SOLUTIONS FOR DYNAMIC STRESSES IN A CATENARY PROFILE OVERLAND CONVEYOR

H.N. DREYER MSc (Eng)
Consulting Mechanical and Electrical Engineer, Coal Div, AAC.

CONTENTS

SYNOPSIS

High oscillating tensions during stopping caused severe damage to the take-up structure of the B18 conveyor at Goedehoop Colliery. Shutdown behaviour of a conveyor belt cannot be studied without also referring to the subsequent restarting behaviour.

Every conveyor installation is unique. It is necessary therefore to study the behaviour of each installation separately in order to optimise the adjustments affecting the performance of the system.

The paper describes the field tests performed to measure the stresses at various locations along the length of this long overland conveyor. Test results are discussed in detail.

Ways of reducing the magnitudes of dynamic stresses and preventing their occurrence in the B18 conveyor are suggested to improve the life and availability of the conveyor.

Controlled starting has been successful on this installation, as in others; but during stopping, when all power is lost, the most effective method of arresting dynamic stresses was found to be the controlled release of 'stored' belt tension.

1. OVERVIEW

1.1 Statement of the problem

Recent years have seen the development of longer and higher-capacity belt-conveyor systems. Part of this development was the introduction of high-speed conveyor belts. This had the desired effect of reducing the capital cost of such systems since relatively narrow belts were now able to convey large quantities of material.

Unfortunately, catastrophic failures started occurring as well. New problems associated mainly with long and/or high-speed conveyor belts were discovered. These mostly related to the presence of dynamic stresses in the belting.

During the acceleration and deceleration phases of the belt motion (i.e. during starting and shutdown) stress waves develop. These stresses were never considered in conventional design calculations and therefore were never predicted. Consequently, structural designers never took this into consideration when designing conveyor structures. Conventional design considered the conveyor belt as a rigid body. This approach assumed that the entire length of belt started moving as the drive pulley started moving.

This assumption is obviously not true, but it simplified design calculations and always seemed to be effective for the conventionally short, low-speed conveyor systems.

1.2 Aim of this study

The dynamic stress-wave problem has only raised its head in the last decade. In this period relatively few systems experienced stress-wave problems to the extent that drastic steps were necessary to overcome them. It is understandable therefore that no set behaviour pattern of conveyor stress waves has been established to date. At least two mathematical models[1,2] have been developed to describe conveyor dynamic stress behaviour but none of these has been calibrated to cater for a variety of conditions pertaining to real-problem installations.

The purpose of this study is to determine from an analysis of test measurements taken over a period the magnitude and motion of the dynamic stresses present in the B18 conveyor belting during the starting and shutdown cycles of the system. The study will also research the origin of these stresses and analyse the factors which influence the dynamic stresses.

2. SOURCE OF DYNAMIC STRESS WAVES

The initial objective of this project was to investigate and analyse the dynamic stress waves in the belt during its stopping sequence. The investigation showed, however, that stopping cannot be considered in isolation.

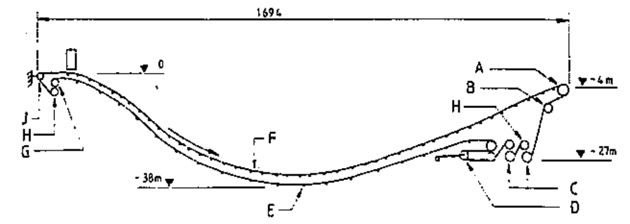
The achievement of the smooth stopping of a conveyor system is only acceptable if the subsequent starting behaviour is within acceptable limits.

It is necessary, therefore, to also refer to start-up behaviour during the discussion of findings.

The main cause of stress waves in the belting is a sudden change in belt velocity.

2.1 System inertia

Figure 2.1 illustrates the elements of the system inertia.



A: Head pulley
B: Bend pulley
C: Drive pulley
D: Take-up pulley
E: Belt-carrying idlers
F: Conveyor belting
G: Brake pulley
H: Snub pulleys
J: Tail pulley

FIGURE 2.1: CONVEYOR MASS DISTRIBUTION

The belting is a long elastic band with evenly-distributed mass, as shown in Figure 2.1. Connected to the belt are a number of masses which influence its behaviour.

The idlers act as small rotating masses equidistantly spaced along the length of the belt — the top strand of the belt is supported by twice as many idlers as the return belt.

Snub, bend, head, tail and take-up pulleys are found at either end of the belt though most are at the drive end of the system. These are larger rotating masses concentrated in areas. Like the belt-carrying idlers above, they are also driven by the belt.

Drive pulleys in the case of the B18 conveyor are placed in the return strand of the belt near the head of the system. The two drive pulleys are connected through solid couplings to bevel gear reducers, the input shafts of which are connected through fluid couplings to 110 kW motors. These rotating masses are the biggest in the system. They are different to all other masses in that they drive the belt to provide motion.

The brake pulley on B18 conveyor is installed in the return strand of the belt near the tail pulley. It has a brake drum attached to each shaft end which adds to its inertia. Braking is achieved when power is removed from the solenoids which keep the spring-loaded brake shoes clear of the brake drums. The brake pulley is driven by the belt.

Each of the above has its own inertia with unique characteristics. The combination of these forms the system.

Every belt installation, therefore, will display its own behaviour pattern.

From the above system inertia description it is clear that all of the masses attached to the belt will affect its behaviour. Because of the elasticity of the belt, high concentrations of inertia have the biggest impact.

It will be shown that belt-carrying idlers have a damping effect on the stress-wave velocity but because of their even distribution and relatively small size play no role in the initiation of the stress wave.

Snub, bend, head, tail and take-up pulleys also have a relatively small inertia compared with that of the system and do not have a significant influence upon the generation of stress waves.

Figure 2.2 shows the drive system, the main cause of stress-wave generation in the system. It has a large concentrated inertia. While driving the belt it exerts high tension, T_1, on the loaded side of the belt, while the return side is being kept tight by the take-up winch exerting a pre-determined tension, T_2.

Under steady running conditions the tension differential across the drive pulleys is a constant 34 kN.

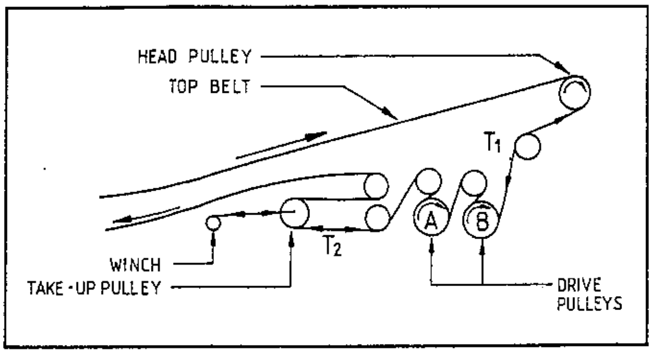


FIGURE 2.2: TYPICAL DOUBLE-DRIVE CONVEYOR UNDER STEADY RUNNING CONDITIONS

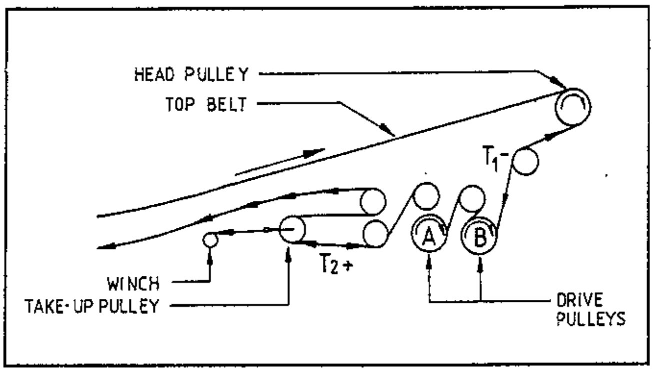


FIGURE 2.3: EFFECT IMMEDIATELY AFTER POWER CUT TO DRIVE PULLEYS

At the instant when the driving power is removed the belt becomes the driving force with the drive pulleys forming a lumped high-inertia-driven load. The immediate effect is a sudden stress reversal in the belt across the drive pulley with the high-tension stress switched to the take-up side of the drive. This initiates a stress wave which propagates along the return belt to the tail pulley as shown in Figure 2.3.

From Figures 2.2 and 2.3 it is seen that the tension in the take-up belt increases immediately after the power cut to the drive pulleys owing to the belt now becoming the driving force and 2,3 seconds later the same effect is detected at the tail pulley, as shown in Figure 2.4.

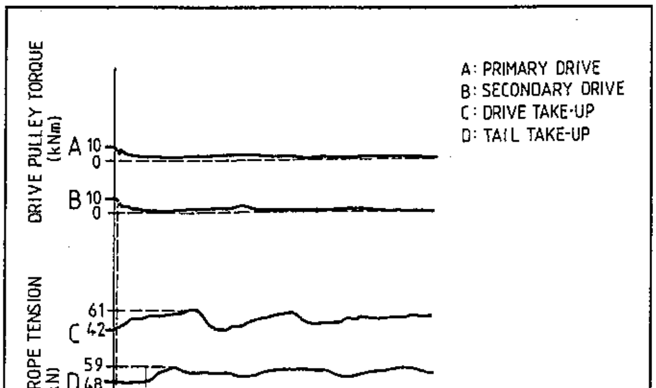


FIGURE 2.4: EFFECT OF CHANGING THE DRIVE PULLEYS INTO A HIGH-INERTIA-DRIVEN LOAD

The sudden addition of the high-inertia drive-train to the work done by the elastic belt is therefore one of the big contributing factors to the generation of the dynamic tensile stress wave in the return belt of the conveyor system. The authors believe that the addition of a high-inertia flywheel to each of the drive gearbox high-speed shafts will largely eliminate the abrupt change from driving force to driven inertia and thereby prevent the generation of the stress wave as described above.

Others have suggested a controlled stopping action by gradually reducing driving torque through the addition of rotor resistance into the driving motors. This proposal is only effective as long as power is available at the drive motors. When a power trip is experienced the above controls are lost and driving torque is again removed instantaneously.

2.2 Local belt velocity variation

Because of the elastic properties of the belting used on belt conveyors, it is to be expected that velocity variations will be present along the length of the belt even during steady running conditions.

During steady running conditions the belting comes into contact with items of different inertia and also passes through the drive section, changing tensions as discussed in section 2.1.

Load variations on the top belt and between top and return belts also cause tension variations.

These tension variations result in local belt-velocity variations as shown in Figure 2.5.

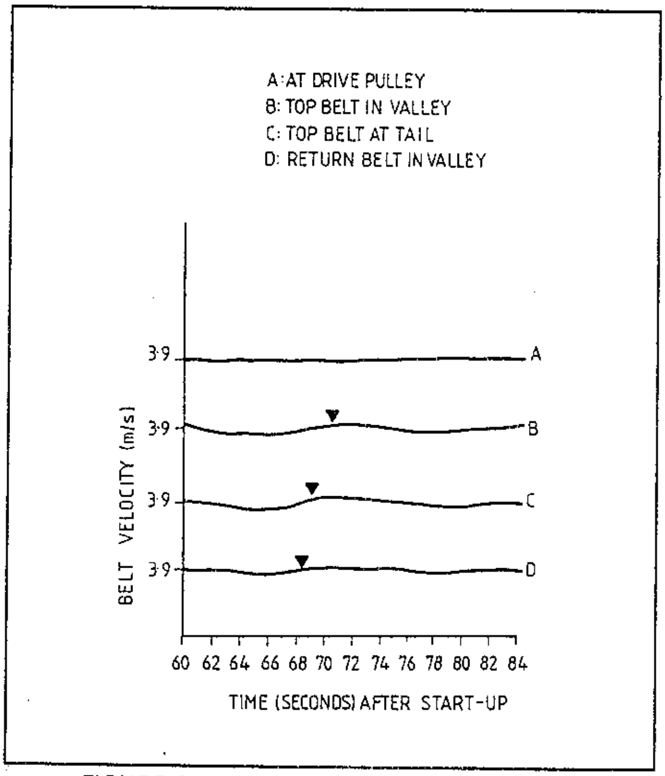


FIGURE 2.5: BELT-VELOCITY VARIATION UNDER STEADY RUNNING CONDITIONS OF B18 CONVEYOR LOADED TO 850 TONS PER HOUR

Figure 2.5 illustrates not only the local velocity variations during steady running conditions but also the propagation of the high-velocity wave in an opposite direction to that of the belt travel.

During the stopping cycle the same phenomena are present but much more pronounced as shown in Figure 2.6.

Figure 2.7 illustrates what happens during an acceleration cycle at 850 tons per hour; Figure 2.8 shows an empty condition.

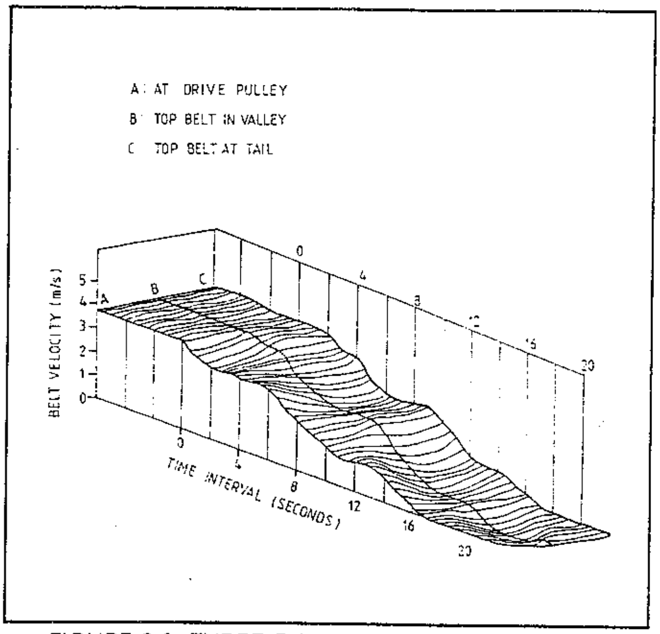


FIGURE 2.6: THREE-DIMENSIONAL PLOT OF BELT VELOCITY AT THREE POINTS ALONG B18 CONVEYOR DURING AN 850 TONS PER HOUR STOP WITH NO BRAKING TORQUE APPLIED

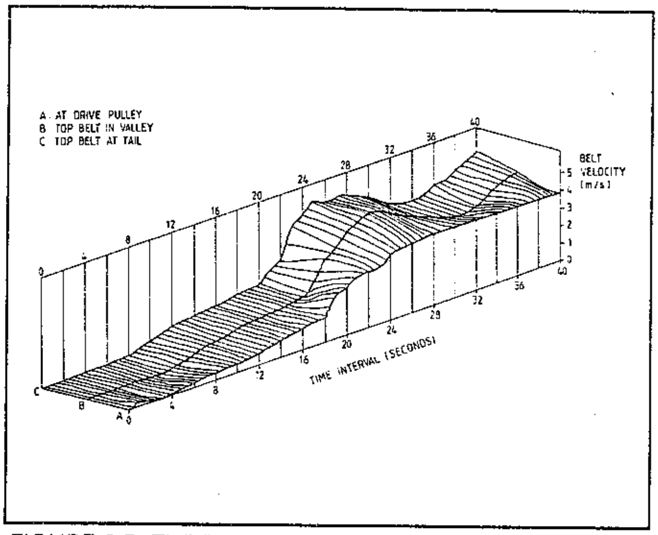


FIGURE 2.7: THREE-DIMENSIONAL PLOT OF VELOCITIES AT THREE POINTS ALONG B18 CONVEYOR DURING AN 850 TONS PER HOUR START-UP

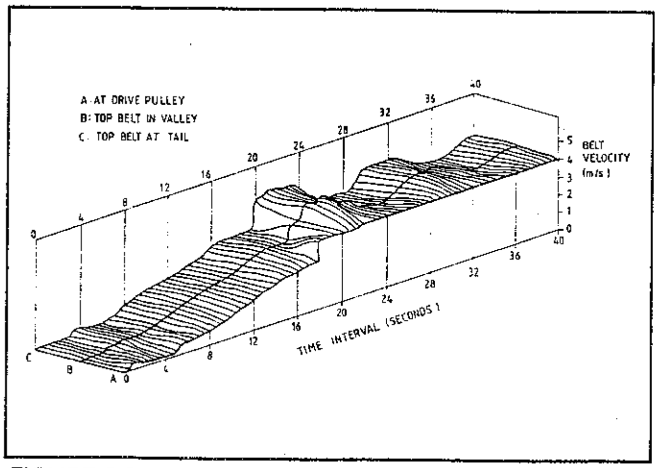


FIGURE 2.8: THREE-DIMENSIONAL PLOT OF VELOCITIES AT THREE POINTS ALONG B18 CONVEYOR DURING AN EMPTY START-UP

Figure 2.9 illustrates the propagation of a velocity wave along the belt and the transformation of the velocity change at point C, at the tail end, into tension. This tension, when measured at the take-up pulley, point A, is identical in shape, but displaced in time, to the velocity graph.

The equivalent comparison during a starting cycle when the belt carried 850 tons per hour is shown in Figure 2.10.

Figure 2.11 shows the relationship between velocities and tensions at the drive and tail sections of the belt during a stopping cycle under loaded conditions.

From the above it is clear that a sudden belt-velocity change at one point converts into a dynamic stress wave transmitted throughout the entire belt length at high speed in the opposite direction to the belt travel.

Prevention of the stresses caused by velocity is similar to that described in section 2.1 namely the utilisation of 'soft'-start and controlled-stop systems.

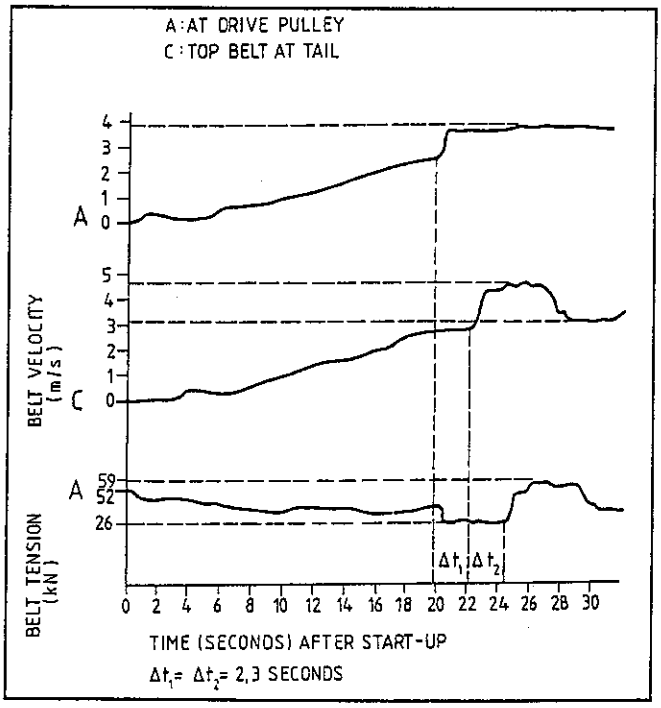


FIGURE 2.9: COMPARISON OF BELT ACCELERATION AT THE DRIVE, WITH BELT VELOCITY AT THE TAIL AND TENSION AT THE TAKE-UP PULLEY DURING AN EMPTY START

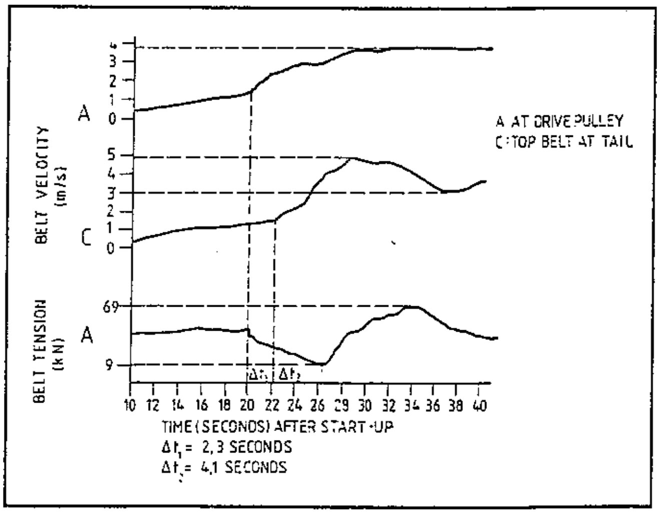


FIGURE 2.10: COMPARISON OF BELT ACCELERATION AT THE DRIVE, WITH BELT VELOCITY AT THE TAIL AND TENSION AT THE TAKE-UP PULLEY DURING AN 850 TONS PER HOUR START-UP CYCLE

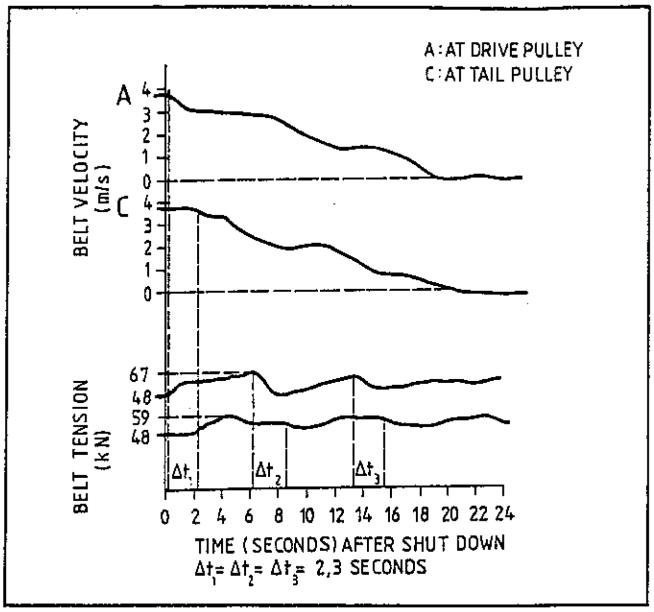


FIGURE 2.11: RELATIONSHIP BETWEEN BELT VELOCITIES AND TENSIONS DURING A SHUT-DOWN CYCLE WITH BELT LOAD AT 850 TONS PER HOUR

3. SHUTDOWN BEHAVIOUR OF B18 CONVEYOR

Having studied the origin of the dynamic stress waves in the B18 conveyor, it was necessary to determine the interrelationship of the variable parameters of the system. Several options were identified to alter the behaviour of the dynamic stresses in the belting.

The shutdown cycle of the system is initiated by the removal of the conveyor driving power. In the case of the B18 conveyor at Goedehoop Colliery this occurs suddenly by cutting the electric supply to both driving motors.

Harrison[3] showed that dynamic stress is proportional to instantaneous belt velocity. He recommended the use of wound-rotor resistance control to apply and remove driving torque in acceptably small increments. While the authors recognise the effectiveness of this solution to prevent the initiation of stress waves, it is necessary to point out that it assumes the availability of electric power at all times during a shutdown cycle. Conditions exist in practice where electric power to the driving motors is totally lost, for example during a total power outage to the complex or during an electric-fault condition in the conveyor-driving or -control systems.

Safe operation of conveyor systems also requires that emergency shutdown brings the belt to a stop in the shortest possible time.

The design of a conveyor system must therefore cater for the sudden removal of electric driving power to the driving motors of the system.

Shutdown variation studied on the B18 conveyor included alterations to braking torque, belt-loading, and take-up tension.

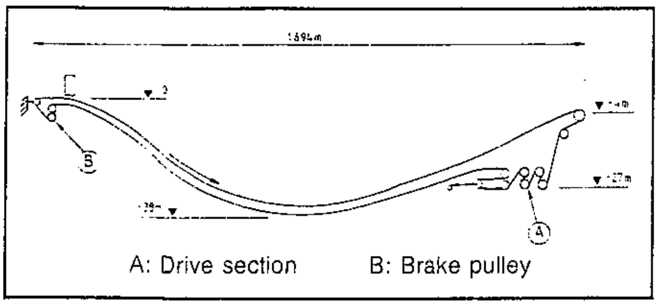


FIGURE 3.1: CROSS-SECTION OF B18 CONVEYOR

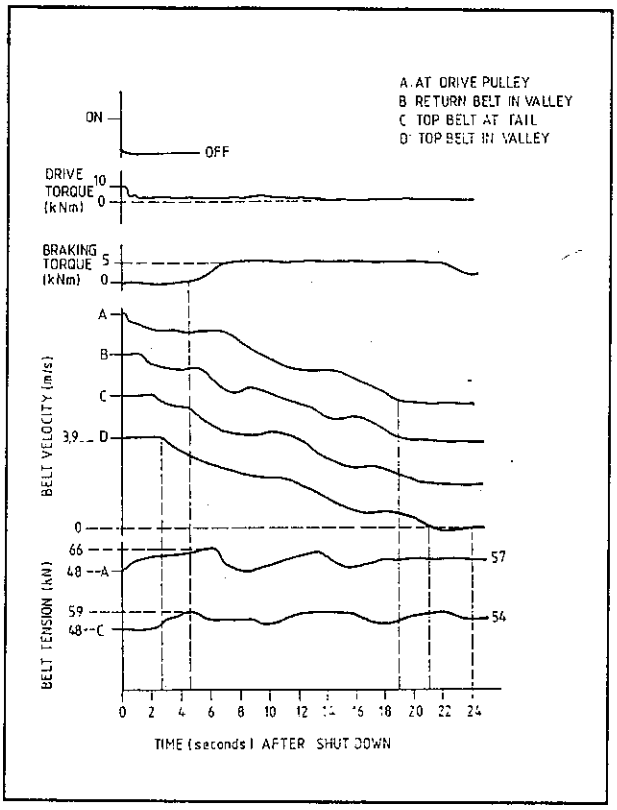


FIGURE 3.2: BEHAVIOUR OF BELT VELOCITY AND TENSION DURING AN 850 TONS PER HOUR SHUTDOWN WITH MINIMUM BRAKING TORQUE APPLIED AT THE TAIL END OF B18 CONVEYOR

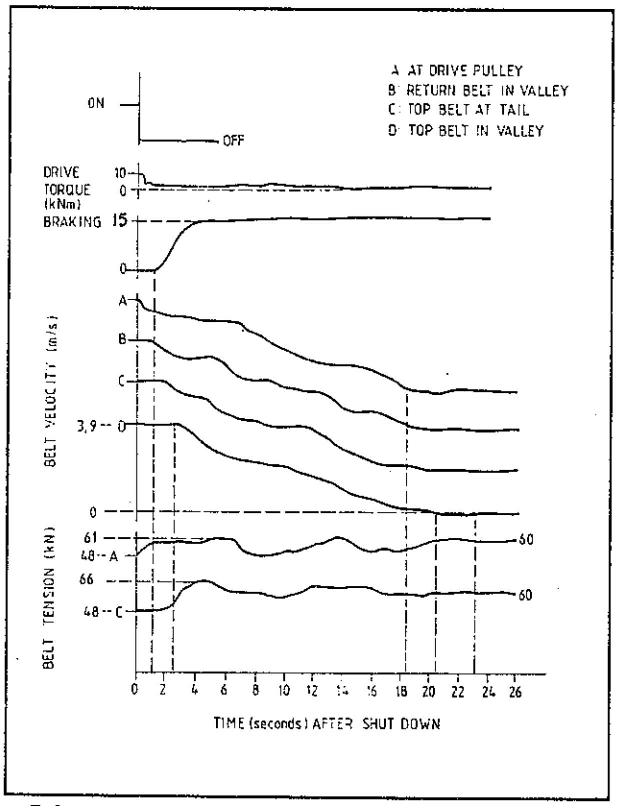


FIGURE 3.3: EFFECT OF HIGH BRAKING TORQUE APPLIED AT THE TAIL END OF B18 CONVEYOR ON BELT VELOCITY AND BELT TENSION DURING AN 850 TONS PER HOUR SHUTDOWN

3.1 Effect of varying braking torque

The B18 conveyor at Goedehoop Colliery was equipped with a brake pulley in the return belt immediately before the conveyor tail end, as shown in Figure 3.1.

The drum brakes attached to the brake-pulley shaft were electric-solenoid-released and spring-applied failing to safety, i.e. brakes on with loss of electric power. Variation of braking torque was obtained by adjusting the brake-shoe travel.

Figure 3.2 illustrates the belt behaviour as measured in terms of velocity and tension at several points along the belt during an 850 tons per hour shutdown with minimum braking torque applied.

Figure 3.3 compares the same measurements during an 850 tons per hour shutdown when maximum braking torque is applied.

In both cases the driving torque of one motor only is shown since both motors behave the same, namely a reduction of 60% of full load torque in 0,25 seconds and 80% of full-load torque in 0,8 seconds, after which the inertia of the drive continues to maintain 20% torque for another 13 seconds.

Figure 3.2 shows the application of brakes at 4,5 seconds after shutdown when braking torque builds up to 5 kNm in 2 seconds, while in the case of Figure 3.3 brakes are applied at 1,1 seconds and braking torque reaches 15 kNm in another 2,5 seconds.

Table 3.1 shows the comparative belt-deceleration rates for the two conditions at various points along the belt, as indicated on Figure 3.4 and referred to in Figures 3.2 and 3.3.

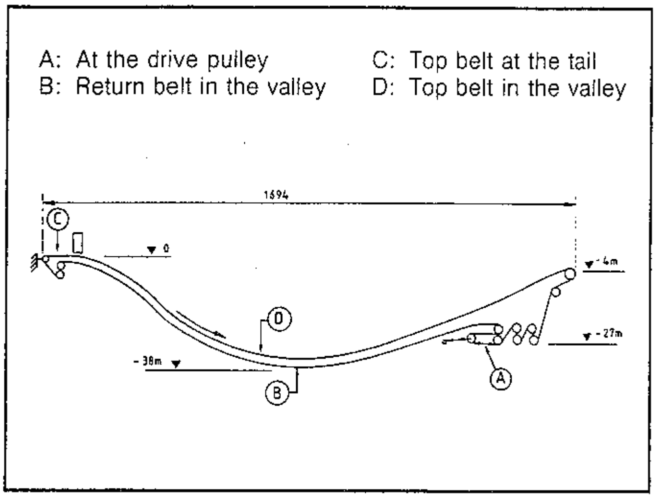


FIGURE 3.4: TACHOMETER LOCATIONS ALONG B18 CONVEYOR

Referring to Figures 3.2, 3.3 and Table 3.1, the following observations were made:

(i) Local velocity variations were less intense with maximum braking torque applied.

(ii) The higher braking torque helped to eliminate the velocity surges of the loaded belt in the valley, with consequent spillage reduction.

(iii) Peak belt tension at the drive was lower at 61 kN compared with 66 kN, with higher braking torque at the tail end of the belt.

Location	Minimum braking Av. deceleration rate (m/s²)	Maximum braking Av. deceleration rate (m/s²)
A	0,205	0,212
B	0,209	0,219
C	0,209	0,215
D	0,212	0,218

TABLE 3.1: COMPARISON OF DECELERATION RATE OF THE GOEDEHOOP B18 CONVEYOR DURING AN 850 TONS PER HOUR SHUTDOWN WITH VARIATION OF BRAKING TORQUE

(iv) Belt-tension fluctuation at the drive was less with the higher braking torque.
(v) The drive take-up tension was higher after the belt came to rest (60 kN compared with 57 kN) with the higher braking torque. This is advantageous for the following start-up cycle to reduce dynamic stresses during the start-up cycle.
(vi) Peak belt tension at the tail was higher at 66 kN compared with 59 kN, with increased braking torque. This largely offsets the advantage gained by reduced belt tension at the drive pulleys.
(vii) Time taken for the dynamic stress wave to travel the 1 678 metres between points A and C along the return belt was 2 seconds, which gave a stress-wave velocity, V_R, of 839 metres per second along the return belt.
(viii) Time taken for the dynamic stress wave to travel the 1 810 metres along the loaded top belt from C via D to A was 4,7 seconds, which gave a stress-wave velocity, V_L, of 385 metres per second along the loaded top belt. This lower stress-wave velocity is due to the damping effect of the load on the belt and the additional carrying idlers in contact with the top belt referred to in section 2.1.

3.2 Effect of varying belt-loading

It was shown in the previous section that belt-loading had a significant damping effect on the dynamic stress-wave velocity. Figures 3.5 and 3.6 compare the shutdown behaviour of the B18 conveyor under empty and carrying 850 tons per hour conditions respectively.

Observations

(i) Belt tensions did not fluctuate much during the empty shutdown when compared with that of the loaded belt.
(ii) Maximum belt tension measured at the take-up pulley during an empty shutdown was 57 kN, while at the tail pulley only 54 kN was measured.
(iii) A fairly constant rate of deceleration was measured during the empty shutdown, with the exception of point C at the tail end of the belt where a slight fluctuation was detected.
(iv) The dynamic stress wave velocity along the return belt, V_R, from A via B to C was the same under both sets of conditions, namely 839 metres per second as before. The load on the top belt had no effect on the dynamic stress-wave velocity in the return belt.
(v) The dynamic stress-wave velocity in the empty top belt, V_E, shown in Figure 3.5 was however significantly higher at 696 metres per second than was the case for the loaded top belt shown in Figure 3.6. As before, the dynamic stress-wave velocity in the belt loaded at 850 tons per hour, V_L, was 385 metres per second. The explanation for the differences between V_R, V_E and V_L is:
   (a) The damping effect of belt-carrying idlers. The top belt is carried by 1 453 idlers and the return belt by 363. While both top and return belts therefore were empty, the damping effect of the idlers resulted in a reduction of dynamic stress-wave velocity from V_R = 839 metres per second to V_E = 696 metres per second.
   (b) The damping effect of the 850 tons per hour load carried by the belt which caused a further reduction from V_E = 696 metres per second to V_L = 385 metres per second.
(vi) The momentum of the loaded belt maintained the full belt speed at point D in the valley for 2,6 seconds after shutdown commenced, while in the case of the empty belt the deceleration at point D commenced 1,5 seconds after starting the shutdown. In the case of the empty belt, the downhill section of the top belt exerted no pull on the belt at point C, as was the case with the loaded belt when deceleration at C began earlier than at D. This explains why the initial deceleration rate at point C was so high for the empty shutdown and hence

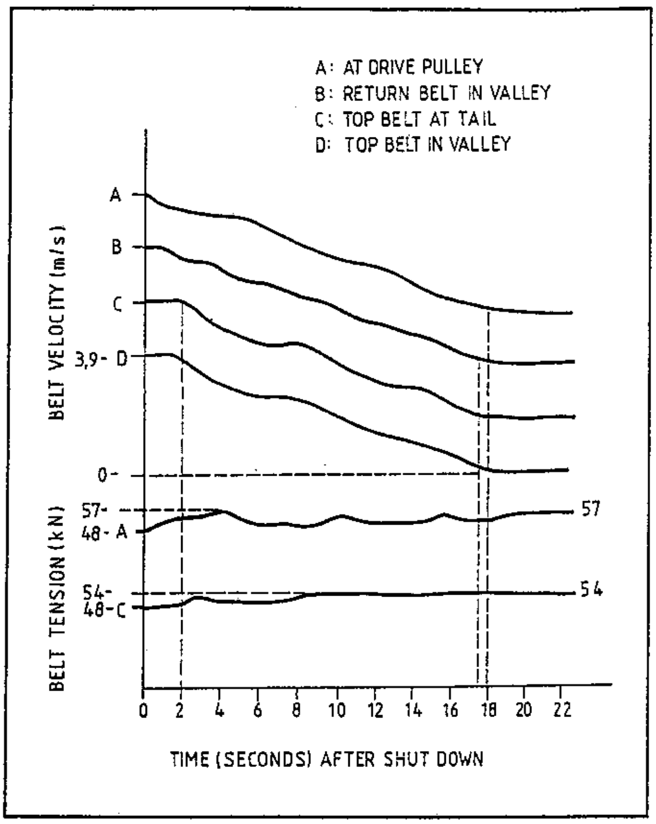


FIGURE 3.5: BELT VELOCITY AND TENSION BEHAVIOUR OF B18 CONVEYOR DURING AN EMPTY SHUTDOWN WITH NO BRAKING TORQUE APPLIED

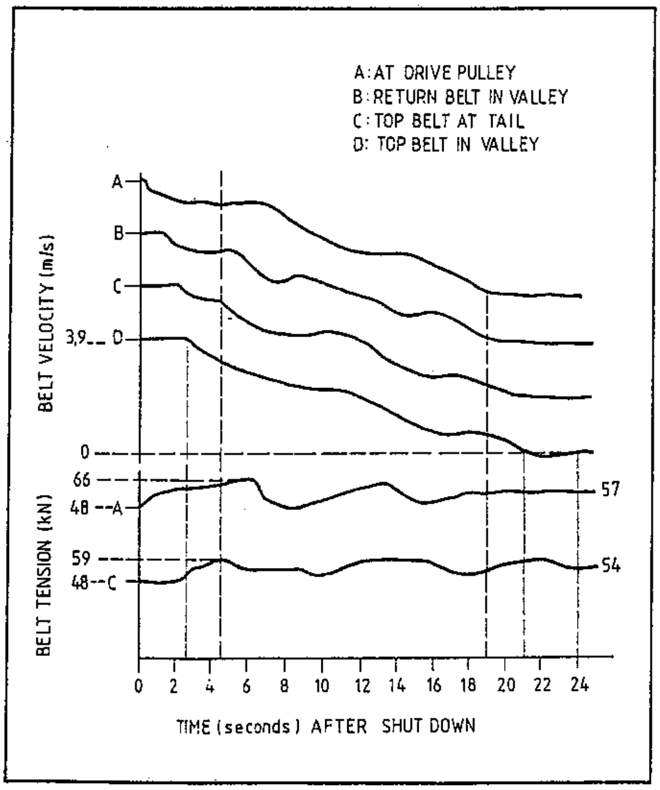


FIGURE 3.6: BEHAVIOUR OF BELT VELOCITY AND TENSION OF B18 CONVEYOR DURING AN 850 TONS PER HOUR SHUTDOWN WITH NO BRAKING TORQUE APPLIED

the significant fluctuations in the velocity curve at point C during the empty shutdown. The pull exerted by the loaded downhill belt was the cause of the momentary acceleration of the belt at point C before the continuation of deceleration at point C at time = 4,7 seconds after shutdown commenced. This effect was totally absent during the empty shutdown.

(viii) Referring to Figure 3.6, a clearly defined secondary dynamic-belt stress wave initiated at point D 2,6 seconds after shutdown when deceleration commenced at this point. This dynamic stress wave travelled in the opposite direction to the initial stress wave, which travelled in the same direction as the belt. In other words, the initial wave commenced at time = 0 and travelled at 839 metres per second from A through B to C and continued at 385 metres per second average from C through D to A. The secondary wave initiated at point D and travelled at 385 metres per second from D back to C and continued at 839 metres per second from C through B to A. Figure 3.7 is a carpet plot of belt velocities illustrating the primary and secondary dynamic stress wave fronts generated in the belting during an 850 tons per hour shutdown cycle. Further stress waves are also seen on the plot; however these are contaminated owing to interaction between the initial waves and reflections from the major pulleys in the system.

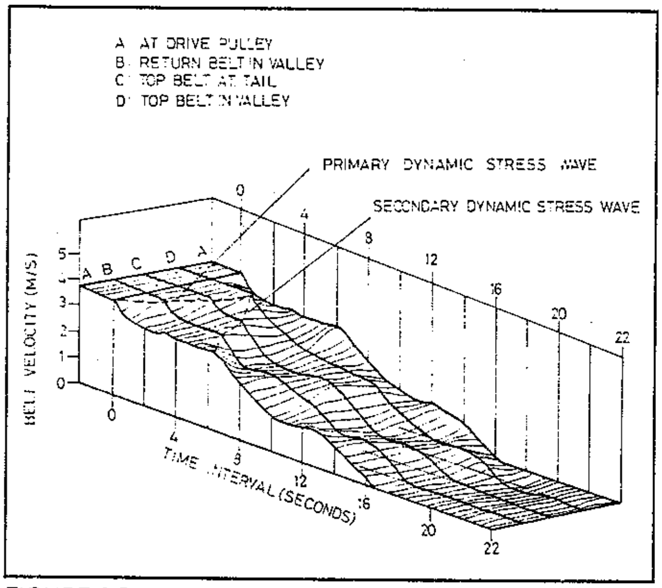


FIGURE 3.7: DYNAMIC STRESS WAVES IN B18 CONVEYOR BELTING DURING AN 850 TONS PER HOUR SHUTDOWN CYCLE

Shutdown behaviour of the B18 conveyor was found to be controllable by application of brakes at the tail of the belt and introduction of slack at the take-up pulley.

Braking is standard practice in many installations but has a negative effect on the system reliability. Some of the most common failures of braking systems are worn brake pads and binding brakes. In addition, incorrectly set brakes can result in severe dynamic-stress generation at the tail pulley of the conveyor.

Introduction of slack at the take-up pulley at the moment of shutdown initiation has not been applied to date as far as the authors could establish. The take-up winch reacts too slowly to provide this slack.

The authors propose that further research should be carried out to design a system of stored tension which can be released with a reaction time of 0,1 second and for long enough to arrest the initial stress build-up after shutdown. The end of the 'slack pay-out cycle' should also be gradual to prevent initiation of yet another shock wave into the system. Care should also be taken to limit the amount of slack released into the system since too much slack will prevent proper pre-tensioning of the belt and will result in severe dynamic stresses induced in the belt during the subsequent start-up cycle.

4. START-UP BEHAVIOUR OF B18 CONVEYOR

The Goedehoop Colliery B18 conveyor starting cycle operates as follows:

(i) The control system will allow a belt start if the safety circuit comprising field-emergency stop switches, equipment sequence interlocking, and oil-cooling system are healthy.
(ii) Start button is pressed.
(iii) The take-up winch winds in to adjust the belt tension to the 'pre-start' value.
(iv) Brakes lift off.
(v) The primary drive starts. This drive is equipped with a high-speed, scoop-controlled fluid coupling. The coupling scoop-tube winds in at a predetermined rate to control the oil supply to the coupling which, in turn, regulates the primary drive torque build-up.
(vi) The secondary drive, which is equipped with a delay-fill fluid coupling, is driven by the belt through its gear reducer and fluid coupling. At a pre-selected time delay after the primary drive start-up, the secondary drive starts and runs up to full speed. The delay-fill fluid coupling has an internal regulator which regulates oil flow from storage to operating chambers inside the coupling. Oil flow in this coupling is sustained by centrifugal force.
(vii) When the belt is up to full speed the take-up winch winds out to reduce belt tension to a pre-selected 'running tension'.

Start-up tests were performed on this conveyor to observe the effects of adjusting the delay time between drives, belt-loading, and take-up pre-tensioning.

4.1 Start-up delay variation

The design specification for B18 conveyor called for a seven-second delay between primary and secondary drive-start initiation.

Figure 4.1 shows a satisfactory acceleration curve under loaded conditions for both a seven-second and a 26,5-second time-delay start-up. This Figure also shows similar behaviour of belt tension at the belt take-up area. The design therefore specified the shorter start-up cycle in order to prevent unnecessary temperature build-up in the fluid couplings. A complete analysis of the loaded start will be done in a later section.

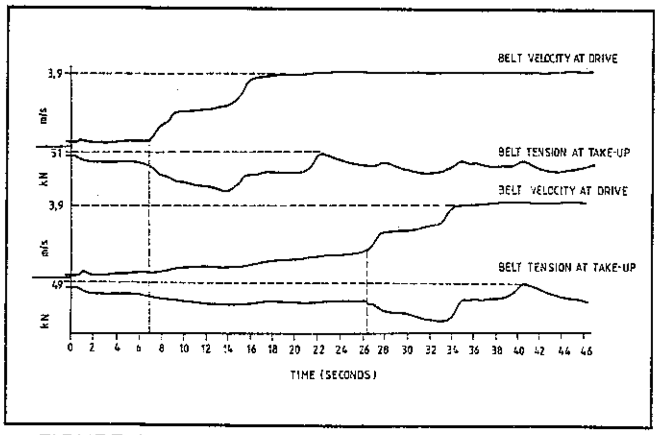


FIGURE 4.1: TIME DELAY VARIATION BETWEEN THE TWO DRIVES OF B18 CONVEYOR AND ITS EFFECT ON BELT ACCELERATION AND TAKE-UP TENSION DURING A 700 TONS PER HOUR START-UP CYCLE

What seemed in order for starting under loaded conditions proved to be unacceptable for starting an empty belt. Figures 4.2, 4.3 and 4.4 show the behaviour of all the belt-start test parameters which were monitored for three different drive-delay conditions, namely seven, 14 and 27 seconds' delay.

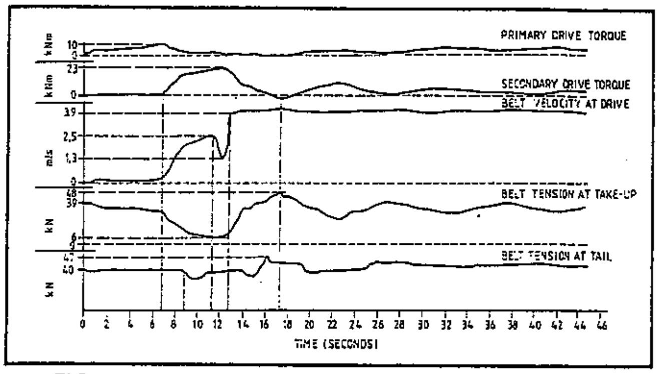


FIGURE 4.2: EMPTY BELT START-UP WITH SEVEN SECONDS' DELAY BETWEEN PRIMARY AND SECONDARY DRIVE MOTORS' ACTIVATION

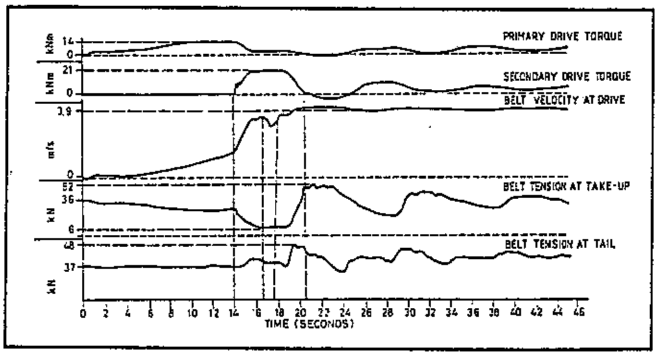


FIGURE 4.3: EMPTY BELT START-UP WITH 14 SECONDS' DELAY BETWEEN PRIMARY AND SECONDARY DRIVE MOTORS' ACTIVATION

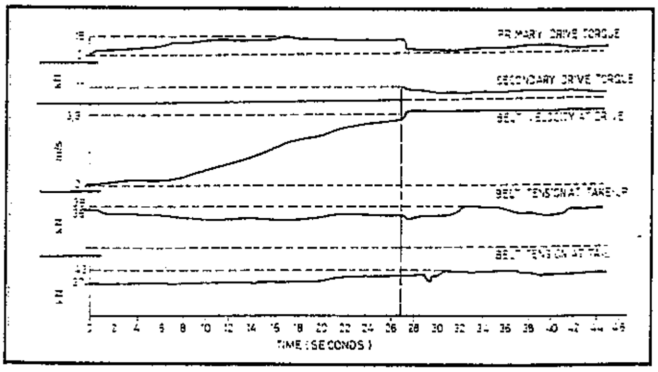


FIGURE 4.4: EMPTY BELT START-UP WITH 27 SECONDS' DELAY BETWEEN PRIMARY AND SECONDARY DRIVE MOTORS' ACTIVATION

Secondary motor delay (s)	7	14	27
Maximum torque (kNm)			
Primary drive	10	14	15
Secondary drive	23	21	11
Percentage of max. belt speed	6	37	93
Maximum acceleration rate (m/s^2)	6.67	1,84	0,98
Take-up belt tension (kN)			
Pre-start	39	36	36
Minimum	6	6	25
Maximum	48	52	39
Maximum tail pulley belt tension (kN)	47	48	43
Acceleration time (s)	13	19	27,5
Time to settle down (s)	45+	45+	37

TABLE 4.1: EMPTY BELT START-UP WITH DIFFERENT TIME DELAYS FOR SECONDARY DRIVE START INITIATION

Table 4.1 summarises some of the important values read from Figures 4.2, 4.3 and 4.4.

Figure 4.5 shows the maximum torque variation of the two drives when starting B18 conveyor with varying time delays between drives under empty conditions.

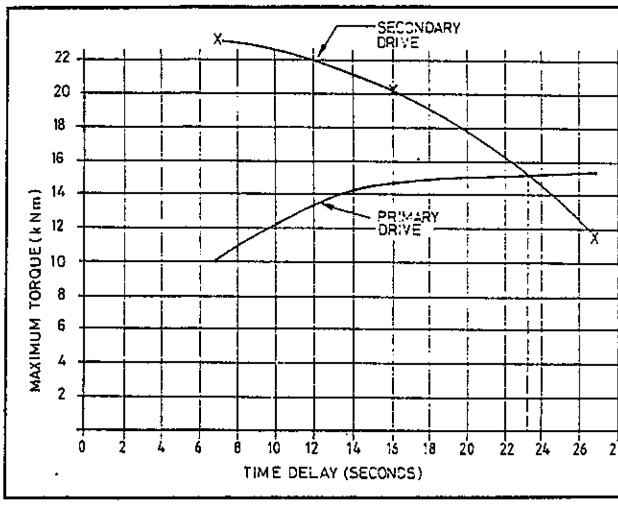


FIGURE 4.5: MAXIMUM TORQUE VARIATION WITH TIME DELAY BETWEEN PRIMARY AND SECONDARY DRIVES WHEN STARTING B18 CONVEYOR EMPTY

Observations

(i) A time delay of approximately 23 seconds gave equal maximum torque transmitted by drives during start-up under empty conditions.

(ii) The shorter time delay required excessively high power input from the secondary drive which, in turn, generated large dynamic stresses in the belting. This was confirmed by the very high rate of acceleration of 6,67 metres per second measured with the seven-second time delay compared with 0,98 metres per second with the 27-second time delay.

(iii) Take-up belt tension fluctuations were much smaller at 14 kN maximum with the 27-second time delay compared with the shorter ones at 42 and 46 kN respectively.

(iv) Belt slip occurred during both the seven- and 14-second time-delay starts. This is seen in Figure 4.2 at 11 seconds and Figure 4.3 at 16,5 seconds. This slipping was the main reason for the high rate of belt acceleration seen with the seven-second delay and the wild take-up tension fluctuations with the seven- and 14-second time-delay starts.

(v) It was noticeable that the belt settled down within 10 seconds after the second motor came on at 27 seconds, while in both of the other tests with shorter time delays the surging continued for a long time.

The longer delay time before starting the secondary drive therefore suited the B18 installation. The external oil coolers of the scoop-controlled fluid coupling proved to be effective in preventing oil overheating.

Replacing the delay-fill fluid coupling of the secondary drive with a double-delay-fill coupling would enable a safer start, with a shorter delay between drives.

The effectiveness of the fluid coupling in the secondary drive was largely lost because this drive was driven by the belt prior to activation of the secondary drive. This meant that by the time it came on line a large quantity of the oil had flown from the storage chamber into the working compartment of the coupling. These couplings work on the assumption that the motor starts with no load and oil-flow into the working compartment provides a smooth load transition to the motor. It is obvious from the above that this advantage is partly lost with secondary and subsequent drives after the belt has started moving — as would be the case with empty belts.

4.2 Effect of belt load on start-up dynamic stresses

Reference was made in section 4.1 to the fact that the loaded belt-acceleration pattern showed little variation between shorter and longer inter-drive start-up delays.

Table 4.2 shows a comparison of belt tension in the take-up area for various load conditions.

Load (t/h)	Take-up tension (kN) Minimum	Take-up tension (kN) Maximum	Tension variance
0	37	51	14
440	21	59	38
726	5	57	52
850	9	66	57

TABLE 4.2: TAKE-UP TENSION VARIATION DURING START-UP FOR VARIOUS LOAD CONDITIONS ON B18 CONVEYOR

From the above table it is seen that:

(i) The stress wave was initiated in every case by the activation of the secondary drive.

(ii) The peak value of the stress wave was proportional to the load carried on the belt.

Figure 4.6 is a carpet plot of B18 conveyor-belt velocities under loaded conditions; Figure 4.7 illustrates an empty belt. Note the presence of a small shock wave immediately after start initiation of the belt and the instantaneous velocity change when the secondary drive was activated at 18 seconds in Figure 4.7. Violent shock waves are clearly seen in the following 20 seconds.

The acceleration rate of the loaded belt in Figure 4.6 was reduced compared with that of the empty condition and this was followed by a lower-velocity stress wave after the activation of the secondary drive.

A comparison of peak velocities, which in both cases occurred at the tail pulley, showed that the loaded belt reached a velocity of approximately 5 metres per second and the empty belt approximately 4,5 metres per second. The corresponding belt tensions were 69 kN and 59 kN respectively.

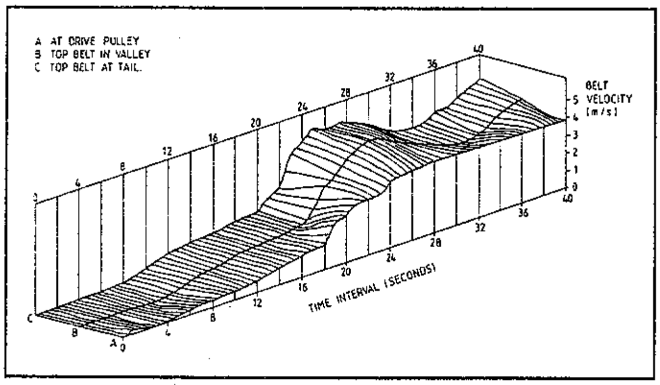


FIGURE 4.6: CARPET PLOT OF B18 CONVEYOR BELT VELOCITIES FOR A LOADED START

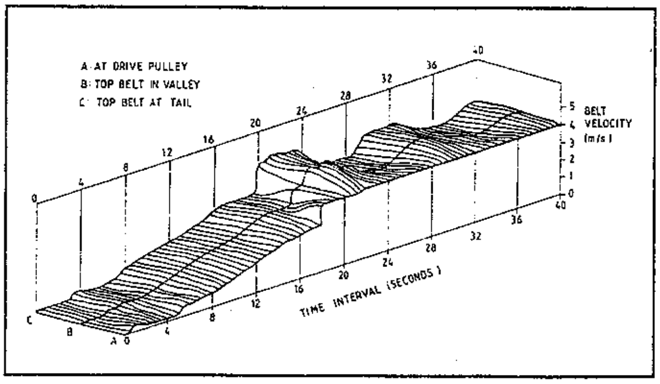


FIGURE 4.7: CARPET PLOT OF B18 CONVEYOR BELT VELOCITIES FOR AN EMPTY START

From the above it would seem as if the loaded belt with its lower acceleration rate should have suffered lower dynamic stresses than the empty belt with its violent velocity change. The advantage of the slower acceleration of the loaded belt in the case of the B18 conveyor is counteracted however by the catenary shape of the conveyor. The downhill section of the belt is assisted by gravity during acceleration, hence the magnification of the acceleration rate of the belt towards the tail section and the resulting higher dynamic stresses.

4.3 Effect of belt pre-tension on start-up behaviour

Harrison[4] proposed optimisation of pre-tensioning of the belt take-up prior to start initiation as a method of limiting dynamic stresses during start-up. This theory was tested on the B18 conveyor. The results are shown in Table 4.3.

	Pre-tension (kN)	Dynamic tension (kN) Minimum	Dynamic tension (kN) Maximum	Tension variance (kN)
(a)	40,9	6,7	47,7	41,0
(b)	42,6	5,2	51,0	45,8
(c)	44,9	10,8	47,7	36,9

TABLE 4.3: EFFECT OF PRE-TENSION VARIATION ON DYNAMIC STRESSES DURING A 730 TONS PER HOUR START

Harrison's theory is not confirmed by the results tabulated above. Test (b) should be discarded however since belt-slip occurred when the take-up tension dropped as low as 5,2 kN. This may explain the subsequent unexpectedly high maximum tension.

A comparison of tests (a) and (c) in Table 4.3 then confirms the theory that a higher pre-tension results in a smoother start-up cycle with lower dynamic-stress variation.

This phenomenon is the main reason why conveyor shutdown behaviour and methods of reducing dynamic stresses during shutting down cannot be viewed in isolation. It was shown before that releasing slack into the take-up belt resulted in a smooth stopping action with minimal dynamic stresses in the belt. The test in question was the one preceding the test in Table 4.3 (a). As seen above, the consequence of the improved stopping achieved by excessive slack-induction, was aggravation of dynamic stresses during the following start cycle.

For the same reason it is not advisable to alter any parameter of the conveyor-control mechanisms without confirming its effect on the behaviour of all the other parameters.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Dynamic stresses in the B18 conveyor at Goedehoop Colliery were found to be initiated both during starting and stopping from the rate of applying and removing the conveyor driving power.

The catenary shape of the overland conveyor complicates the belt's dynamic-stress behaviour, but was not found to be the source from which dynamic-stress waves were initiated.

The braking system installed at the tail end of the conveyor had a damping effect on circulating dynamic stresses during the shutdown cycle. At the same time, the application of brakes increased the belt tension at the tail pulley. Brake adjustment for braking torque and rate of application proved to be critical. Poor maintenance of brakes can result in brakes binding during normal running of the belt and an excessive braking torque applied during stopping. This, in turn, will initiate destructive dynamic stresses at the tail end of the belt during the stopping cycle.

The winch-controlled take-up which replaced the gravity take-up system on the B18 conveyor proved to be successful in withstanding the large circulating stresses in the belt. It also served a useful purpose in providing sufficient pre-tensioning of the belt for the starting cycle — a factor which served to reduce peak stresses in the belting. During stopping cycles the winch was successfully employed to release initial stress build-up in the take-up belt which in turn dampened the circulating dynamic stresses in the conveyor belt.

The load carried by the belt had a damping effect on the stress-wave velocity. This made stress peaks during starting less critical. At the same time, however, belt loading increased dynamic stress peaks during the stopping cycle, a phenomenon which limited the B18 belt's safe carrying capacity to 800 tons per hour. The use of brakes at the tail end of the conveyor allowed a safe carrying capacity of 1 000 tons per hour, which was in line with the designed capacity of the system.

Controlling the application and removal of belt-driving power of this installation was limited to variation of the scoop-controlled coupling torque build-up and the time interval between initiation of primary and secondary drives. The primary-scoop-controlled coupling drive was never a factor in the generation of dynamic stresses while the delay-fill hydraulic-coupling secondary drive proved to be the source of dynamic stresses during the starting cycle. The timing between drives initiation was not as critical when starting a loaded belt from the point of stress generation as was the case when starting an empty belt. A far greater time delay than that recommended by the equipment suppliers proved to be the optimum setting to give satisfactory start-up behaviour under loaded and empty conditions.

Controlled driving torque removal during stopping was ruled out as a means of reducing dynamic stress peaks. Although the effectiveness of the method is recognised by the authors, the practicality of it can be questioned in the case of the B18 conveyor installation. This conveyor is at the rear end of a whole train of equipment that is all sequence-interlocked — which means that any item stopping ahead of the B18 conveyor would result in an emergency stop of the B18. In addition, the B18 is fitted with emergency devices which, again, could cause emergency stops. It is necessary, therefore, to ensure that the system design should cater for the conditions when all driving power is removed instantaneously, as is also the case during a total power failure.

5.2 Recommendations

Dynamic stress waves in the belting of this conveyor installation will never be entirely eliminated. Steps can be taken, however, to minimise these stresses.

1. Braking system

The present braking system is to be maintained in order to enable the belt to carry the system-designed capacity of 1 000 tons per hour. Care should be taken that brakes are correctly adjusted at all times to operate effectively without inducing excessive belt stress at the tail end of the belt.

2. Shock-absorbing system

Releasing slack into the belt take-up during stopping proved to be partly successful in absorbing the shock wave initiated by the sudden removal of driving power. Further research in this area should be done to develop a system capable of releasing the reauired slack with a response time of 0,1 second.

3. Pre-tensioning

The winch-take-up control system on this conveyor must be maintained to provide a belt pre-tension of between 45 kN and 50 kN before the belt start-up sequence is initiated. This will assist in limiting dynamic stress build-up during belt start-up. Once the belt is up to full speed, the take-up tension can be released to between 25 kN and 35 kN .

The reason for giving a range within which to operate take-up tension is to prevent hunting of the winch while attempting to control to a single set point. It was shown previously that belt tension varies all the time during full-speed running conditions.

It should not be attempted to control belt tension with the winch during the shut-down cycle. Apart from the fact that the winch reaction time is far too slow to follow dynamic stress waves passing through the take-up area, there is also a real danger that winch movement during shutdown could oppose a dynamic stress wave passing over the take-up pulley, resulting in instantaneous doubling of the peak-stress value. This, in turn, could cause snapping of the conveyor belt.

4. Drive-starting torque

The present drive configuration of primary drive with scoop-controlled fluid coupling and secondary drive with delay-fill fluid coupling is unsatisfactory.

The time delay between primary and secondary drives starting under these conditions must be between 20 and 30 seconds to minimise dynamic-stress generation.

It is recommended to replace the secondary-drive delay-fill fluid coupling with a double-delay-fill fluid coupling to reduce the unsatisfactory rapid torque build-up rate, when this drive is started, to an acceptable level.

Such a modification will also enable a shorter delay between primary and secondary drives' starting.

6. ACKNOWLEDGEMENTS

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