to carry out a linear viscoelastic analysis. This was achieved by modifying the global structural stiffness equation (Equation 1 – where [k]: the global stiffness matrix and {F}: the vector of nodal forces are the known and {D}: the vector of nodal displacements is the unknown) of the model so that the solution could be extracted by commercial software – which in this case was the Strand7 FEA package. Also utilised was Strand7's application programming interface (API) with the FORTRAN programming language to construct the models and carry out the calculations required for the linear viscoelastic analysis. The use of FORTRAN as the API programming language was convenient as it allowed parts of Wheeler's code which was also written in FORTRAN to be reused directly:

$$[K]\{D\} = \{F\} \qquad 1$$

The first model implemented in Strand7 was almost identical to that programmed by Wheeler, differing solely in the type of contact model used. Wheeler used an algorithm to detect boundary nodes which came under tensile loads and released them. Conversely, the algorithm fixed nodes in position that were detected as having passed through the imaginary boundary of the conveyor idler roll. The new model used a series of special links and contact elements to simulate a rigid conveyor idler roll boundary. This new contact model meant that for the first time the user could simply supply a desired load and the software takes care of the contact area with no further input from the user and the FORTRAN program or costly iterations to arrive at the desired load. The modelling with Strand7 proved to be quite successful and allowed Wheeler's FEA model to be viewed for the very first time. The Strand7 post processor facilitated visualisation of the belt deformation and made possible the analysis of the stresses through and along the belt. The use of the Strand7 solvers also reduced the solution time from several days to just a few hours for a range of conditions.

The improvements made to the implementation of the model and the speed at which it could now solve allowed the investigation of the effects of other variations to be conducted. These changes are detailed in the following sections, beginning with a review of Wheeler's model as implemented with Strand7.

2.1 Linear Triangle Finite Element Analysis IRR Model

The finite element analysis (FEA) models used by both Lynch and Wheeler use the linear triangle element, also known as the constant strain triangle (CST), to discretise the physical domains under consideration and plain-strain conditions are assumed. The CST is the simplest plain-strain element to implement and is less computationally expensive than other element types used in plain-strain analysis.

The two dimensional linear viscoelastic model developed by Wheeler and subsequently modified by Munzenberger is shown in Figure 1. The model is shown with twice normal deformation to emphasise the area of contact. The model is constructed entirely from CSTs and has modelled the conveyor idler roll as a group of contact elements that effectively models the roll as a rigid structure. The CSTs are modelled in two groups; a finely spaced group of layers in the contact region where the stress gradients are higher, and a coarser group of layers in the rest of the model away from the contact area. The size of the CSTs are constant along the model as a requirement of the linear viscoelastic analysis is that the elements be laid out in uniform rows in the direction of travel – which in Figure 1 is left to right.

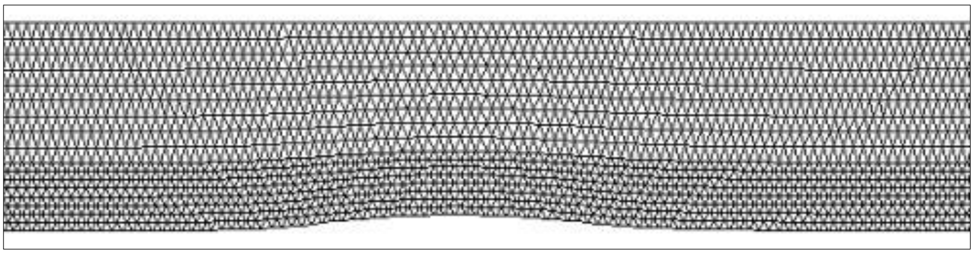

Figure 1. CST finite element analysis model

Although not immediately obvious in Figure 1, it is in fact, the solution to what is known as a quasistatic linear viscoelastic analysis. “Quasistatic” implies that the FEA solution is that of a static model while the “linear viscoelastic analysis” applied to the finite element model simulates the motion – which in this case and all others that follow is at 4 m/s. If the distortion applied to the model is increased to 300 times and the conveyor idler roll contact area is removed so that the displacements before and after the contact zone may be investigated, Figure 2 gives the result. Shown here is a build-up of material before the contact zone, while after the contact zone the gradual relaxation of the rubber is clearly evident. The contact zone is influencing the right hand side of the model and thereby simulating motion of the conveyor belt.

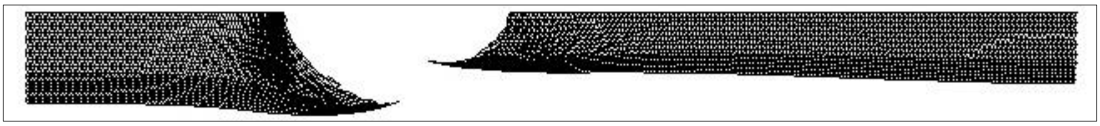

Figure 2. CST model with distortion magnified 300 times

2.2 Bilinear Rectangle Finite Element Analysis IRR model

The major problem with the model described in the last section was its use of CST elements. Even though they are easy to implement, they have a poor ability in representing volumetric strains and pure bending.[10] The IRR model does not include pure bending conditions nor does it totally restrict changes in volume, but the use of CST elements still produces a model that is much stiffer than it should be. To help alleviate the over-stiffness of the CST model, the domain was rebuilt using bilinear or Q4 rectangles. Q4 rectangles suffer from the same problems as CST elements, though to a lesser degree. The deformed Q4 mesh is shown in Figure 3. Magnified distortion looks much the same as in Figure 2. A comparison of the results generated by identical models constructed with CST and Q4 elements is shown in the graph of Figure 4 where it can be seen that the less stiff Q4 elements produce higher results.

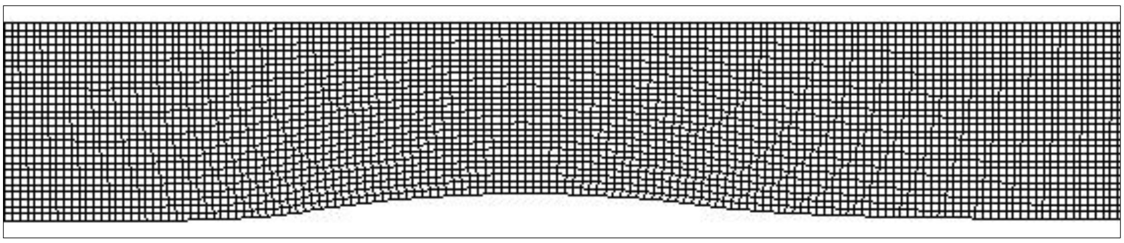

Figure 3. Q4 rectangular element deformed mesh

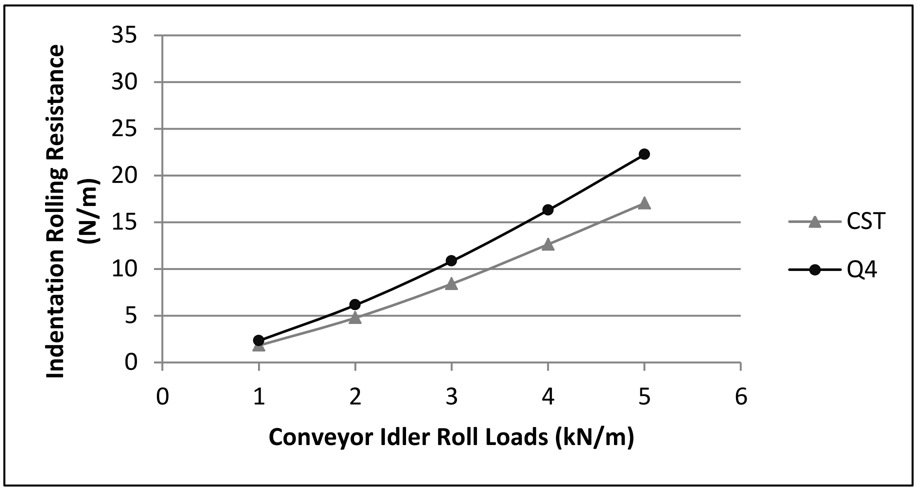

Figure 4. Result comparison for identical models made from different elements

Unfortunately, even though the Q4 rectangles provide better results than CST elements for the same model, they are much more computationally expensive. The main computational expense for the Q4 rectangle is the integration of Equation 2. In Equation 2, [B], is the element strain-displacement matrix, [E] is the constitutive matrix, t is the thickness, J is the Jacobian that transforms ξη coordinates to xy coordinates and [k] is the element stiffness matrix. For CST elements, this integration produces a constant result and so only needs to be done once and implemented across an entire model of CSTs. For Q4 elements, the result of integrating Equation 1 is not a constant and it must be carried out on an element by element basis. For the model itself, the integrating is automatically carried out by the Strand7 software. However, for the viscoelastic analysis, this integration must be carried out many thousands of times, which results in a significant time penalty (although results are still obtained more quickly than before).

$$[k] = \int_{-1}^{1} \int_{-1}^{1} [B]^T [E][B] \, t \, J \, d\xi \, d\eta \qquad 2$$

3.3 Apparent Cover Thickness

The experimental results that are intended for comparison with the computational FEA model were found by testing a steel cord belt, but the model presently being investigated is a two dimensional model which can only model a belt cover of uniform thickness. Wheeler and Munzenberger showed, with a series of static FEA models of steel cord conveyor belt, that the internal stresses caused by the belt's contact with a conveyor idler roll are not only seen in the bottom cover below the cables, they also have an effect between the cables as well as slightly above them. The internal stress patterns are shown in Figure 5 and the apparent bottom cover thickness is also marked. In the current two dimensional model under consideration, only a constant value for cover thickness can be included. In this case the thickness of the cover plus half the cable diameter is included and the result is a rough average thickness of rubber that is stressed by the rolling contact.

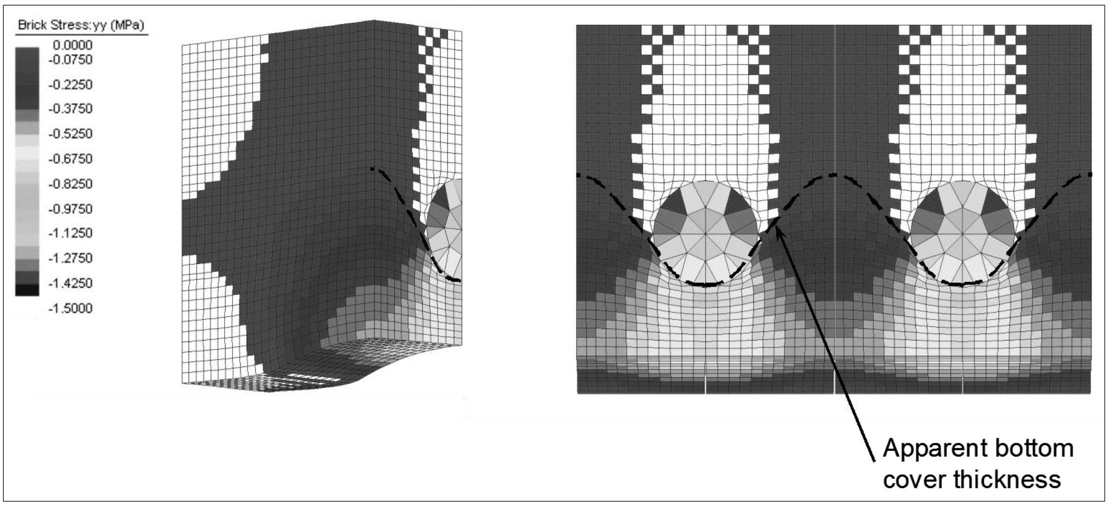

Figure 5. Apparent bottom cover thickness[11]

The results of using the modified cover thickness are given in Figure 6 where it can clearly be seen that increasing the cover thickness increases the IRR results.

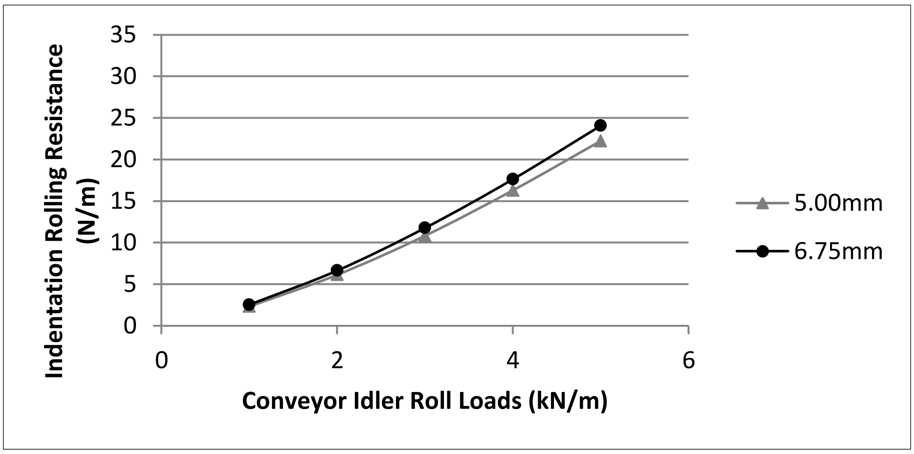

Figure 6. Comparison of results from models representing alternate cover thicknesses

3.4 Model Length

In the past, the speed of the solution limited the number of elements that could be included in the model, thus limiting the size of the model that could be investigated. In particular, since the cover thickness is fixed and must be modelled fully, the length of the model was often made quite short. Normally, when interested in studying the effect of a load or other features on a small section of a large domain, it is customary to model enough of that domain to ensure that the stresses at the boundary of the domain are essentially zero in order to provide the most accurate results. When modelling a conveyor belt it is therefore important to model enough of the belt after the conveyor idler roll contact zone to ensure that the belt has relaxed after the contact. Figure 7 is a view of an inadequately long model that shows Von-Mises' stress contours for stresses between 0 Pa and 5,500 Pa. The contours clearly show that the stress levels at the right end are still above zero, and thus the belt has not relaxed and the results are not as accurate as they could be. Note that in Figure 7, the high stresses of the contact area are being ignored and only the low stresses present in the model are considered.

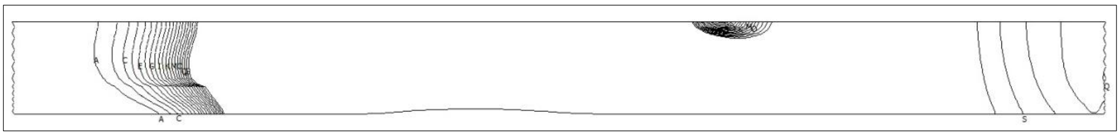

Figure 7. Model showing very low stress contours to demonstrate that the model is experiencing stress on its right boundary

Now that commercial FEA software is being used and the solution times have been shortened, it is possible for longer models to be investigated (although it must be remembered that solution times increase substantially with a rise in the number of elements making up the model). Figure 8 shows the effect of changing the model length from 100 mm to 200 mm. In the graph it can be seen that the indentation rolling resistance predicted by the longer model is higher; an even longer model should produce still more accurate results, though to a lesser and lesser degree due to stresses at the end of the model approaching zero.

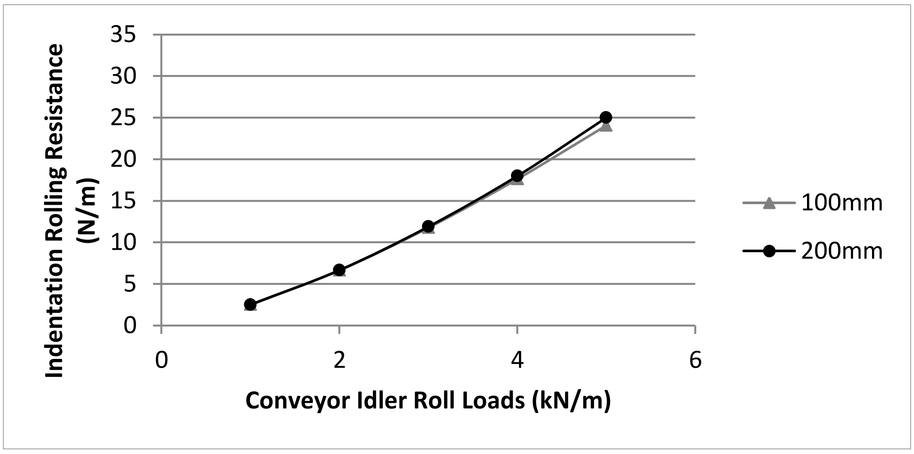

Figure 8. Results for models of different lengths

3.5 Numerical and Experimental Results Comparison

At this point a brief explanation is given as to how the data presented above compares with data derived from experiments. The IRR data generated by experiment is not directly comparable with the numerical results as it includes an amount of belt flexure due to the way in which the experiments are conducted. To account for belt flexure, Equation 3 – in which y is IRR, x is load and b is the offset due to belt flexure – is fitted to the data with a “least squares” technique. The curve fit with the belt flexure component removed is given in Figure 9 alongside all of the data presented thus far.

$$y = b + x^{4/3} \qquad (3)$$

It can be seen that the individual data presented in Figure 9 indicates that each time a change is justified and made, the results become more accurate. However, it is clear that a truly accurate model capable of modelling the experiment has not yet materialised. Up to this point, many changes have been made to the original FEA model that have improved it considerably. There are more changes that need to be made in the future. Information about these changes follow.

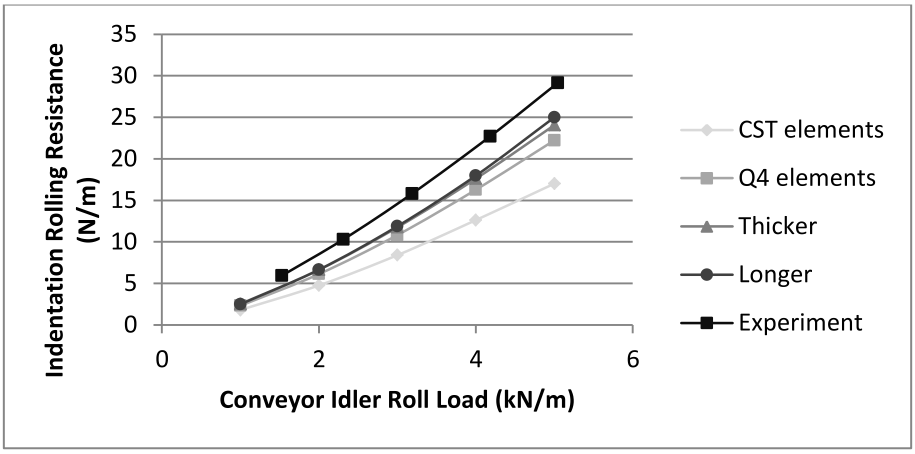

Figure 9. Comparison of experimental and numerical data

3.6 Stress Magnitude Corrections

The only material property inputs used in the FEA model are a graph of shear relaxation against time, and a bulk modulus. From this information all other properties – including the linear viscoelastic analysis – are calculated. The key decision to make is at what temperature and strain rate the shear relaxation graph should be generated. Temperature is taken as the ambient temperature at which the belt conveyor operates, with summer highs and winter lows providing the range for temperature measurement. The decision regarding the level of strain is much harder. The strain level in question refers to the strain level at which the conveyor belt rubber was tested to generate the data for the shear relaxation graph. Testing is performed on a dynamic mechanical analyser (DMA) machine with time-temperature superposition (TTS) used to shift the measured data in the frequency domain.

The DMA machine's construction, as well as the oscillating nature of the test, limits the strain levels to just a few per cent; the results presented here were found with data generated during a 2% strain test. However, the average strain levels measured through a belt model under higher loads can reach as much as 6% or 7%. Elements closer to the conveyor idler roll contact layer absorb more strain than those further away. In the future, a reliable method needs to be found that can extrapolate higher strain rate data from the lower strain rate tests carried out with the DMA machine. This new data will either be applied on a whole model basis or alternatively, it can be used on a layer by layer basis over the individual rows of the model to provide an even more realistic model.

3.7 Three Dimensional Modelling

The only way to truly model a steel cord conveyor belt is to use three dimensional finite element models similar to the one shown in Figure 10. The three dimensional model incorporates the bottom cover, the top cover, the carcass rubber and most importantly, the cable itself. Only with this type of FEA model can the stress concentrating effect of the cable be properly captured and included in the linear viscoelastic analysis. The three dimensional model removes any assumptions with regards to cover thickness, and each strip of elements' ability to affect its neighbour.

Quite a lot of work remains to implement an accurate three dimensional linear viscoelastic model. Furthermore, it should be noted that this model will take significantly longer to solve because of the extra calculations involved with adding the third dimension.

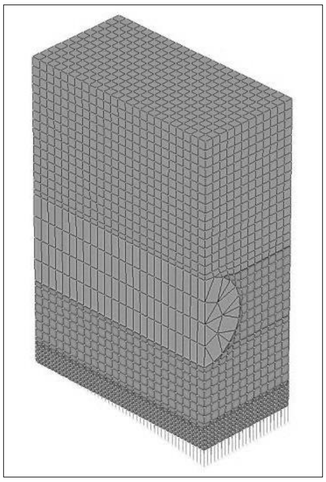

Figure 10. Three dimensional conveyor belt model [11]

3.8 Other Options

By the time all the model changes discussed above have been incorporated into a numerical model for conveyor belt IRR, much of the model accuracy lacking will have been found. At this point in time though, there will still be a few areas that are worth investigating which should help in the effort to build a more accurate model.

One area that is often assumed to be insignificant in most IRR analyses is friction but, even though the contact between the belt and conveyor idler roll is a rolling contact and friction forces tend to be small, they are nevertheless present. Since the steel roll is effectively rigid, it is the rubber belt that experiences all of the deformation of the contact and generally extrudes to either side of the apex of the roll, becoming thinner towards the centre of the contact zone. Under motion, the deformation process causes localised differential velocities between the surfaces of the belt and the roll, where at the start of the contact, the belt surface is moving slower than the roll surface and then gradually speeds up until it is moving faster than the roll surface at the end of the contact. The sliding motion that must occur to allow for the velocity differentials is the cause of the friction, and the development of the friction drag force that should ideally be accounted for. The friction force is thought to be small, and to date has been neglected in the numerical analysis of IRR. However, this does not mean its study should be neglected, especially since the use of commercial FEA software has made this possibility much easier.

The phenomenon of momentum is also often ignored in an IRR analysis, and the results presented above are no exception. The effects of momentum are thought to be even less than those due to friction, but implementation within the IRR FEA model should be simpler. The magnitude and direction of the momentum of every element within the FEA model can be calculated for any point in time. These momentums can be summed in the vertical and horizontal directions and the results added to the IRR to further improve its accuracy.

No discussion of improving the current IRR analysis would be complete without mentioning the fact that the analysis uses assumptions of linearity at virtually every stage of its development; indeed, the whole analysis process is known as a linear viscoelastic analysis. In the work presented here, the experimental data shows that the linear assumptions used have not overestimated the results; however, as technological improvements allow rubber to be used at greater stress levels, then new conveyor belts will be operating under conditions that are well removed from the small linear strain region. At this point it could become important to begin removing some or all of the linearity assumptions from the modelling and develop a truly correct model in all aspects. Removing the assumptions of linearity will be difficult and no plans have been made to consider this area further.

One final area that could be studied is the effect of pre-strain on IRR. Current IRR models assume that the conveyor belt is fully relaxed at the beginning of the modelling, whereas an actual conveyor may be operating at a speed where the belt does not have time to relax between contact zones and thus the belt will enter each contact zone with some level of pre-strain. Implementing pre-strain in the IRR model would be quite simple but solution times would rise significantly without resorting to more assumptions to reduce the size of the FEA model.

3. CONCLUSION

This paper has shown that by utilising sensible arguments and exercising care, a numerical linear viscoelastic finite element analysis model of indentation rolling resistance may be adjusted so that it is better able to represent reality and as a result, provide theoretical data that is much closer to values obtained through experimental means.

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