FATIGUE ON FULL LOCKED COIL ROPE UNDER BENDING IN TRAMWAYS SYSTEMS.

G. CRESPO and Z. CASSIER
Department of Mechanic, Universidad Simón Bolívar,
Apdo 89000, Caracas 1086-A, Venezuela

ABSTRACT

The mechanical behavior of full locked coil ropes (46 and 50 mm diameter) under bending in tramways systems was studied and the additional tension for the mixing fatigue stress state on the wires was determined. Ropes in tension with a 25% of the rupture tension load were tested in bending on pulleys with no additional load until 350,000 cycles of simple bending. The relation between the pulley diameter to rope diameter was 60 and the length test was 22.5 times the diameter of the rope. It was found the beginning of fatigue crack nucleation and initial propagation on the second layer of round wires (with a value of 90% of additional tension) while the outside square wires kept unbroken. These results were compared with the behavior of the ropes in Mérida-Venezuela tramway which had been working for 32 years without slipping until they finally got broken or underwent fatigue failure.

KEYWORDS

Ropes, wires, crack growth initiation, tramways, failure analysis, life extension.

INTRODUCTION

It is well known that the cyclic movement of ropes (such as Seale, Filler or Warrington ropes) on pulleys or chains produces fatigue failure for any specific load (Rosetti 1973, Voigt 1986, Bahke 1980, Feyrer & Jahne 1992). However, the causes have not been well determined for full locked coil ropes because the fatigue stress state is very complex (Pantucek 1977). Some researches have estimated with several equations the additional tension value on ropes for bending but with theoretical assumptions (Calderale 1972, Leider 1974, Apel & Nuenninghoff 1983). It is difficult to get the current behavior of full locked coil ropes for (see Fig.1) tramways systems because these ropes are slipped or retired before the fatigue appears on wires, in attention to standard security procedures which are very high. In the laboratory, testing these ropes, has become very expensive.

In Mérida-Venezuela tramway (the longest and highest of the world for many years), ropes of 46 and 50 mm diameter were working continuously for 32 years without any slip. This is a go-back system with only two cabins, one end remains fixed and the other one has a counterweight. After 350,000 cycles of use approximately, on November 1991, one of these ropes broke and two people died. The failure was due to fatigue just in the zone where the rope was working with simple bending. The other ropes were slipped and the same zone was analyzed in the laboratory. In this work the results of this analysis is showed in comparison to the laboratory tests.

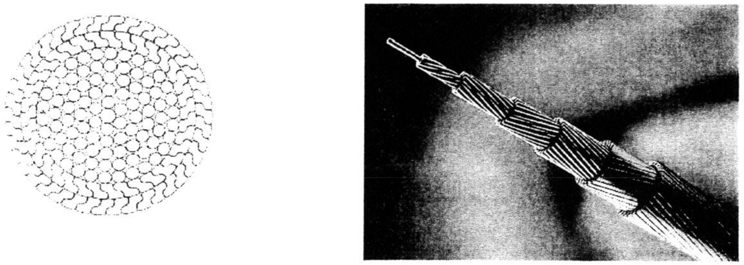

Fig. 1: Full locked coil rope for tramways systems.

MERIDA´S ROPE ANALYSIS

The Merida tramway was built in 1959 on four steps, using full locked coil ropes 46 and 50 mm diameter for the track ropes. The counterweight exerts a 25% of the tension rupture load on each rope, which move on a chain without sliding. Such counterweight is located at the tension station. These ropes have two square wire layers (4.5 mm) and 6 or 7 round wire layers (3.2 mm diameter approximately) and they were working continuously during 32 years without slipping. In one of the ropes at the fourth step (50 mm diameter), a fatigue failure was present, the cabin crashed down and two people died. The number of cycles for fatigue bending on the rope is around 350,000. The first four ropes (46 mm diameter and 212 tons rupture load) were retired or slip and the laboratory analysis showed that the second round wire layer in almost all the ropes practically disappeared and multiple fatigue fractures were observed in all the wires of this layer. The number of broken wires are reduced to zero both outside and inside the rope. On Table 1 the number of broken wires per layer are showed.

Table 1: Broken wires per layer on 46 mm diameter ropes after 350,000 cycles of bending in Merida-Venezuela tramway.

Layer	**Wire Diameter or Height (mm)**	**Wires per Layer**	**Broken wires on Rope N° 1**	**Broken wires on Rope N° 2**	**Broken wires on Rope N° 3**	**Broken wires on Rope N° 4**
1st "z"	4,50	38	0	0	0	2
2nd "z"	4,50	30	0	0	0	3
1st round	3,15	23	9	5	6	5
2nd round	3,15	18	18	12	18	14
3rd round	3,15	12	6	3	5	6
4th round	3,25	6	0	0	0	0
Central	3,80	1	0	0	0	0

Fig. 2 and 3, shows the SEM fractography analysis. The fatigue crack growth from the wire surface perpendicular to the axis of the wire and change 90% following the cold drawing orientation. Secondary cracks are visible. In Fig. 2, the effect of the plastic local deformation by the contact of wires of different layers for the crack nucleation is observed.

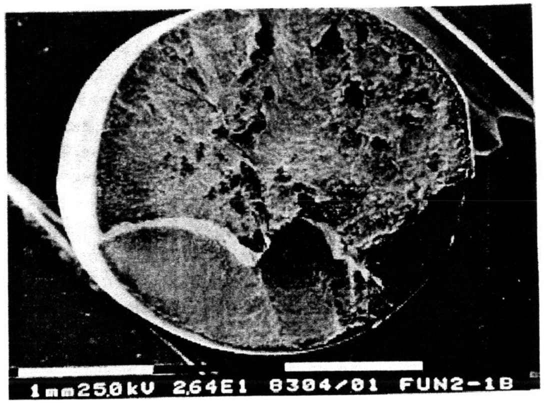

Fig. 2: Fatigue fracture zone of a round wire from second layer in Rope N° 1.

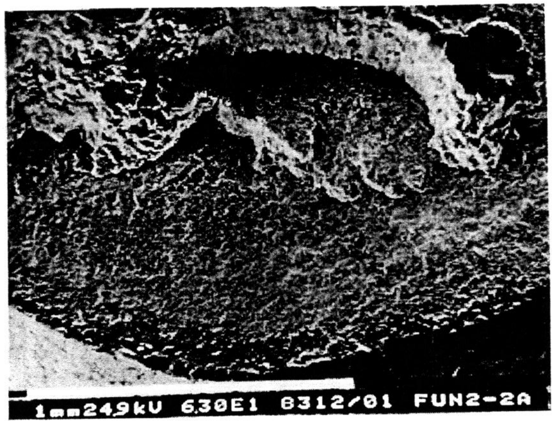

Fig. 3: Magnification of fracture zone of Fig. 1. Secondary cracks may be observed.

The multiple (triaxial) stress on this zone, where axial tension, bending tension, torsion, and punctual compression with tangential stress due to the relative slide and friction between wires during bending, make this problem very complicated. The best way to estimate the real stress state is by considering only two stresses: the axial stress for the straight rope which is always known and the additional tension stress which is the sum of all the effects due to bending, torsion, local compression and friction. With the results and data from Merida ropes, the next step in this research was to reproduce the same conditions at the laboratory and determine the value of an unique axial tension in order to produce the same area reduction in the rope (due to broken wires) in comparison with simple bending of the rope under 25% of rupture load axial tension.

EXPERIMENTAL

Samples were taken from new ropes with similar wire arrangements (46 mm diameter and 212 tons rupture load) were tested both in straight axial tension fatigue load and simple bending fatigue. For the latter experiments, it was possible to get the same conditions of Merida's tramway in the sense of that area reduction (as a measure of broken wires) after 350,000 cycles load was similar, with a relation between pulley diameter to rope diameter of 60 and a bending length of 22.5 times the rope diameter. The mean value of area reduction was 18.84%. In axial tension fatigue, different loads were superimposed alternatively to a minimum of 25% to determine the additional tension that produced the same area reduction. Therefore, the maximum loads were 64, 85 and 106 tons for each fatigue test that mean 30, 40 and 50% of rupture load. On Table 2, the broken wires per layer and area reduction for the ropes under tension fatigue tests are showed.

Table 2: Broken wires per layer and area reduction after 350,000 cycles of load under tension fatigue in comparison with bending fatigue for 46 mm diameter ropes.

Maximum Load (tons)	Wires per layer	Broken wires per layer under tension fatigue	Area reduction under bending fatigue (%)	Area reduction under tension fatigue (%)
64 30% rupture load	38	0	18.84	9.94
	30	2		
	23	3		
	18	10		
	12	2		
	6	0		
	1	0		
85 40% rupture load	38	2	18.84	17.56
	30	4		
	23	8		
	18	11		
	12	4		
	6	0		
	1	0		
106 50% rupture load	38	6	18.84	34.48
	30	8		
	23	14		
	18	18		
	12	10		
	6	0		
	1	0		

Fig. 4 shows the SEM fractography of one of the round wires from second layer. The morphology is similar to those from bending fatigue.

Fig. 4: SEM fractography of fracture fatigue surface of a round wire from the second layer of 46 mm diameter rope under tensile fatigue.

DISCUSSION

From Table 2 and Fig. 4, it is possible to see that the broken wire distribution and the fracture zone surface under SEM for tension fatigue is quite similar to bending fatigue. When the maximum load in tension fatigue test is approximately 42% of rupture load for the 46 mm diameter rope, then the area reduction for both bending and tension remains the same. It seems that in real conditions on the pulley, bending aids 40% of the total load or 40% of additional stress on the rope.

The same tests were developed for 50 mm diameter ropes (280 tons rupture load) and the results were similar for the distribution and fractography of broken wires, but identical area reduction was achieved when the maximum load was 47% of rupture load. This means a 46.7% of total load.

In tramways systems with counterweights, as Merida's system is, the axial tension on the rope is practically constant for any load and position of the cabin. So that the movement of the rope on the pulley or chain in this case, increases the real load on the rope from 25% of rupture load when it is in the straight zone to approximately a 42% of rupture load when bending on the chain. And, what is worse, the continuous displacement of the rope on the chain make this cyclical. The stress factor concentration, the relative movement of the wires with high compression loads plus the increase of stress due to static bending, at the loads levels measured, make it logical that these ropes fatigued. An alternative for decreasing this effect is to eliminate the counterweights and use a fixed end system, but for tramways as Merida it is not possible.

The fact that the second layer of round wires is first destroyed, is due to major contact forces between wires of the first two layers. Outside layers show more movement when the rope is bending on the chain or pulley and the squeeze and local compression is higher.

On the other hand, it is important to note that the central wire of the rope and the six wires layer never broke under any load conditions. The real stress on the inner wires must be less than other round wires in upper layers.

The square or "z" wires on the original design of full locked coil rope have a hardness less than those for round wires. Perhaps, the expected mechanical behavior for the designer and manufacturer is that the first broken wires appears on the first square layer and the inspector can easily see them when the rope begins to fail. But this is not true for this kind of rope. The failure starts inside the rope on round wires and visual inspection is not recommended. The Magnetic Flux Leak test (MFL) can not inspect the rope on the chain, pulleys or towers due to ferromagnetic effects.

IMPROVE THE ROPE

As a consequence of this study, information for improving the design and manufacturing of full locked coil rope was obtained. The fatigue life of this kind of rope might be increased by avoiding the contact between the first two round wires using an elastomer and increasing the cold work on the square wires. For keeping the same nominal diameter of the rope, the six round wires layer may be removed and recovering the central wire with an elastomer.

CONCLUSIONS

The additional stress when a full locked coil rope (46 or 50 mm diameter) bends on a pulley or chain in tramways systems with counterweights is 40 to 46.7% respectively of the total load acting on the rope. The nucleation and propagation of the fatigue failure begins in round wires in the inner of these ropes. The design may be improved by filling with elastomer the contact zone between the round wires layers and increasing the cold work of the square outside wires.

REFERENCES

Apel, G. and Nuenninghoff, R. (1983). Improving the properties of high tensile wire ropes by optimisation of the rope construction. Part II. *Wire*, **33**, 3, 102-104.

Bahke, E. (1980). Principles defining the strength of wire ropes and chains - 1. *Wire*, **30**, 2, 54-61.

Calderale, P. M. (1972). Bending fatigue tests on wire rope and statistic evaluation of the results. *Wire*, **23**, 12, 763-767.

Feyrer, K. and Jhane, K. (1992). Duración de los cables en caso de contraflexión. *Alambre*, **42**, 1, 64-70.

Leider, M.G. (1974). On secondary stresses in the bending of wire ropes. *Wire*, **24**, 3, 119-126.

Pantucek, P. and Bahke, E. (1977). Effect of transverse compression on wire rope under tensile and bending loads. *Wire*, **28**, 3, 95-100.

Rosetti, U. (1973), Contribution á l´évaluation de la sécurité en service et des critéres de depose des cables par l´essai d´endurance. OIPEEC, Round Table, Milano, 208-216.

Voigt, P. (1986). Influencia de los nuevos diseños de cables y tecnologías de fabricación en la vida útil de cables metálicos. *Alambre*, **36**, 3, 115-119.