

INDENTATION ROLLING RESISTANCE MEASUREMENT

Craig Wheeler and Paul Munzenberger

TUNRA Bulk Solids Research Associates
The University of Newcastle, Australia

ABSTRACT

This paper describes in detail a purpose built laboratory test facility designed to measure the indentation rolling resistance of conveyor belts. Results are presented for a range of test parameters, including vertical load, belt speed, idler roll diameter and bottom cover compound. Furthermore, a field test apparatus is described that enables the main resistance to be measured at any point along the carry side of an operating belt conveyor.

1. INTRODUCTION

The cyclic indentation of the bottom cover of the belt as it passes over the idler rolls generates indentation rolling resistance due to the hysteresis losses of the rubber. As the conveyor belt travels over the idler roll the bottom cover of the belt is indented due to the weight of the belt and bulk solid. The contact region consists of an area of increasing pressure as the belt drives into the rigid roll, followed by an area of decreasing pressure as the belt travels over the roll. The cyclic indentation of the bottom cover of the belt as it passes over the idler rolls generates a resistance to motion due to the formation of an asymmetric pressure distribution within the contact area of the idler roll and belt.

A variety of analytical and computational methods exist for calculating the indentation rolling resistance of conveyor belts. These include both one and two-dimensional analytical approaches [1-5], and two-dimensional finite element methods [6,7,8]. Traditionally, each of these methods assumes the bottom cover is bonded to a rigid boundary, assuming no influence of the belt carcass. However, research [9,10] has shown the influence of the carcass construction can have a significant effect on the indentation rolling resistance.

Analytical and computational methods rely on the measurement of the dynamic mechanical properties of the bottom cover compounds. These properties are typically measured using Dynamic Mechanical Analysis (DMA) equipment. DMA machines rely on time-temperature-transformations to simulate high frequency cyclic tests, where low frequency, low temperature data is shifted along the frequency axis to simulate higher frequency tests at the temperature being analysed. The measured rubber properties are then used in the theoretical models based on the frequency of indentation and operating temperature. In most cases, the accuracy of these models is heavily influenced by the DMA test procedure and post-analysis techniques, particularly when working in the non-linear viscoelastic region.

This paper describes a laboratory test facility specifically designed to measure the indentation rolling resistance of conveyor belts. The test facility allows a range of operational variables to be tested and facilitates verification of the theoretical models. Furthermore, a field test apparatus is also described that enables the main resistance at any point along the length of an operating belt conveyor to be measured. While the measured resistance includes the other components of the main resistance, including rim drag of the conveyor idler rolls (which is measured as a separate component) and the belt and bulk material flexure, the data obtained from the field tests will provide valuable information to further improve the theoretical models under actual operating conditions, rather than an idealised laboratory environment.

2. INDENTATION ROLLING RESISTANCE MEASUREMENT

Direct measurement methods of the indentation rolling resistance of conveyor belts vary considerably. They include bench scale test facilities like pendulum tests and declined plane tests, and other larger scale facilities that allow for the influence of belt speed to be determined, such as the rotating drum test [8] and recirculating belt loop test facilities like

those at Hannover University in Germany [11], and the University of Newcastle, Australia [6]. This section will describe a new recirculating belt loop test facility recently commissioned at the University of Newcastle.

Original Indentation Rolling Resistance Test Facility

Figure 1 shows schematically the original indentation rolling resistance test facility at the University of Newcastle. This test facility has worked satisfactorily for many years but has several limitations that have begun to reduce its industrial relevance. The major limitation of this facility is its inability to test steel cord conveyor belts due to the relatively small diameter pulleys. Furthermore, the test facility is not able to test at high belt speeds due to the relatively short length of the system. The limited length means the splice can influence the measurements, as some time is required for the measurement system to settle after the splice passes the measurement idler roll. The induced vibrations are dependent on the belt thickness variation across the splice and the change in belt stiffness due to the splice. Additionally, design constraints have also limited the maximum idler roll diameter that can be measured on the facility to $\text{Ø}150\text{ mm}$.

The test facility utilised a deadweight loading system as shown in Figure 1, where the vertical load is applied by a series of weights to the top side of the belt via a low friction liner. Alternatively, the vertical load could also be applied via the vertical component of belt tension, as shown in Figure 2.

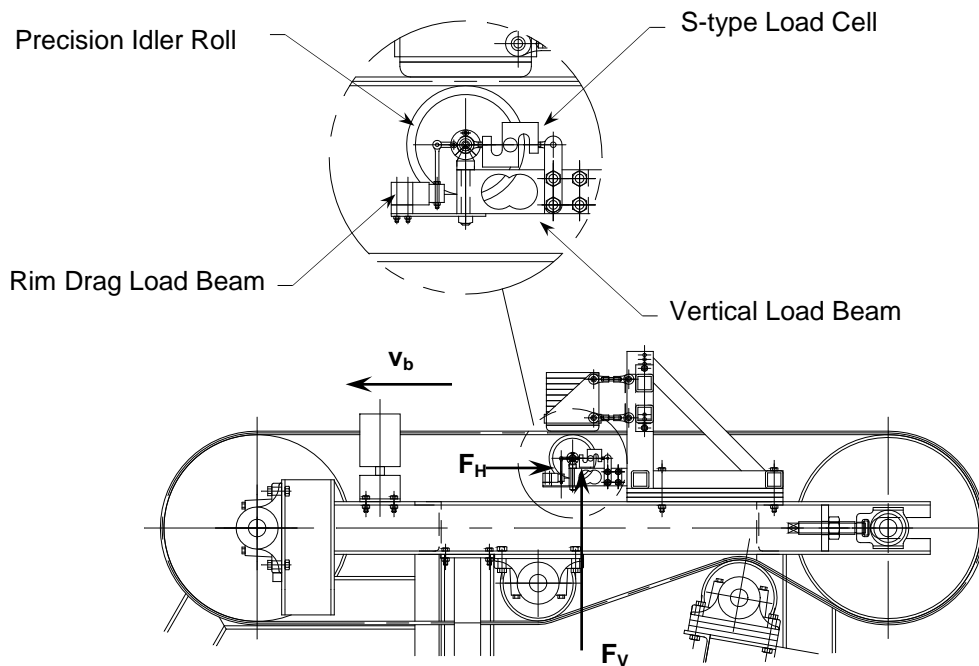


Figure 1. Original indentation rolling resistance test facility with deadweight load application.

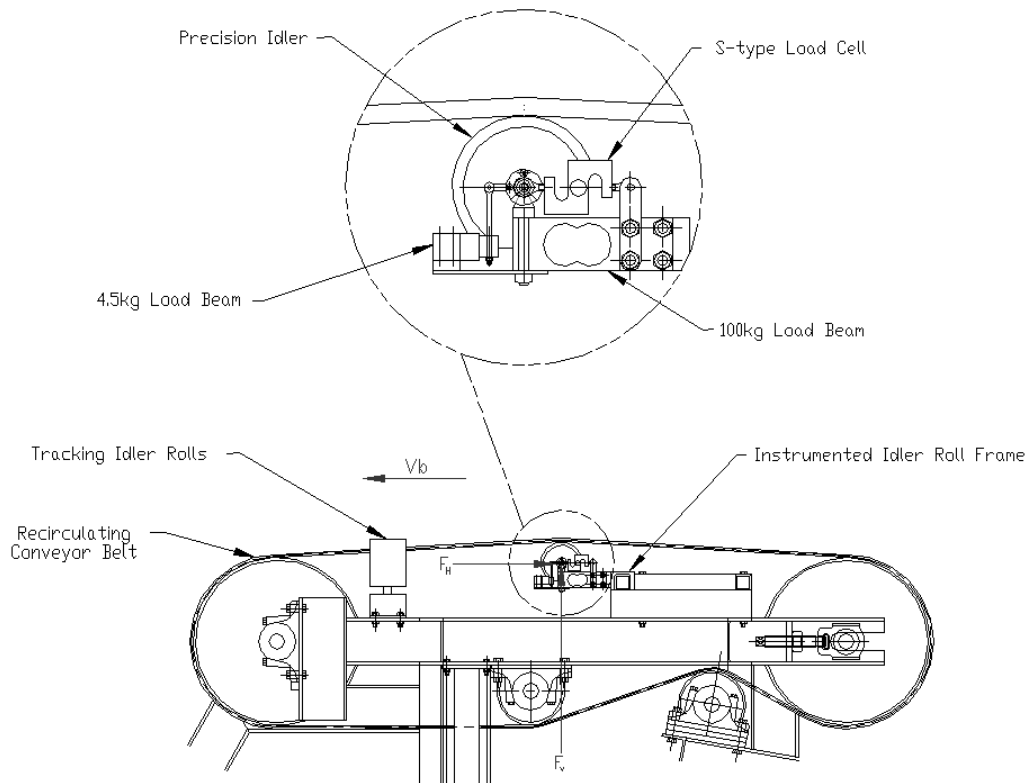


Figure 2. Original indentation rolling resistance test facility using belt deflection loading.

The original test facility relied upon a 'rolling knife-edge' system to support the measurement roll. This system, which is shown in Figure 3, is devised to allow the torque, horizontal and vertical load to be measured independently of each other. Briefly, the 'rolling knife-edge' system allows the vertical load to be transmitted through it, and allows the horizontal load cell to extend with its frictionless rolling action. This enables the measurement roll's shaft to pivot freely on its sharp upper edge (the so called 'knife-edge') and allows the resistance due to the bearings and seals to be measured.

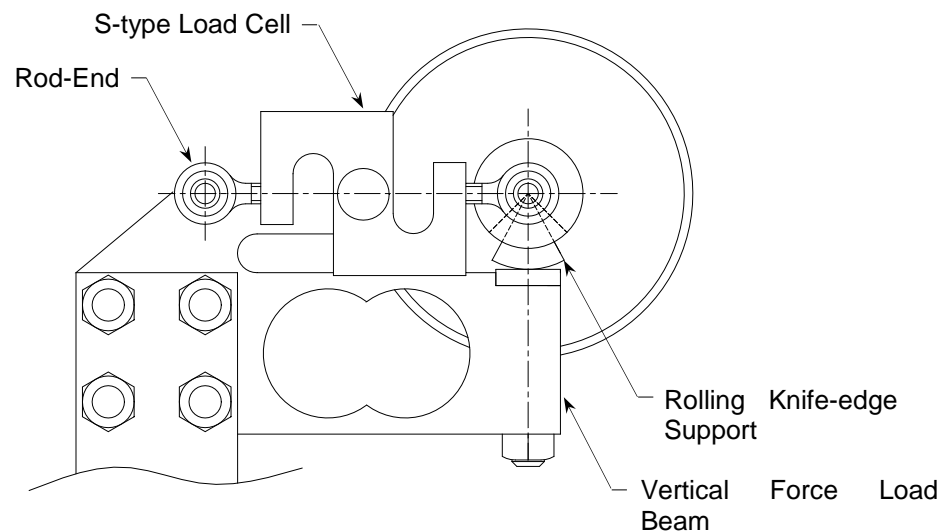


Figure 3. 'Rolling knife-edge' measurement system

The 'rolling knife-edge' system is effective but it is difficult to set up. It required not only that the seats upon which the knife-edges rolled were level, but also that the two seats – one on either end of the measurement roll – were at the same height. This was further complicated

by the need to have the mounting frame level, and also the need to move the entire frame for each different diameter idler roll that was tested by using sets of specially machined mounts.

New Indentation Rolling Resistance Test Facility

In order to overcome the limitations of the original indentation rolling resistance test facility, a new facility was designed and constructed as an integral part of an Australian Research Council (ARC) Linkage Project. A photograph of the new test facility is shown in Figure 4. The new facility is designed to operate at belt speeds up to 10 m/s, apply a range of vertical loads, and accept idler roll diameters from 100 mm to 219 mm. The test facility accepts pre-spliced endless belt samples 29 m in length and up to 600 mm wide and employs 1000 and 1200 mm diameter pulleys that are tensioned by two 10 tonne hydraulic cylinders. The cylinders can be mechanically locked during testing if desired.

While the physical testing capabilities of the facility have been greatly enhanced, the most significant change is the method used to measure the indentation rolling resistance and the load application method.

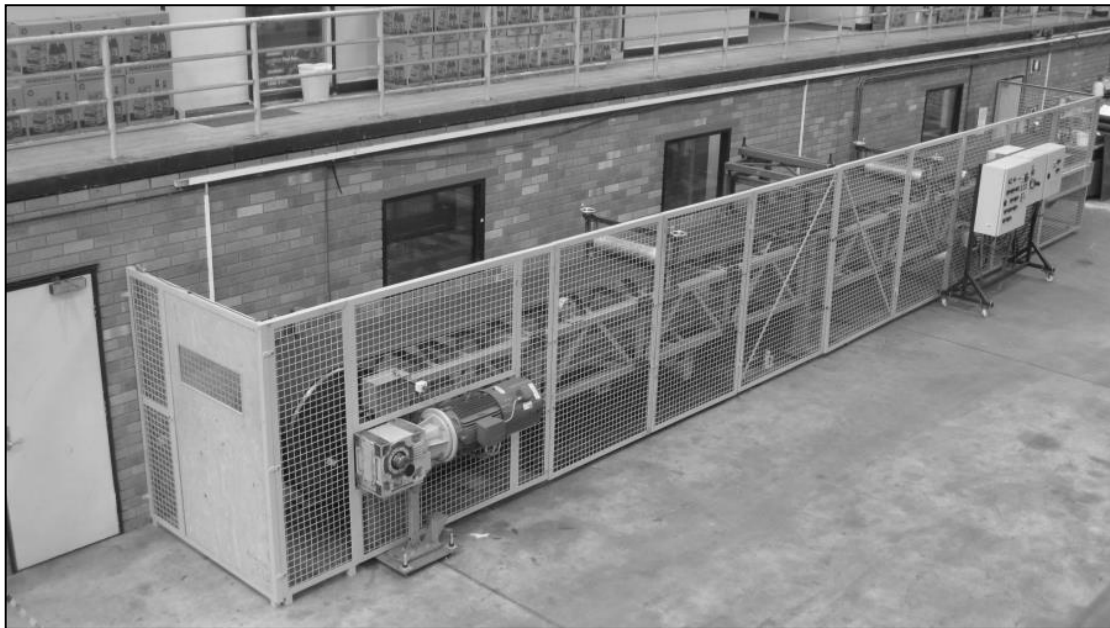


Figure 4. Indentation rolling resistance test facility

New Horizontal Force Measurement System

A new horizontal force measurement system was specifically developed for the test facility. The new system simplifies the assembly and alignment process and avoids many of the problems that are associated with the 'rolling knife-edge' system. The measurement system designed for the new test facility is shown schematically in Figure 5.

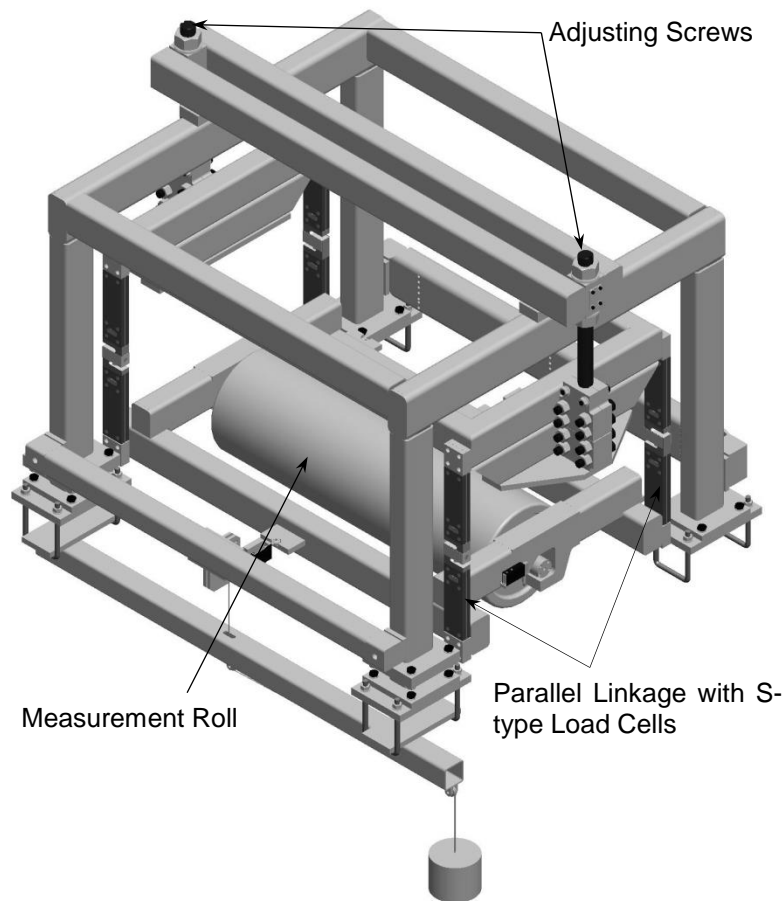


Figure 5. New horizontal force measurement system and support frame

The main feature of the new measurement system is the use of two sets of virtual parallel linkages that connect the idler frame to the rest of the measurement frame. A side view of the virtual parallel linkage is shown in Figure 6. The virtual parallel linkage can be imagined as bars with tie rod ends in the positions of the four circles marked in Figure 6, however, instead of using tie rod ends - which always have some friction that resists their movement - 0.55 mm thick by 50 mm wide steel strips are used. The strips are held rigid for most of their length by thick steel plates, but a 2 mm section on each strip is allowed to bend as required, thereby forming a virtual hinge that is located in each of the circles in Figure 6, where the imaginary tie rod ends would be.

The thin virtual hinges are frictionless due to the fact that an un deformed component has no resistance to bending, even from a very small force. The advantage of the virtual hinges is that there is no friction to be overcome before the horizontal load cell will read a force, which helps to improve the accuracy of results. The obvious disadvantage of using thin steel strips to mimic hinges is that they will develop resistance if they are deformed too much, but this is prevented in this system by the extension of the horizontal load cell, which is approximately 75 μm under full load, and the long length of the parallel links that are nearly 400 mm long which helps to minimise the angle that they flex in operation. Furthermore, since the virtual links behave like normal pinned links in that they can only be in tension or compression and are unable to transmit bending forces, they are therefore in the perfect position to incorporate load cells to measure the vertical load acting on the measurement roll. As such, each of the four links has a load cell incorporated into its length. These load cells are clearly visible in Figures 5 and 6.

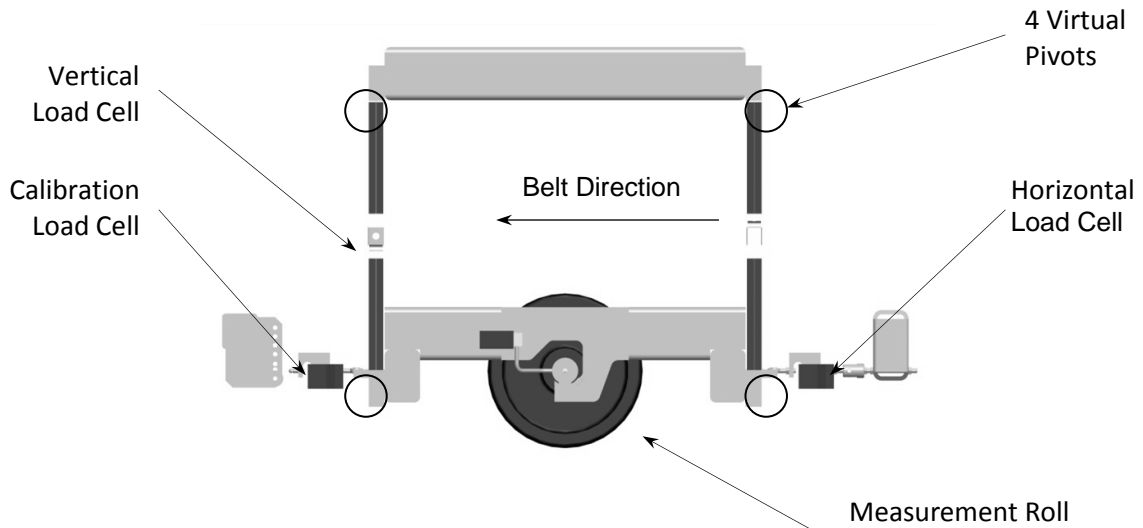


Figure 6. Virtual parallel linkages.

Aside from the minute build-up of resistance in the virtual hinges, there is also a resistance from the weight of the frame and measurement roll which results in a force component. This component acts to reduce the horizontal force that is measured when the parallel links form an angle due to the action of the drag force. The component of the weight force is very small due to the length of the links, and in any case, the system may be tested by simulating the horizontal load with the calibration load cell and checking that both load cells are reading the same force. The calibration load cell is not used for testing under normal operating conditions.

When the horizontal force is measured by the load cell, a component of that force is the belt line force required to rotate the bearings and seals of the measurement roll. This force is commonly known as the rim drag. In order for the rim drag to be subtracted from the overall horizontal force it must be measured, ideally at the same time. This is achieved by measuring the torque transferred to the shaft of the measurement roll by its bearings and seals with the system shown in Figure 7.

In Figure 7, it can be seen that the measurement roll shaft is resting on a fixed knife-edge support (there is in fact a fixed knife-edge at each end of the idler roll) where the sharp edge of the knife-edge is located at the centre of the measurement roll shaft. The shaft is free to rotate a few degrees either way on the knife-edge, and any friction caused by the metal to metal contact manifests itself as a negligible torque resistance due to the very small radius of contact on the sharp knife-edge. The torque is then measured through the torque arm by a load cell and hence the rim drag may be determined.

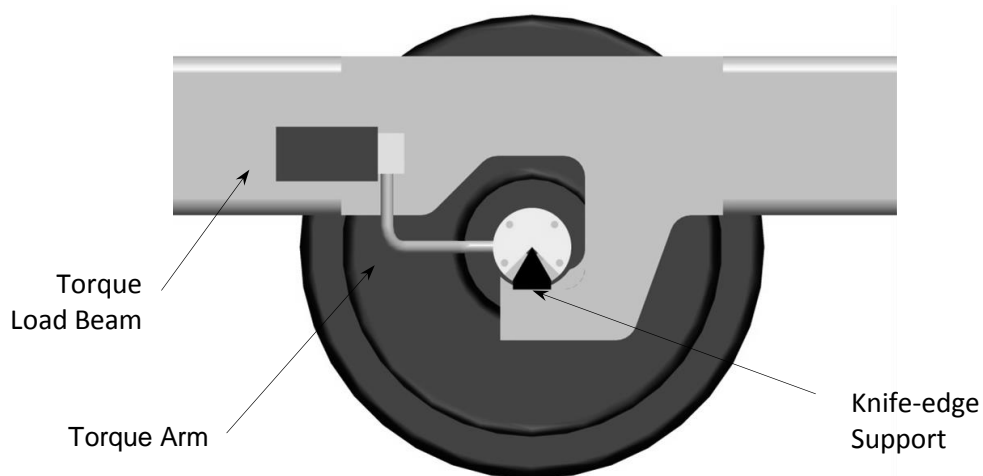


Figure 7. Knife-edge support.

The indentation rolling resistance measurement apparatus is shown positioned midway along the top side of the test facility in Figure 8 (the belt has been removed for clarity), but it may also be placed at the head end of the indentation rolling resistance test facility immediately behind the drive drum. The new measurement apparatus is very quick to set up after it has been disturbed and the incorporation of adjusting screws make changing measurement roll to another diameter a simple process. The new measurement apparatus overcomes all of the deficiencies of the previous 'rolling knife-edge' system.

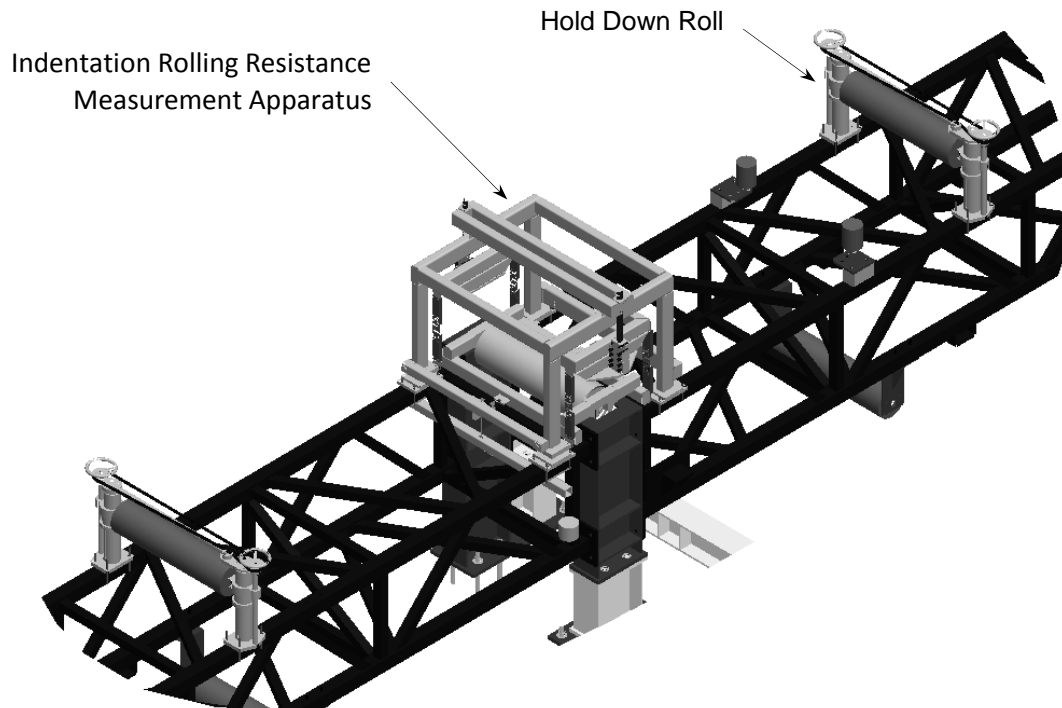


Figure 8. Indentation rolling resistance measurement apparatus and hold down rolls

Vertical Load Application

To conduct an indentation rolling resistance test a load needs to be applied to the measurement roll. The load also needs to be varied to achieve a range of data which means that the constant weight of the belt is not sufficient, and some other load needs to be applied in addition to the self-weight of the belt. The indentation rolling resistance test facility detailed in this paper uses two methods to apply a variable load to the test conveyor idler roll.

One method used to vary the load on the measurement roll is shown in Figure 9. The 'hold down rolls' are used to push the top of the belt down on either side of the measurement roll with both being at equal distances from the centre. When the 'hold down rolls' are used, the weight is applied to the measurement roll via the vertical component of the belt tension due to the angle formed by the belt. The effect of the 'hold down rolls' on the belt is shown in Figure 9. The load on the measurement roll may be varied by either changing the degree of belt deflection or by changing the belt tension by moving the tail end belt drum; usually the hold down rolls remain in a fixed position and the load varied by moving the tail end drum. The advantage of this type of testing is found when testing steel cord reinforced conveyor belt as it allows the load to be applied to the measurement roll directly through the steel cords, simulating the loading mechanics and sag of an actual conveyor belt. It has been found with this type of load application that varying the belt deflection, or equivalent sag ratio, does have an influence on the indentation rolling resistance results. This influence will be described further in the results section.

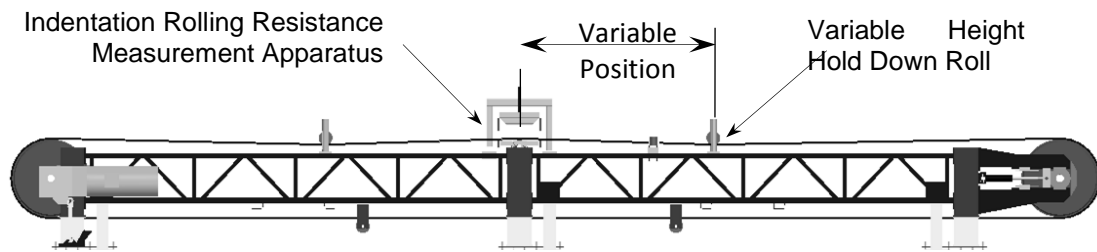


Figure 9. Belt path induced by 'hold down rolls'

Another way in which the vertical load can be applied is via the deadweight load application device illustrated in Figure 10. This system relies on weights to apply the load through the belt to the roll via a second belt driven by the test belt. The belt in this case is a lightweight thin belt supported by a stainless steel backing plate. The primary advantage of this system is that it provides greater loading capability since the system is not limited by belt tension and the influence of belt deflection is not present. This system also avoids the need to apply the load through a sliding plate directly on the test belt like the original system, which not only requires lubrication but can cause heat build-up and localised distortion of the conveyor belt in the test area due to friction. A potential drawback of this system is that the load is not applied through the belt carcass and thus the compression of the belt in the indentation zone is not truly representative of the actual belt loading mechanics, further research is being undertaken to investigate this influence.

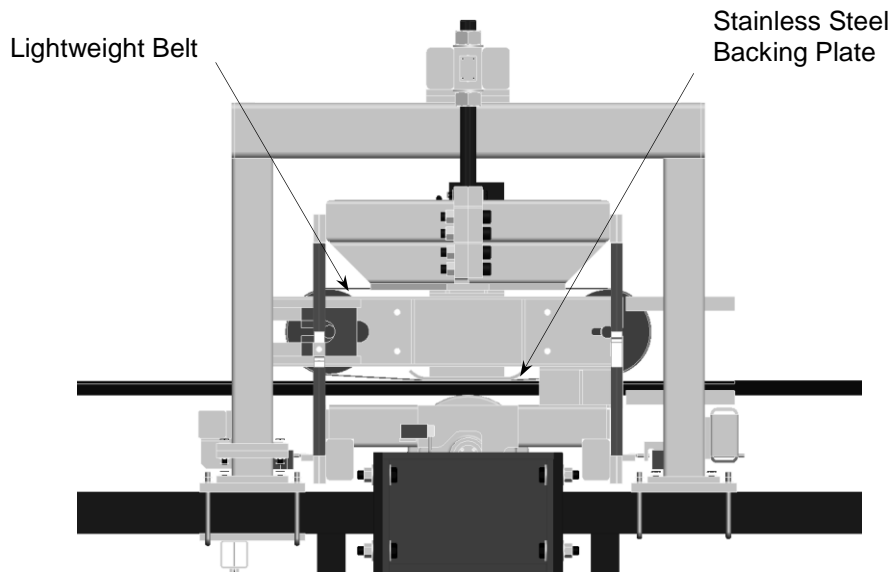


Figure 10. Deadweight vertical load application device.

Test Results

Figures 11 to 16 show results from a belt test for a range of vertical loads, belt speeds and idler roll diameters. The data presented is for a 400 mm wide belt sample with a low rolling resistance bottom cover compound. The bottom cover is 5 mm thick and the data is presented for belt temperatures in the range of $18 \pm 2^\circ\text{C}$.

Figures 11 and 12 show data for a $\text{Ø}125$ mm roll tested over a range of belt speeds and vertical loads. Figure 11 shows the loads applied to the belt. In this case five loading conditions are shown, ranging from 1.4 kN/m to 5.7 kN/m, expressed as a load per unit width of the belt. Figure 12 shows the measured indentation rolling resistance for each loading

condition as a function of belt speed. The data shown excludes the rim drag of the idler roll, which is measured and subtracted for each test.

Figure 13 shows the indentation rolling resistance data for the Ø125 mm roll versus vertical load for a range of belt speeds. The data shows an increase in indentation rolling resistance with increasing vertical load and also a marginal increase with belt speed. To show the influence of idler roll diameter, Figures 14 and 15 show similar indentation rolling resistance data for Ø150 mm and Ø178 mm rolls respectively. As expected, comparison of Figures 13, 14 and 15 show a decrease in measured indentation rolling resistance with increasing idler roll diameter for all comparable loading conditions.

In addition to the data presented for the low rolling resistance bottom cover compound, data is also presented for a DIN-X compound. Figure 16 shows indentation rolling resistance data for a Ø178 mm roll tested at $18\pm 2^{\circ}\text{C}$ over a similar loading range and equivalent belt speeds to those detailed for the low rolling resistance compound.

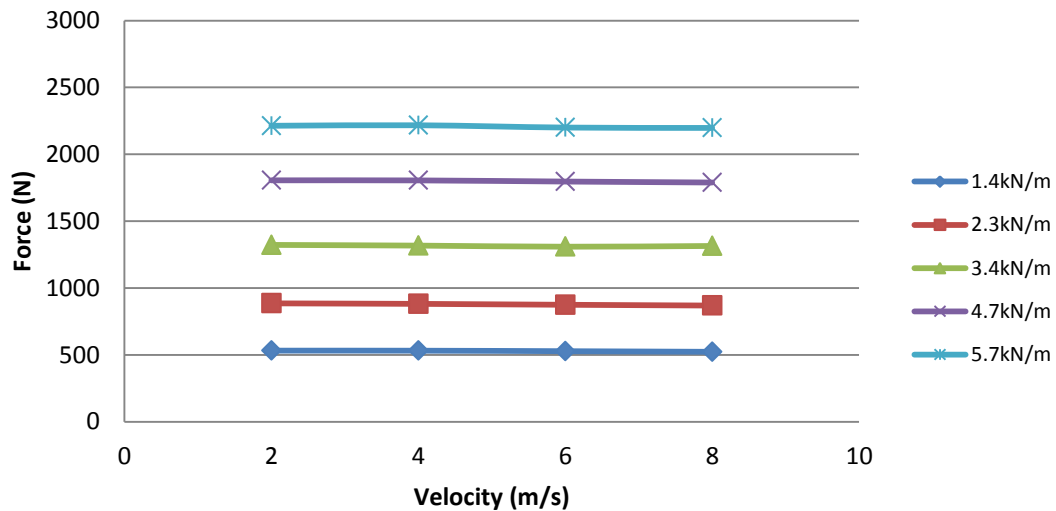


Figure 11. Applied vertical load for a range of belt speeds - Ø125 mm roll.

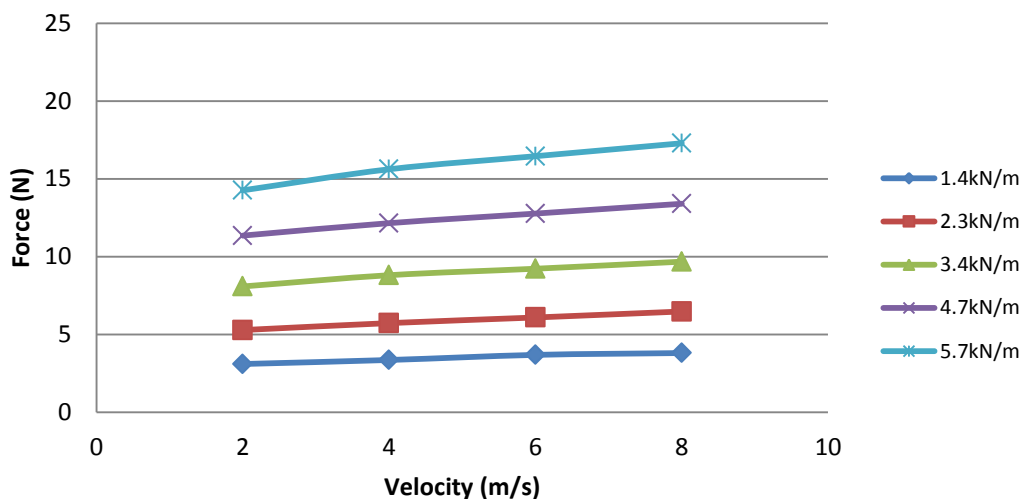


Figure 12. Measured force due to indentation rolling resistance for a range of vertical loads and belt speeds - Ø125 mm roll.

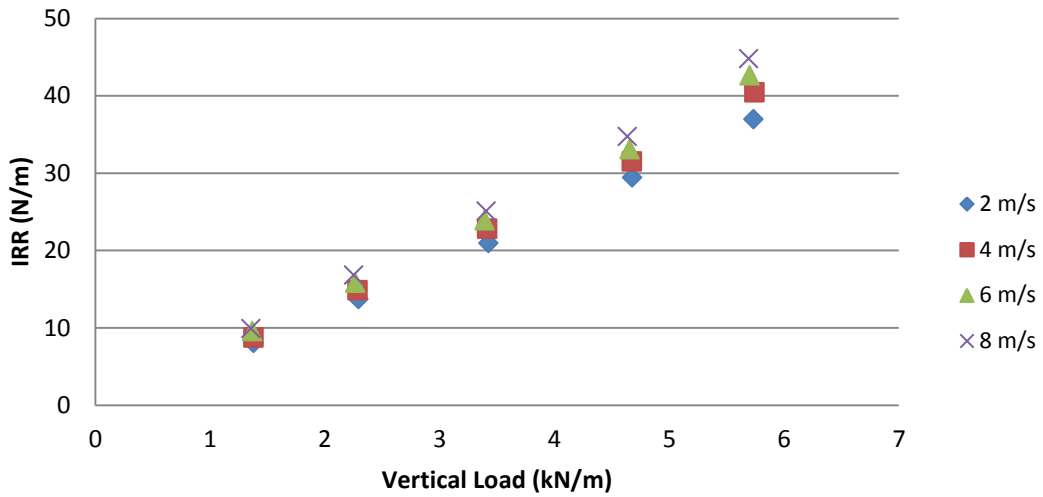


Figure 13. Indentation rolling resistance data for a Ø125 mm roll versus vertical load for a range of belt speeds.

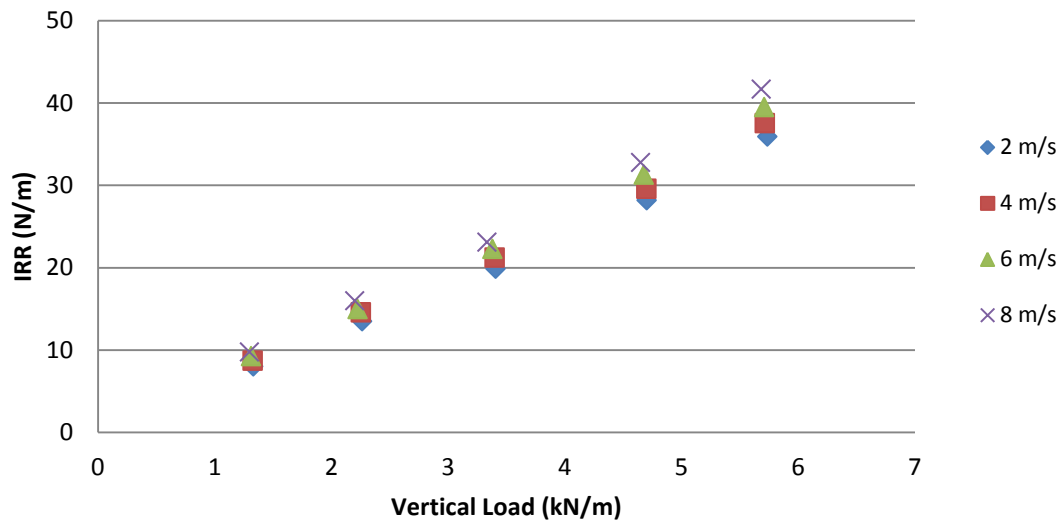


Figure 14 Indentation rolling resistance data for a Ø150 mm roll versus vertical load for a range of belt speeds.

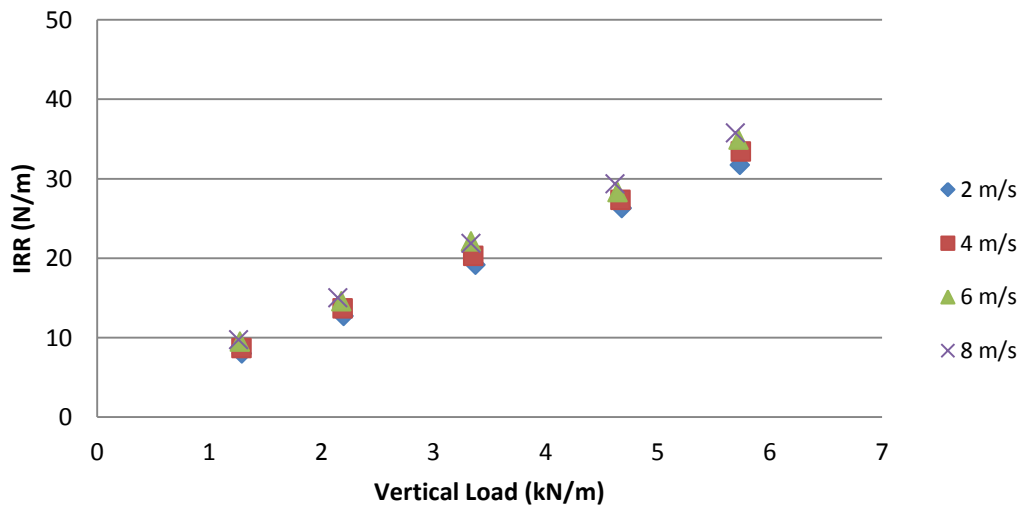


Figure 15. Indentation rolling resistance data for a Ø178 mm roll versus vertical load for a range of belt speeds.

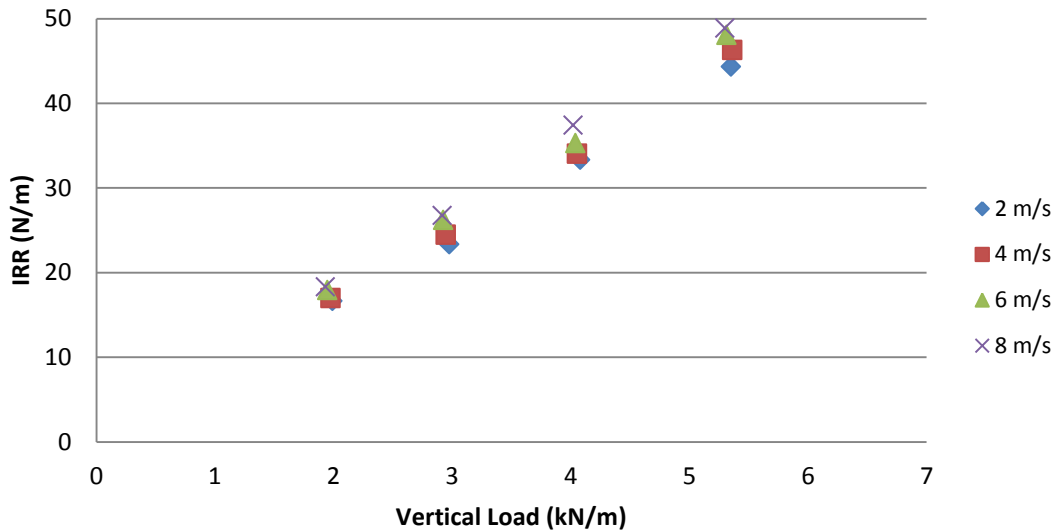


Figure 16. Indentation rolling resistance data for a DIN -X cover compound - Ø178 mm roll versus vertical load for a range of belt speeds.

To investigate the influence of deflecting the belt over the instrumented idler roll a series of tests were undertaken. In these tests, the relative heights of the hold down rolls either side of the instrumented idler roll were varied to provide a different belt deflection angle over the roll, or an equivalent sag value. The resulting vertical load was then increased by increasing the belt tension using the hydraulic cylinders at the tail pulley. Figure 17 shows indentation rolling resistance data versus vertical load for the low rolling resistance compound tested at a belt speed of 4 m/s. The results indicate a small increase with increasing belt deflection. This increase is most likely due to greater belt flexure resistance as the belt is deflected over the measurement roll.

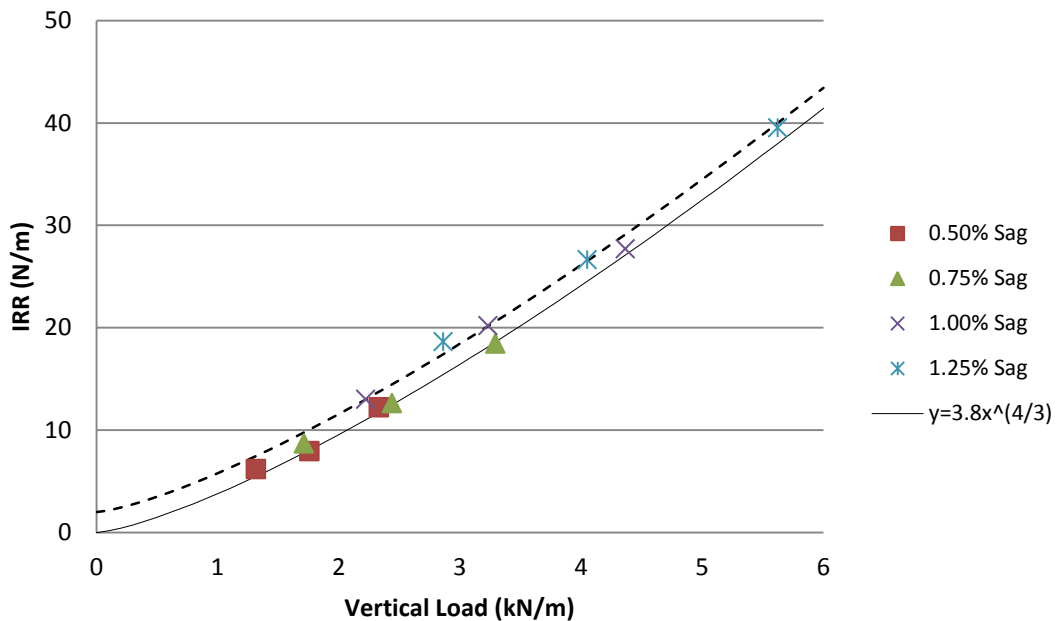


Figure 17. Indentation rolling resistance data versus vertical load for a range of equivalent sag values

4. APPLICATION TO DESIGN

Typical data used by the conveyor designer will take the form of that presented in Figures 13 to 16, i.e.; indentation rolling resistance versus vertical load for a particular belt speed and

idler roll diameter. The total indentation rolling resistance per idler roll set is then simply calculated by summing the contribution per idler roll based on the distributed load along its length.

Clearly, an important consideration in an accurate assessment of the indentation rolling resistance component is the varying load distribution across the idler rolls. Figure 18 (a) shows a schematic of the likely contact pressure for a steel cord belt at the belt and idler roll interface ([10], while (b) shows a simplified approximation of this load. Both Spaans [3] and Jonkers [2] have provided load distributions based on Figure 18 (b), while Tapp [12] proposes the loading assumptions shown in Table 1.

Material and Belt Load Distribution		
Troughing Angle	Centre Roll	Each Side Roll
20°	60%	20%
35°	68%	16%
45°	75%	12.5%

Table 1. Material and belt load distribution

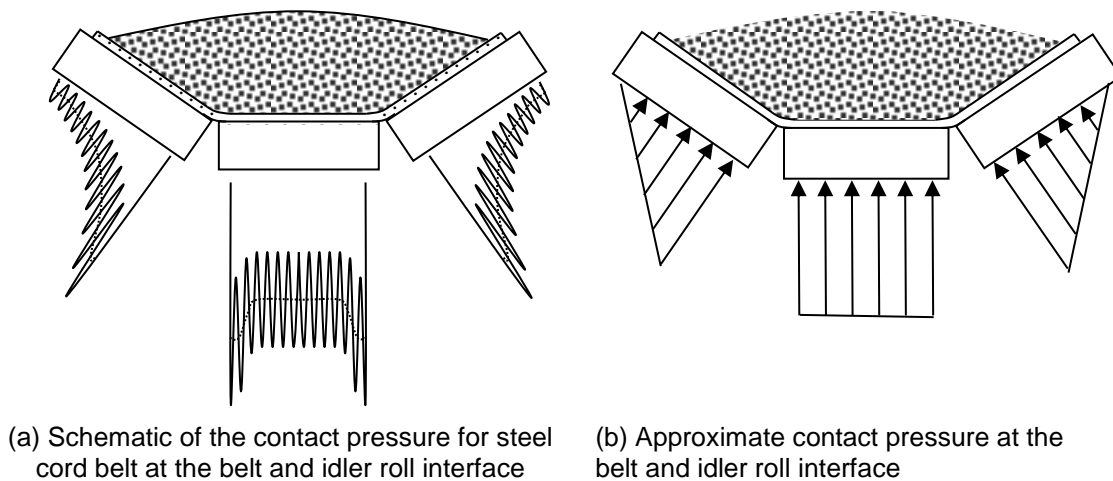


Figure 18. Contact pressure distribution at conveyor belt and roll interface

5. FUTURE WORK - FIELD TEST APPARATUS

Field testing will also be undertaken as an integral part of the research project. A field test apparatus has been designed to measure the main resistance of an in-service belt conveyor. The test facility measures the horizontal force on a suspended idler roll frame, thereby measuring the total main resistance at this point on the conveyor.

Figure 19 shows the test facility that was designed and built. It consists of two main parts: a heavy foundation frame that is rigidly mounted to the ground on four large concrete footings, and an idler roll frame that is mounted to the foundation frame on a set of virtual parallel linkages and four hydraulic cylinders.

Directly mounted to the foundation frame are three idler frames with three sets of conveyor idler rolls installed on them that are identical to the carry and return side frames on the rest of the conveyor. The primary function for these idlers is to prevent the conveyor belt from coming into contact with any part of the measurement facility; however, the two sets of conveyor idler rolls on the carry side perform the additional function of fully supporting the belt when testing is not being conducted.

The function of the hydraulic cylinders is to raise the main measurement frame into position for testing. When the measurement frame is raised it causes the measurement idler rolls - which are weigh quality - to lift the belt and load clear of the adjacent supporting carry side

idler rolls. When it is at its highest position the measurement idler rolls are at the same height as the original conveyor idler rolls, and in line with idler sets either side of the test facility. When the measurement frame is lowered it removes the measuring equipment from the conveyor belt and eliminates the risk of damage to the conveyor belt due to potential failure of a load cell or a virtual linkage.

The virtual parallel linkages used in the field test facility are identical to the system that is used on the laboratory test facility, though their length is roughly half due to space constraints. The virtual hinges are made from the same 0.55 mm thick by 50 mm wide steel strips that are used in the laboratory and have a load cell - which measures the vertical load - mounted along their length. However, unlike the laboratory based indentation rolling resistance test facility which uses only one load cell to restrain the measurement roll from movement in the horizontal direction, the field test facility uses two. The field test facility is shown in Figure 20 as it was installed on the conveyor and in the test position with the test frame in the raised position.

The primary design criterion for this test facility was that it had to be safe to use when it was installed on the conveyor. This significant design aspect is the reason for using a hydraulic raising and lowering system so that testing could be started and stopped without people needing to go near to the conveyor and make adjustments, additionally, the test facility's design allowed all adjustments and calibrations to be conducted during installation and thereby further ensuring safe and reliable operation.

The data obtained from the field test apparatus measures the total main resistance at this point in the system. The rim drag of the idler rolls are measured independently and can be subtracted, leaving the indentation rolling resistance of the belt, in addition to the belt and bulk material flexure resistance.

To date, the field test facility has been successfully commissioned during a series of onsite trials. A comprehensive testing program is planned to complement the laboratory testing.

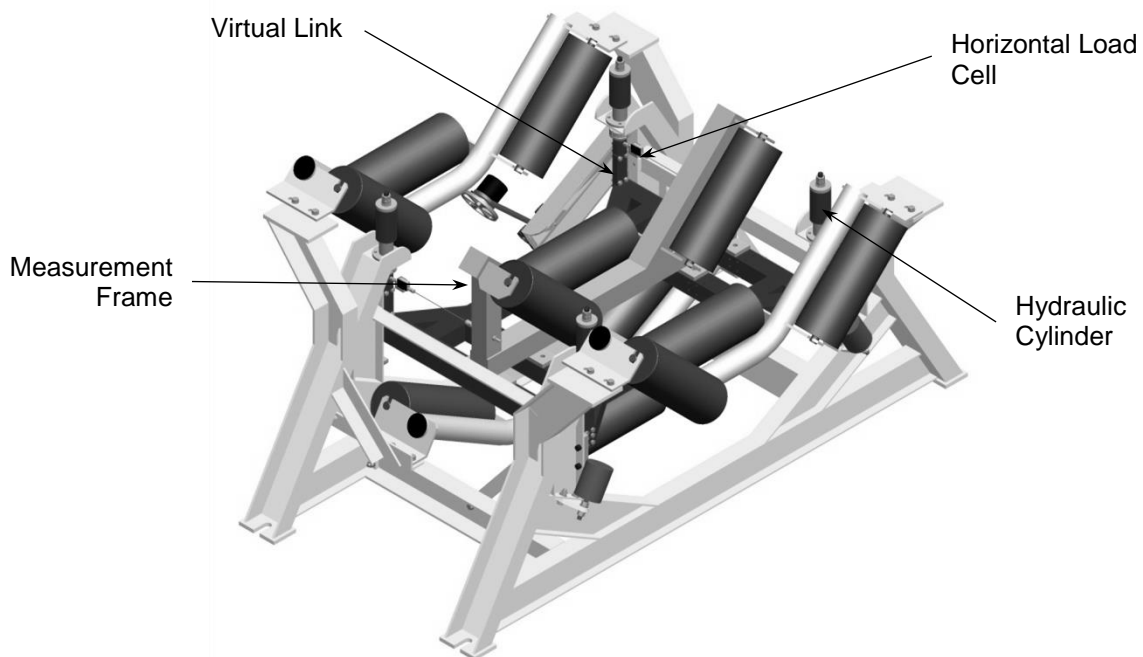


Figure 19. CAD view of field test apparatus



Figure 20. Main resistance measurement apparatus pictured during field tests

6. CONCLUSION

This paper has described the details of a new purpose built laboratory test facility designed to measure the indentation rolling resistance of conveyor belts. The test facility enables a wide range of variables to be tested and will assist in verifying the accuracy of existing and new theoretical models. Results were presented for a number of key parameters, including belt speed, vertical load, idler roll diameter and cover compound. The application of the test results to conveyor design was discussed, as was a field test apparatus that will be used to acquire site data.

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ABOUT THE AUTHORS

CRAIG WHEELER

Craig Wheeler is an Associate Professor in the School of Engineering at the University of Newcastle and Associate Director of TUNRA Bulk Solids. He worked as a Mechanical Engineer for BHP Billiton for eleven years and then as a Research Fellow at the Centre for Bulk Solids and Particulate Technologies for four years prior to his current position in the School of Engineering.

Craig Wheeler

School of Engineering
The University of Newcastle
University Drive
Callaghan NSW 2308 AUSTRALIA
Email: Craig.Wheeler@newcastle.edu.au

PAUL MUNZENBERGER

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 Bachelor's 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.

Paul Munzenberger

TUNRA Bulk Solids Research Associates
The University of Newcastle
University Drive
Callaghan NSW 2308 AUSTRALIA
Email: Paul.Munzenberger@newcastle.edu.au