Summary

Wire ropes play an important role in technology. They are very useful due to their low bending stiffness and high tensile strength. In many transportation equipment we encounter wire ropes. You can think about cranes, winches and drums and elevators. But wire ropes are also more or less used in static applications such as cable bridges. The history of wire ropes goes back to 1834. The mining engineer Julius Albert has replaced a link chain by a wire rope. The first wire ropes cannot be compared to the current wire ropes. It appears that the history of wire ropes still nearly goes back 20 years, because in the beginning of the 19^{th} century they used wire ropes for cable bridges. During a time of nearly 200 years much research has been performed onto wire ropes. All those researches have had a fourfold objective, namely: decreasing the bending stiffness, increasing the tensile strength, and reducing the wear and increasing the endurance. With respect to the tensile stress, a large progress has been made. The strength is increase by more than factor 4 compared to 200 years ago. The increase in strength can be attributed to the increased knowledge with respect to material science. Wear and bending stiffness are reduced by another lay configuration as in the past; this has resulted in wire ropes with a larger endurance. Unfortunately, wear remains an important issue. Müller (1977) founded that lubrication increases strongly the endurance of wire ropes. Waterhouse and Taylor (1971) have established three requirements to which the lubricant must fulfill.

There is performed much research into the mechanics of wire ropes. Benndorf (1904) found that the modulus of elasticity of wire ropes is not constant, but varies with the geometric properties of the wire rope. He has drawn up an equation to calculate the modulus of elasticity for one type of wire rope. The Poisson ratio appears not to be constant too, this value can be determined only by using experiments. During endurance experiments they encountered another problem, wire ropes break at the end terminations. This problem makes the whole experiment useless. The end connection has to be stronger than the wire rope itself, if this is realized the experimental results can be used. Drooger (1962) discusses different end terminations in his book, the resin socket is seen as the best end termination.

To be able to determine and calculate stresses in the wire rope a mathematical model of the wire rope should be developed. This model describes with three coordinates the curve of a wire in a 3D space. The simplest model is a single wire in a straight strand. The model becomes much more complicated when a wire is considered in a strand which is laid around a core strand. By using the parametric equations, the bending and torsion stresses can be calculated. Schiffner (1986) was the first who made a distinction between wire ropes with much and less lateral space during the development of the parametric equations of a strand bent over sheave. Wiek (1986) is the only one as far as known who has studied the first and second tangent problem. The tangent problem means that wires with the right diameter are braid into a wire rope in such a way that the wires in one layer touches each other, and that the upper layer is aligned with the underlying layer.

Besides torsion and bending stresses there occur of course tensile stresses in the wire rope. This stress can be determined in a simple way when the shear stress which is discovered by Berg(1907) is

neglected. Benndorf (1904) and Feyrer (2007) have derived equations from which the tensile stress in wire ropes can be calculated.

As mentioned, bending stresses can be calculated by using the parametric equations of the wire rope. The calculation of these stresses has a rich history. Reuleaux thought that this stress has a constant value, but finally Leider (1977) and Shiffner (1986) have found the right relation. They found that the bending stress has a sinus relation as function of the winding angle. Besides tensile, bending and torsion stresses there occur secondary tensile stresses according to Andorfer (1983) and Schmidt (1965). This stress is caused by the friction between the wires. When in a wire rope the individual wires cross each other, secondary bending stresses will occur. When a wire rope is bent over a sheave, rope ovalisation stresses will occur. Between the wire rope and sheave will occur high pressures, this pressure can cause local yielding. Wiek en Häberle have both investigated the distribution of the wire rope pressure in the groove of the sheave. Wiek was the first who investigated this, Häberle's experimental research results were in agreement of Wiek's theoretical results. Not only between the sheave and wire rope occur high contact forces, but between wires too. Starkey and Cress (1959) investigated those contact forces. They conclude that wire rope failure is often caused by high contact stresses in the wire rope itself.

Besides tensile and bending a wire rope is subjected to torsion. In some cases (for example at non guided loads) you want to prevent the wire rope from turning around its axis under influence of the load. A non-rotating rope can be the solution, but these wire ropes contain point contacts. This results in high point contact stresses. Therefore sometimes in practice they don't choose non rotating wire ropes. Especially in offshore applications the tension-torsion behaviour of wire ropes can be a problem, wire ropes which are used for mooring application are subjected continuously to fluctuating tensile forces. This tensile force induces torsion in the wire rope. A continuously changing torque load in a wire rope can cause eventually fretting fatigue.

One of the main things that really always play a role in the research onto wire ropes is: how to improve and optimize the endurance? There are performed many experiments from which they want to determine the endurance of the wire rope. There can be made a distinction between wire ropes which are only subjected to fluctuating loads and wire ropes which are continuously bent possibly combined with a tensile load. There are many parameters which determine the fatigue strength of wire ropes which are subjected to bending. A few parameters are the ratio between the sheave and wire diameter, the diameter of the wire rope, the groove radius, groove material, multi-layer spooling and the lubrication/lubricant of the wire rope. Müller is one of the researchers who performed very much research about the effect of different parameters onto the endurance of wire ropes bent over sheaves. He has finally shown that there exists an optimal wire rope diameter. Wiek emphasizes that wire rope fracture is caused in many cases not by fatigue, but it is a combination between wear, fatigue, destruction and corrosion. Because there are different factors which determine the endurance of wire ropes, it is very difficult to estimate in advance when to discard the wire rope. For example, wrong storage of the wire rope (before installation) can decrease the wire rope endurance significantly. It is therefore necessary that the wire rope is stored, installed and maintained according to the standards and rules. Subsequently the user is responsible for which discard criteria he uses. The standards give guidelines with respect to discarding a wire rope. The use of different non-destructive testing methods can help to assess the wire rope.

During the design of rope drives it is necessarily that the bending length, the load and the number of bending's are determined. Based on this information and the Dutch or European standards a good design can be made. Comparison between the standards and the theory shows clearly that the results of the experiments are included in the standards. Manufacturers of wire ropes have much experience to which wire rope type can be used for which application. Especially KISWIRE and CASAR give much information about this subject.

The last decennia there can be observed an increasing interest in the use of finite element modeling of the wire rope. The benefit of a finite element model is that this model takes into account the non-linear effects. As expected, the existing models and results of experiments are in agreement to the finite element models. There is one large disadvantage of modeling with FEM, you need many elements for an accurate FEM model of a wire rope. This results in a very long calculation time.