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Space Mountain at Euro Disney: A 120 million dollar wire rope test machine

Summary

The service conditions of the ropes from the Space Mountain rope-drive at Euro Disney are discussed. These ropes are discarded after about 3 months and 120,000 catapult operations, a figure which was predicted in the design phase using modern wire rope endurance prediction methods. Every rope section is subjected to the same conditions every 36 seconds, the mode of operation never changes. Some rope sections are only subjected to tension-tension fatigue, others to tension-tension and bending fatigue. Daily visual rope inspections and magnetic rope testing at regular intervals, as well as destructive rope tests after discard, provide an enormous amount of "real life" data which has been compared with the theoretical predictions. The paper also presents a method of determining the most favourable length of rope to slip and cut and discuss the results of this procedure.

1. What is Space Mountain?

Space Mountain is a 120 million dollar visitor attraction at Euro Disney in Paris. Every 36 seconds 24 passengers are shot into a huge dome by means of a rope driven catapult. Figure 1 shows an outside view of Space Mountain, Figure 2 shows a detailed view of the catapult.

When the passengers are seated and secured, when glasses have been taken off and false teeth are stored in the pocket, the train moves down to the bottom of the canon slope by means of gravity. Then the catapult pusher loads the canon: It moves the train into the departure position in the lower section of the track which is 50m long and inclined by 32 degrees (Figure 3).

After a short waiting time increasing the tension of the passengers the canon is fired: the background music is interrupted by a loud bang, smoke comes out the canon, and the train rapidly takes off. Under the acceleration of 1.3 g the passengers are pressed into their seats and the train reaches a speed of more than 50 km/h in less than 2 seconds.

Shortly before the summit of the slope is reached, the pusher decelerates. The train enters the dome, subjecting the passengers to a short moment of weightless condition. After another 90 seconds of breathtaking roller coaster trip the passengers will again arrive at their point of departure (Figure 4).

Space Mountain was opened in May 1995. At the time of writing this article (April 1997), already more than 17 million passengers have been shot into space by the rope driven catapult.

2. Why do wire rope researchers love Space Mountain?

Space Mountain is a very interesting source for wire rope fatigue data. It represents one of the very rare wire rope applications where the operating conditions are not only very *severe* but also *known* in every detail. In addition, conditions are constantly being monitored throughout the whole wire rope life.

Every rope section is subjected to the same conditions every 36 seconds; the mode of operation *never* changes. At wire rope discard, every section will have undergone the same stress history 120,000 times. At the time of writing this article, 8 ropes have been discarded and analyzed, representing the fatigue data of about 1 million catapult shots.

3 A short technical description of the catapult system

The catapult reeving is a pretensioned 'closed loop' system. It consists of

- a grooved drum of 1000 mm diameter;
- a pushing device attached to the rope, called the 'pusher';
- a headstock sheave of 1200 mm diameter;
- a midspan supporting sheave of 400 mm; and,
- a 185m long steel wire rope (Figure 5).

3.1 The rope

The steel wire rope type Casar Turboplast has a nominal diameter of 36 mm, a wire grade of 1770 N/mm^2 and consists of an independent steel wire rope core, a plastic layer and eight compacted outer strands (Figure 6).

The rope travels from the drum through the pusher, where it is held by friction, to the headstock sheave where it is deflected by 180º. It travels back to the drum via the midspan supporting sheave.

The two rope ends are attached to the drum by correspondingly overwinding and underwinding. As the drum rotates, one rope end is wound onto the drum and the other end is payed off. As a consequence, the rope length stored on the drum always remains the same: it corresponds to the length of the pusher stroke plus the required dead wraps. This configuration allowed the design of a very short drum with only one wrap empty, resulting in very small fleet angles for the wire rope.

3.2 The tailstock drum

The tailstock drum is made out of forged alloy steel. After tempering, an additional heat treatment has been applied in order to increase the groove hardness. The procedure has proven extremely successful: during each operation, every section of the groove accommodates the rope once in the launching phase and then once in the reel-back phase. In April 1997, after about one million catapult operations, every groove section has wound the rope on and off about 2 million times. Still almost no wear can be measured in the grooves. Disney has a spare drum in stock. It looks as if it will be there for a while.

Maybe the improved contact conditions of the compacted outer strands of the rope have helped the situation. But still the result is astonishing.

3.3 The headstock sheave

The headstock sheave is made out of the same material and has been subjected to the same treatment as the drum. The sheave moves on its own track to allow for rope tensioning by means of a screw actuated tensioning system.

Normally, in similar arrangements, counterweight systems would be used to keep the reelback rope under constant tension. Because of the extreme accelerations of the catapult, however, the reaction time of any such system would not have been satisfactory. Therefore it was decided to pretension the 'closed loop' system to a constant level by means of screw actuators acting on the headstock sheave. The level of pretension is constantly being monitored. Whenever a reduction is measured, the headstock sheave is unlocked and moved until the required level of pretension is re-established. Then the sheave is locked again for the launch phase.

3.4 The pusher

The pusher is a carriage running on its own track about 1 m below the train tracks. Its purpose is to push the train in the loading and launching phase by means of a fin.

The pusher is fixed on the rope by means of two sets of aluminum friction sheaves. The diameter of the sheaves is about 20 times the diameter of the rope (Fig. 7). At the entrance and at the exit of the pusher, the wire rope is deflected by saddles with a radius of about 80 times the rope diameter.

During the installation procedure, the friction sheaves in the pusher are free to rotate. Therefore the rope can simply be pulled through the sheave system. After the rope is installed, the position of the pusher is adjusted and the pretension is applied. As the sheaves in the pusher are still able to rotate, the pretension forces can also be transmitted to the rope length stored in the pusher. In this condition, the rotation of the friction sheave sets in the pusher is blocked, converting the system into a double bollard.

In order to minimize the fleet angles between the sheaves (which would twist the rope during installation), one of the sets of sheaves is inclined relative to the other. The number of friction sheaves was calculated so that the rope would not move in any part of the pusher under the differences in line pull occuring during operation. In case the rope might still show some movement, a fixing point for a clamp had been included at the end of each saddle. Experience has shown, however, that these clamps are not necessary.

By attaching the pusher to the rope by means of the double-bollard arrangement, one continuous rope length could be used instead of using two ropes. This not only allowed for a much easier rope installation and an easy adjustment of the pusher position, it also avoided the use of two rope end connections which could have been susceptible to tension-tension fatigue. In addition, the arrangement allows the use of a magnetic rope test for the whole rope length. Furthermore, if ever the pusher gets stuck, the rope can slip over the friction sheaves instead of destroying the whole power train.

The most important argument, however, was that this arrangement makes it possible to move the pusher along the rope after a certain number of catapult operations. This shifts the zones of maximum stresses along the rope length, thereby increasing the wire rope service life.

4 The rope stresses

At every catapult operation, different zones of the steel wire rope are subjected to different stresses. Some areas are subjected to tension-tension stresses only, while others in addition are subjected to bending on the headstock sheave or the drum. Seven different zones A to G can be distinguished (Figure 8). Figure 9 lists the loading modes in the different zones.

Figure 10 shows the line pull of the traction rope (zones D to G) and of the reel back rope (zones A and B) as well as the carriage velocity as a function of time. During the acceleration phase the forces in the traction rope increase dramatically, while the forces in the reelback rope are reduced.

As the line pull changes dramatically during one catapult operation, different rope sections will be bent on the tailstock winch or the headstock sheave under different levels of line pull. Figure 11 shows the line pull when bending, as a function of the rope length. Two rope lengths of about 20 m (zones B, C and D) and of 9 m (zone F) are not subjected to bending.

The level of pretension was based on three main factors. First of all the catapult had to fit into the dimensions set by the building. This only allows for a very limited wire rope sag and therefore requires the maximum possible level of pretension.

Another argument for a high pretension was the fact that the pusher is attached to the rope by friction only. Therefore the system would react very sensitively to variations of the rope tension. Especially throughout the launch phase a minimum level of tension had to be guaranteed in the reelback rope to avoid slippage. On the other hand, with increasing level of pretension the rope would be wound on and off the drum and travel over the headstock sheave under much higher tension. Therefore with increasing level of pretension an increasing reduction in service life could be expected.

Therefore wire rope service life prediction methods had to be used to find the maximum possible pretension which would give a satisfactory service life.

5 The application of wire rope service life prediction methods in the design phase

For the bending fatigue prediction a program based on the Feyrer (1993) formula was used. The program would not only predict the number of cycles to discard and break for the given set of data, but would also illustrate the influence of the different parameters on the result.

As an example, Figures 12 to 14 show the service life to discard (lower curve) and to break (upper curve) depending on the nominal rope diameter (Figure 12), on the sheave diameter (Figure 13) and on the line pull (Figure 14).

Figure 12 shows a pronounced maximum for the service life at a nominal rope diameter of 40mm. Ropes with smaller diameters have a lower service life because of the specifically higher line pull, ropes with bigger diameters have a lower service life because of the relatively higher bending stresses.

The tension-tension behaviour of the rope was determined by a large number of tests using the 240 t dynamic rope tester at Casar.

The influence of the combined action of bending and tension-tension fatigue was calculated using the Palmgren-Miner rule.

The results of the service life predictions influenced the design and the dimensions of the rope which in turn influenced the design of all other components of the catapult.

5.1 The wire rope selection

The wire rope for the catapult had to fulfill a certain number of criteria: it had to have a very high breaking strength, good abrasion resistance, a good structural stability and a high bending and tension-tension fatigue resistance.

Charts such as Figure 10 were sent to a many different rope manufacturers. Most of them declined even to make a proposal.

Finally, several ropes were given closer consideration. The bending fatigue behavior could be predicted by the program, whereas very little was known on the tension-tension fatigue behaviour of the ropes. Therefore a large number of tension-tension fatigue tests have been carried out with different rope designs in diameters between 36 and 42 mm.

Both the bending fatigue calculations and the tension-tension test results showed that a rope Casar Turboplast would be the most suitable choice.

5.2 The mode of calculation

Starting from a relatively low rope diameter for ease of installation, the final rope diameter, the level of pretension, and the sheave and drum dimensions have been calculated iteratively for different rope zones as shown in Figure 15.

For the final layout and the final operating conditions, a total number of 110,000 catapult cycles to discard has been predicted.

6 Wire rope inspection

The wire rope of the Space Mountain catapult is being regularly inspected by visual inspection and magnetic testing.

6.1 Visual inspection on site

During the first week after the installation, the rope is subjected to a daily visual inspection. This is to detect any possible problems created by the new rope or the installation process. Then the intervals between the inspections are increased to one week. After the first wire breaks have been detected either by visual or magnetic inspection, the inspection intervals are again reduced.

Figure 16 shows a typical view of the wire rope after about 80,000 catapult cycles. Two fatigue wire breaks are visible. With an increasing number of catapult cycles, the ends of the broken wires will be pulled apart and stand out. In this condition they would damage the magnetic tester and the grooves of the drum or the sheave. Therefore they are removed mechanically by bending the ends back and forth until they break. The number of broken wires is noted in order to monitor the progressing rope damage and for comparison with the figures obtained by the magnetic testing.

6.2 Magnetic testing on site

Immediately after the installation a magnetic rope inspection is carried out in order to provide a reference diagram. The next magnetic tests are carried out after about 20,000 and 40,000 catapult cycles. After the first wire breaks have been detected, the inspection intervals are reduced to about 8,000 catapult cycles. Immediately before discarding the rope, a final magnetic test is performed on the catapult. During every test, the wire breaks along the rope length are recorded on a chart.

About twelve meters of rope are constantly stored in the pusher and are therefore not accessible for magnetic testing. As there was concern that the rope sections entering and leaving the pusher could be subject to particular tension-tension fatigue, for the first wire ropes the aluminum friction sheaves of the pusher have been unlocked and the pusher has been shifted. Then the rope length normally stored in the pusher was also tested. During these procedures, not a single broken wire has ever been found in the pusher length, an observation that was always confirmed later both by the manual and the magnetic inspection of the total discarded rope length in the workshop. Therefore this time-consuming procedure was abandoned.

The numbers of broken wires found during the magnetic testing are entered into a spreadsheet and analysed.

6.3 Magnetic testing of the discarded rope

The eight ropes discarded so far have been shipped back to the Casar workshop for further tests. First the wire ropes have been subjected to a magnetic test using the same tester as at Euro Disney. So far the charts obtained in the workshop always show a few more wire breaks than the charts obtained immediately before discarding the rope. This could be explained by additional damage to the rope during removal and by the fact that the test performed on the catapult is always carried out under a pretension of 125,000 N, whereas in the workshop the rope is always tested without tension.

6.4 Destructive testing of the discarded rope

After the magnetic test, the seven different rope zones defined in Figure 8 are marked. Then samples are taken from these different zones for destructive tests. One length is always subjected to a pulltest to destruction, while the adjacent length is dismantled in order to detect internal wire breaks and to examine the condition of the plastic layer.

The first wire ropes were discarded at about 100,000 catapult cycles when the discard criteria of DIN 15 020, part 2 had been reached in the rope zones spooling on and off the drum. In a pull test to destruction, the worst sections of these ropes achieved an average 93% of the breaking strength of the new rope. Only very few internal wire breaks were found, and the plastic layer of the rope was still in very good condition. Therefore it was decided to allow for a greater number of wire breaks for the following ropes. These have been operated with successively increasing numbers of catapult cycles, up to a figure of 130,000 catapult cycles.

As could be expected, the number of visible broken wires showed a disproportionate increase with the number of catapult cycles. It was also no surprise that the break tests of the discarded ropes showed a continuous decline in remaining rope breaking strength with increasing number of catapult cycles (Figure 17).

7 Service life analysis: Comparison of predictions and real life fatigue data

For the service life predictions, zones A, E and G, which are the only zones subjected to both bending and tension-tension loading, have been analyzed. Spooling on and off the drum, zones A and G undergo one bending cycle during every catapult cycle. At the same time, zone E undergoes two bending cycles on the headstock sheave which has a 20% bigger diameter than the drum. The calculation showed that zone E was more critical.

Figure 18 shows a typical chart of the broken wire density on 30 x *d* after 100,000 catapult cycles as a function of position along the rope length. The rope zones which travel over the headstock sheave and on and off the drum during launch can clearly be identified. In zone E, the discard number of 35 wires on 30 x *d* has not yet been reached.

A pronounced peak is visible on the traction rope at about 147 m. This rope section spools onto the drum when the pusher attaches to the train. The shockload during attachment had not been foreseen in the design stage. In the meantime measures have been taken to eliminate this shock.

7.1 Zones B, C, D and F (tension-tension only)

It is remarkable that in spite of the high dynamic forces wire breaks can only be found in those areas which are subjected to bending. All rope zones which experience tension-tension only (zones B, D, F) and the length stored in the pusher (zone C) do not show a single wire break at discard. So the influence of tension-tension only is obviously not too harmful.

7.2 Zone E (traveling over the headstock sheave)

The service life under the combined influence of tension-tension and bending stresses has been predicted to 110,000 catapult cycles for zone E.

Zone E behaves just as predicted. The discard number of wire breaks is reached at about 110,000 catapult cycles.

7.3 Zones A and G (spooling on and off the drum)

In zones A and G, we can distinguish between zones spooling on and off the drum under relatively constant line pull, and zones which at the same time undergo a sharp change in line pull. The zones with the relatively constant line pull behave just as predicted.

In zones with a combination of bending and load changes, however, the density of wire breaks increases at a faster rate towards the end of the rope life.

In the first half of the rope life, the wire density in zones A and G is lower than in zone E, just as predicted. In the second half of the rope life, however, the wire breaks develop at a faster rate in zones A and G, so that finally the discard criteria are reached in these zones which spool on and off the drum after about 100,000 catapult cycles. It was only after we had decided to keep the ropes in operation even after the discard criteria were reached in zones A and G that we found that the discard criteria were reached in zone E at about 110,000 cycles, as predicted.

Other than on the headstock sheave, the combined influence of tension-tension and bending stresses on the drum is much more pronounced than the application of the Palmgren-Miner rule would suggest.

A possible explanation could be the fact that the rope is lengthened during every load change. For a rope section lying on the sheave, a length adjustment is possible on both sides, and a relative motion between the headstock sheave and rope is possible. This explanation is supported by the observation that after every catapult cycle, the sheave must be set back by 20mm.

On the drum, however, a length adjustment is only possible towards one side.

8 Increasing the service life by shifting the rope

On lifting devices with a continuously changing mode of operation, with every lift different rope sections are subjected to tension-tension or bending fatigue. Therefore these machines normally show a random distribution of wire breaks along the rope length.

On machines with repetitive motions, like automatic stackers, on the other hand, with every lift the same rope sections are subjected to the same stresses. Therefore these machines tend to show concentrations of wire breaks in a few areas of high fatigue.

The catapult was designed to repeat exactly the same operation 100,000 times with the same rope. Therefore a concentration of wire breaks in a few limited areas could also be expected here. This is why in the design stage of the catapult the possibility of shifting the wire rope by moving the pusher has been anticipated.

8.1 The optimum shifting length

Whenever a rope is shifted, the area of the highest fatigue will be moved to an area of lower fatigue. But what is the optimum shifting length? How do we make sure we do not move the most damaged zones into other problem areas?

It was decided to use the broken wire density in any position as a measure of the level of fatigue any section of wire rope would undergo at this position. Then by taking the average of the original and the shifted position, we would have a rough estimation of the average level of fatigue any rope section would be subjected to if it would work half the time in the one, and half the time in the other position.

Therefore the first ropes were operated without shifting in order to measure the broken wire densities along the rope length and to locate the areas of maximum rope damage. Then an optimum shifting length was determined by means of calculation. Figure 19 shows the average broken wire densities of the original and the shifted position as a function of the shifting length.

Let us take a closer look at the curve of the density after 110,300 catapult cycles. Here, the maximum broken wire density on 30 x *d* is 32. If the rope is not shifted (=shifting length 0 meters), the average stays the same. If we shift the rope by 2 meters, the density of 32 is moved to a position of lower density. In this case, the original density for that position was 4, so the average drops to 18. If we shift the rope by 4 meters, the critical zone is shifted to a position of density 10, so the average increases again. The local minima of the curves indicate the optimum shifting length, in this case they are at 3.5 and 6.5 meters.

8.2 The effect of the catapult rope shifting

It was decided that the ropes should be shifted at about 45,000 catapult cycles, slightly below 50% of their expected service life. Two ropes have been shifted by 3.5 meters so far. The first one has been discarded early (after 85,000 cycles) in order to avoid a rope change during the main season when the catapult operates 16 hours a day. The second rope is in operation with about the same number of catapult cycles at the time of writing. Both ropes show a much better distribution of the wire breaks after 80,000 catapult cycles.

9 Concluding remarks

The authors would like to thank Euro Disney for building the Space Mountain wire rope test machine. We would not have had the 120 million dollars required to do so. The readers should not miss the opportunity to visit Space Mountain. It is a good excuse to go to Paris in order to do some rope research.

10 References

Feyrer, K., (1993) *Endurance calculation of wire rope running over sheaves* Proc. OIPEEC Round Table Conference Delft September 1993 pp 2-I.15.

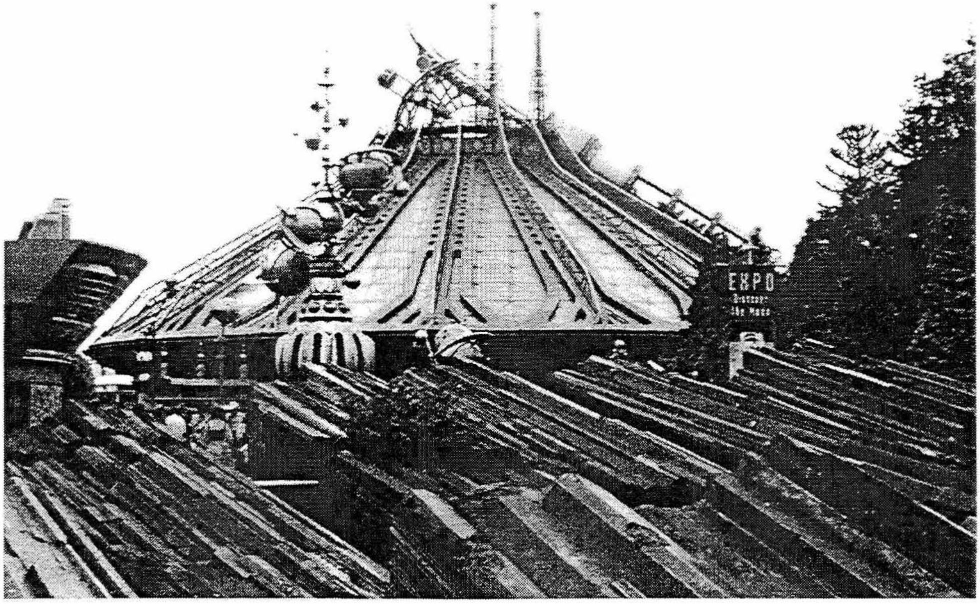

Figure 1: Outside view of Space Mountain.

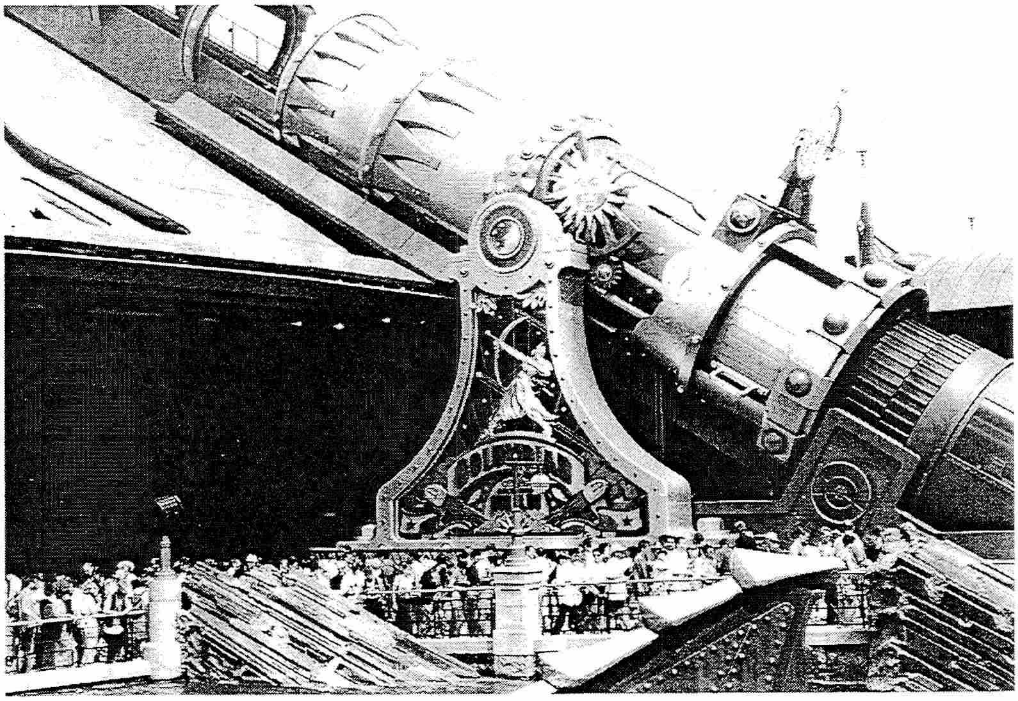

Figure 2: Outside view of the catapult.

Figure 3: Inside view of catapult.

Figure 4: Arrival of the train.

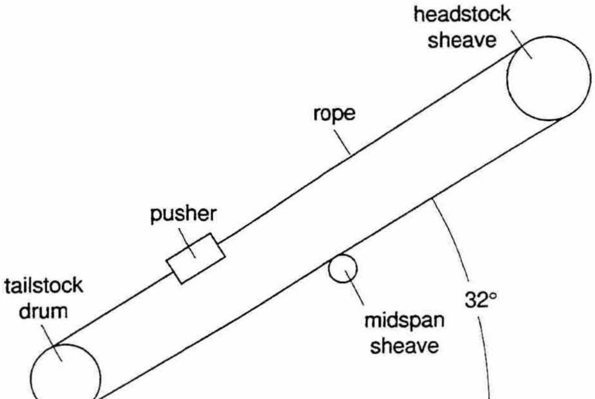

Figure 5: Schematic drawing of the catapult.

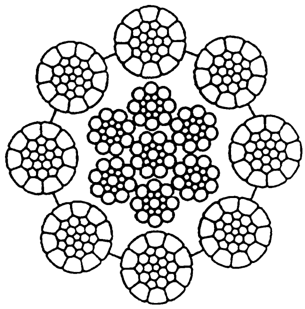

Figure 6: The rope: Casar Turboplast.

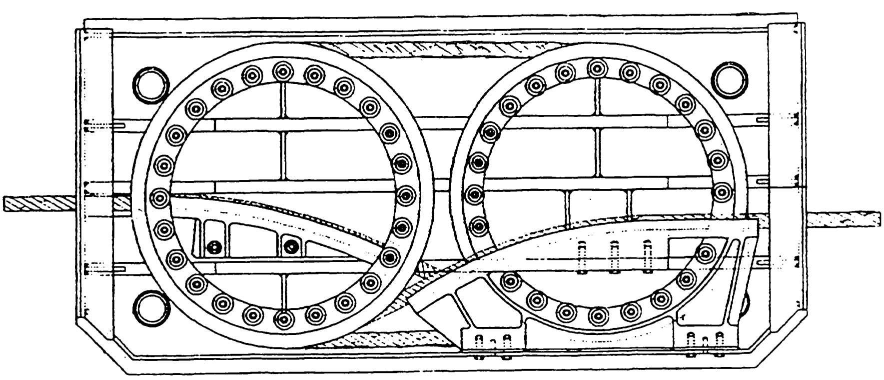

Figure 7: The pusher .

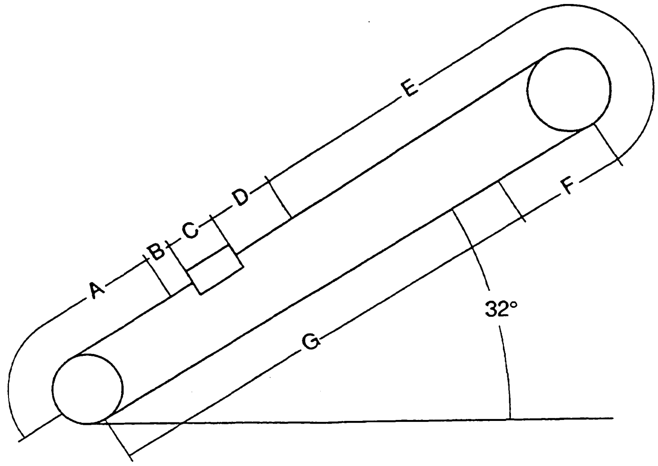

Figure 8: Zones A through G.

Zone	Length [m]	Tension-Tension	Bending
A	41	•	• (on drum)
B	2	•	–
C	12	•	–
D	6	•	–
E	39	•	• • (on sheave)
F	9	•	–
G	41	•	• (on drum)

Figure 9: Stress modes in different rope zones.

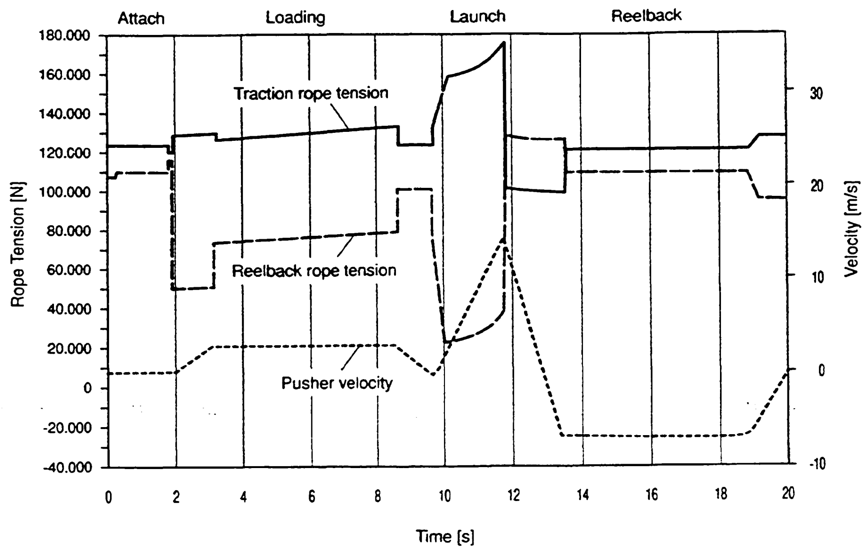

Figure 10: Rope tensions and train velocity over time.

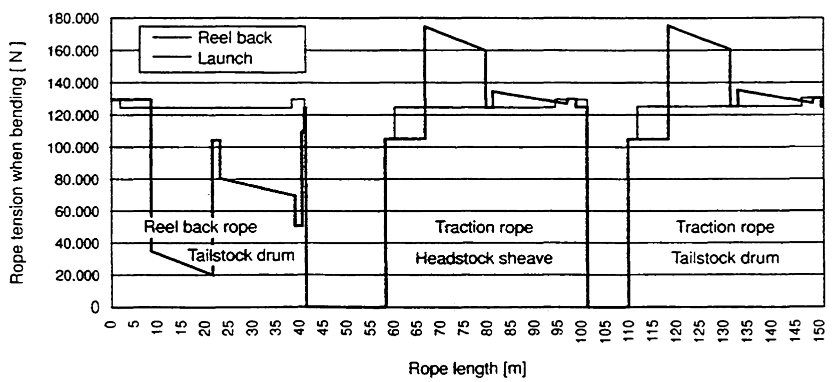

Figure 11: Line pull while bending.

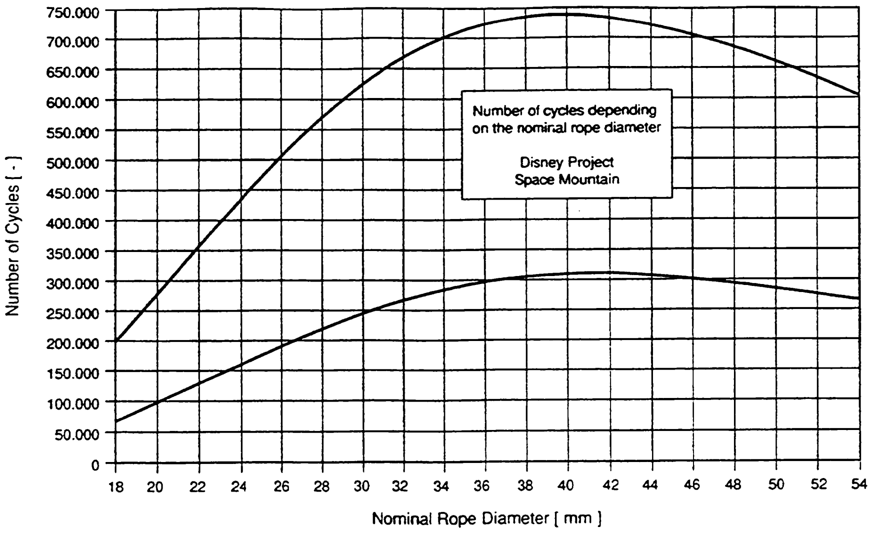

Figure 12: Number of cycles depending on the nominal rope diameter.

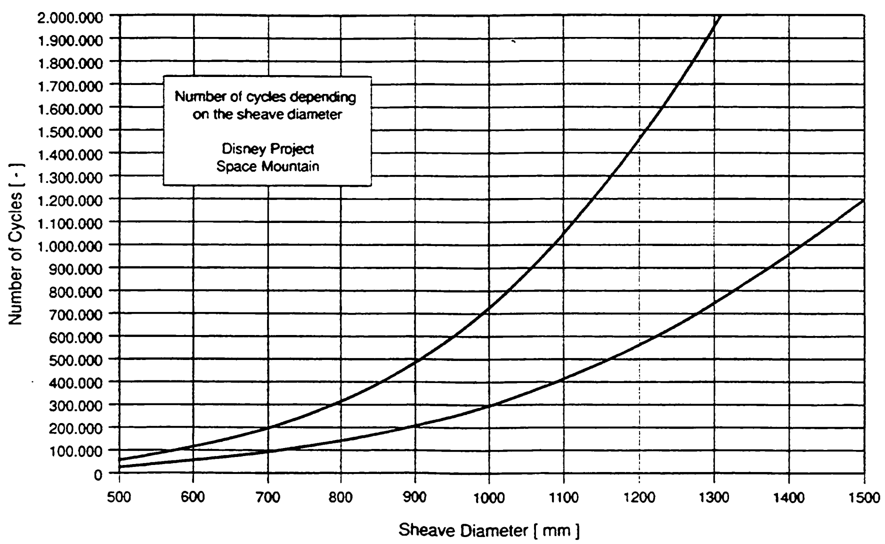

Figure 13: Number of cycles depending on the sheave diameter.

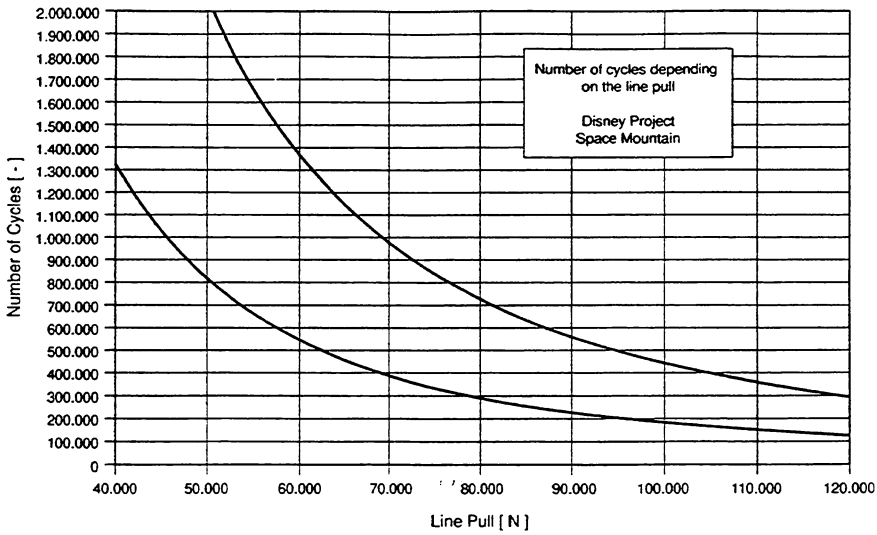

Figure 14: Number of cycles depending on the line pull.

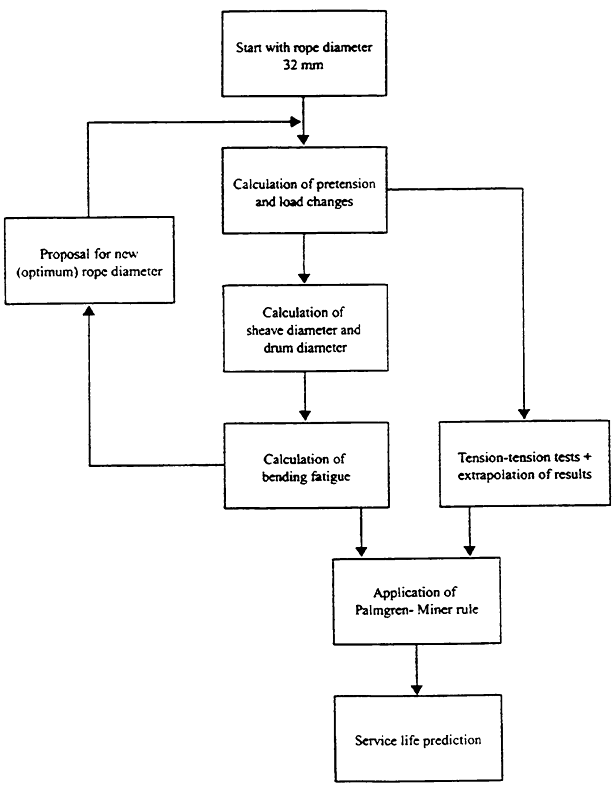

Figure 15: Flow chart showing the calculation procedure

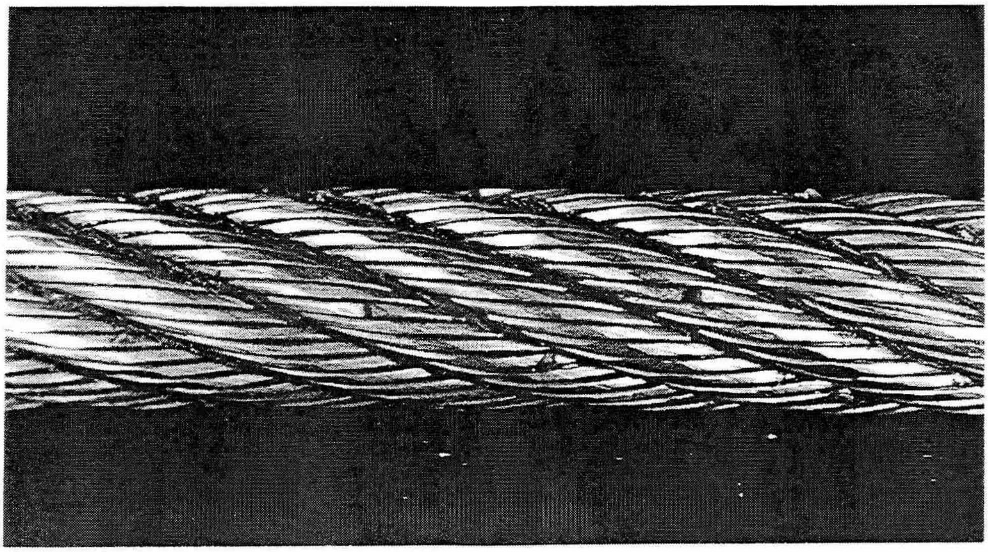

Figure 16: Typical view of the rope after about 80.000 catapult cycles.

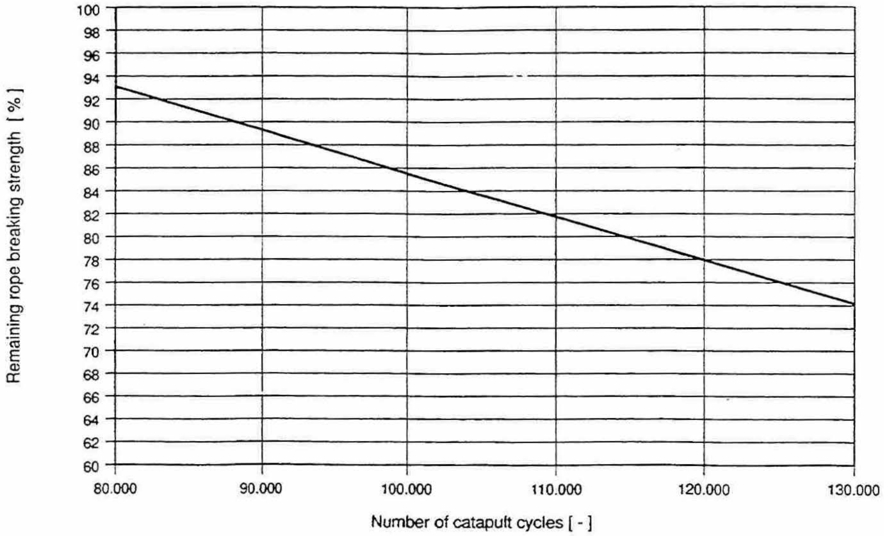

Figure 17: Remaining breaking strength of the rope as a function of the number of catapult cycles.

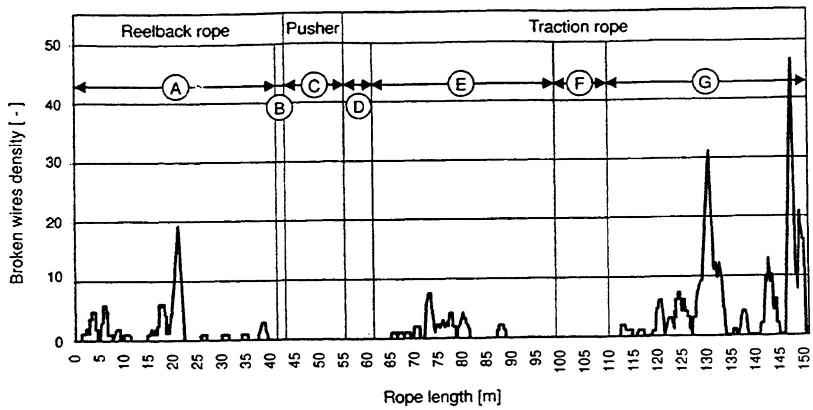

Figure 18: Broken wire density on 30 x d as a function of the rope length.

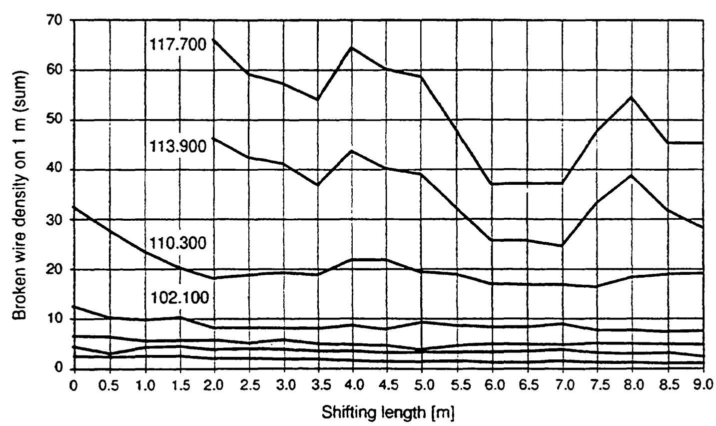

Figure 19: Hypothetical number of wire breaks depending on the shifting length.