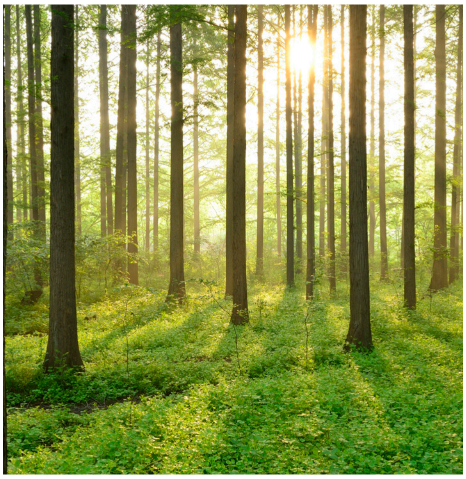
LONG TERM STABILITY OF TENDONS AND POST TENSIONING WIRES

REPORT 2016:244



NUCLEAR CONCRETE RESEARCH PROGRAMME

Energiforsk

Long term stability of tendons and post tensioning wires

Effect on relaxation and mechanical properties

STIG-BJÖRN WESTBERG, VATTENFALL RESEARCH AND DEVELOPMENT

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Foreword

The tendons and post tensioning wires are an important part of the design of the reactor containment. Material properties and structure of the wires and tendons change over time in a post tensioned design, and it is important to investigate the long term performance.

This project is based on a literature study and data from long term measurements from surveillance data from reactor containments in the nuclear power plants Ringhals and Forsmark. The steering group of the Energiforsk Nuclear Concrete research programme has had a dialogue with the author about the findings of the project, and it should be noted that the analysis and conclusions have been drawn by the author. Further research on this important subject is needed, and further projects on analyzing measured data from tendon tensioning force have been started within the project.

The study has been carried out within the Energiforsk Nuclear Concrete research programme, with the aim to initiate research and development that will contribute to a safe and cost effective long term operation of Swedish and Finnish nuclear power. The program is financed by Vattenfall, E.ON, Fortum, Skellefteå Kraft, Karlstads Energi, Strålsäkerhetsmyndigheten (SSM) and Teollisuuden Voima Oy (TVO).

Sammanfattning

BAKGRUND

Den svenska sammanfattningen tjänar förutom syftet att sammanfatta rapporten, också som en introduktion till rapporten som i övrigt är skriven på engelska. På grund av detta är den engelska och den svenska sammanfattningen olika långa.

Syftet med arbetet har varit att bistå med underlag till att besvara följande frågeställningar:

- Hur förändras struktur och egenskaper för stål som används för spännarmering över dess livslängd, och vilka är de mekanismer som orsakar förändringar?
- Finns det idag signifikant påverkan på specifika egenskaper såsom 0,2%-gräns, gränstöjning och värden från upprepade böjtester, och vilken påverkan kan förväntas i framtiden?
- Går det att utifrån stålens materialegenskaper att avgöra om det är problemfritt att återuppspänna spännstål, eller om det är bättre att återuppspänna till en lägre kraft än initialkraften?

Eftersom tidigare arbeten till övervägande del har varit inriktade på betongens egenskaper så är denna rapport inriktad på spännarmeringen och stålets egenskaper. Analyserna är gjorda utifrån antagandet att förlust av spännkraft enbart beror på stålets relaxation, dvs. den omgivande betongkonstruktionens krympning pga. t.ex. kristallisering bortses från. Detta antagande gör att resultaten skall ses som konservativa.

Arbetet baseras på underlag från:

- en inom ramen för arbetet genomförd litteraturstudie om långtidsegenskaper hos spänntrådar vid rumstemperatur,
- mätresultat som tillgängliggjorts av Forsmark och Ringhals, från fortlöpande inspektioner, och
- laboratorieprovningar vid Vattenfall Research and Development AB av spänntråd och lina som med tioårsintervall sedan tidigt 80-talet har tagits ut från Forsmarks och Ringhals reaktorinneslutningar.

Inom ramen för arbetet så har även en regressionsanalysmetod tagits fram för trendanalys av data från inspektioner av spännkabelkrafter.

I rapporten redogörs för sambandet mellan struktur och deformation. Vid både krypdeformation och relaxation sker deformationer genom termiskt aktiverade dislokationsrörelser. Vid elastisk deformation återgår belastade trådars längd till den ursprungliga efter avlastning. Plastisk deformation resulterar däremot i permanent formförändring. En spännkabels deformationsegenskaper kan testas genom mekanisk dragprovning som resulterar i en dragprovkurva över dragkraft och förlängning. Från kurvan erhålls värden för proportionalitetsgräns, maximal dragkraft och gränstöjning. Resultaten kan variera från provning till provning pga. att enskilda trådar kan har varit utsatta för något olika mekanisk belastningshistoria.

RESULTAT

Vid utvärderingen av de uppmätta kvarvarande spännkabelkrafterna visade sig mätvärdenas spridning vara av samma storlek som skillnaden mellan uppspänningskraft och minsta tillåtna kraft. Största förlusten av uppspänningskraft inträffar mellan uppspänningstillfället och första inspektionstillfället. Denna spännkraftförlust beror på att relaxationen är störst i initialt, att betongens bidrag till förlusten inte ingår och att de i kablarna ingående linorna har belastats olika vilket ger högre relaxationshastighet medan belastningen omfördelas.

Efter bortrensning av uppspänningskrafter så uppvisar endast ett fåtal av kabeltyperna påtaglig spännkraftförlust. Tydligaste förlust uppvisade samtliga spännkablar från Ringhals 2 och Forsmark 2.

Den mekaniska egenskap som har förändrats påvisbart är minskning av töjningsgräns för alla kablar i Ringhals 2. Orsaken till förändringen över tid av trådars egenskaper kan förklaras med kvalitetsskillnader, dvs. enskilda trådar eller trådleveranser för vilka egenskaperna förändras med tiden . Jämförelse av de uppmätta mekaniska egenskaperna visar att:

- Förändringen var liten eller osäker för proportionalitetsgränsen och maximal dragkraft. Det är i linje med vad som kan förväntas i och med att skulle en sådan förändring finnas så är den liten i förhållande till brottlasten vilket gör att den döljs av mätosäkerheten och spridningen i de uppmätta värdena.
- Fordran för gränstöjningen (3,5 %) överskrids i tidiga provningar med marginal, men avtar med tiden och ligger numera på eller under fordran. Tydligast är trenden för trådar från Ringhals 2, men även trådar från Forsmark 3 och Ringhals 3 visar minskande gränstöjning. Trådar tagna från Ringhals 4 har gränstöjning i närheten av fordran från början, men därefter har gränstöjningen inte förändrats.

FÖRSLAG TILL FORTSATT ARBETE

Kryptest med hög precision bör genomföras både på driftutsatta trådar och nya trådar för att skapa klarhet i vilken spännkraftförlust som kan förväntas i framtiden. Krypprovning kan betraktas som ett relaxationsförsök i vilket uppspänningskraften kontinuerligt justeras till den ursprungliga. Sådana test kan svara på frågor som:

- Hur stor deformation, översatt till kryp eller relaxation, finns det redan i tråden?
- Kommer kryp- eller relaxationshastigheten att öka eller minska med tiden vid ursprunglig kraft?
- Vad händer om en stabiliserad tråd av misstag råkar spännas till plastisk töjning?
- Finns det skillnader mellan trådar i kryp eller relaxationsbeteendet uttryckt som olika krypekvationer?

En fördjupad studie av de omspända kablarna rekommenderas för att utreda orsaken till de indikationer som finns från Ringhals 2-mätningarna av kvarvarande uppspänningskraft där effekten av återuppspänning går förlorad snabbare än förväntat.

Vid planering fortsatt arbete med bäring mot omspänning av kablar så rekommenderas att beakta att spridningen i kvarvarande uppspänningskraft kan vara stor, och att omspänningen därför endast görs på kablar med låg uppmätt uppspänningskraft (dvs. inte alla kablar av ett visst slag). Eftersom trådar redan kan ha deformerats permanent genom relaxation och vissa eventuellt mer än andra så finns det viss risk att en omspänning inte ger den lilla relaxation som man skulle kunna förvänta sig vid omspänning av en enskild tråd under väl kontrollerade förhållanden. Relaxationshastigheten skulle då kunna vara väsentligt högre, där vissa trådar skulle kunna komma upp i hög dragkraft eller motsvarande deformation, med som resultat oväntat hög spännkraftförlust efter omspänning. Vid omspänning bör därför inte ursprunglig spännkraft eftersträvas utan till exempel någon som motsvarar den som uppmättes vid första inspektionen.

Summary

The scope of the project covers finding answer to the following questions:

- How does the material structure and properties change with the long times involved and what are the mechanisms, which causes the changes;
- Has the properties of the steel, such as 0,2 % limit, elongation limit, repeated bending test values etc. changed in a noticeable way and what can be expected in the future;
- Is it from the tendon materials characteristics possible to carry out a re-tensioning of the tendons without problem or is it desirable to re-tension to a lower force than the initial?

The scope covers finding ways to present and analyse the data from the measurements of the tendon forces from all the containments, and when that was made.

This project is focused on collation of experiences and finding out what can be found using the tendon materials data already available. The steel tendons are stressed to high loads in post tensioning and are therefore prone to relaxation. The project assumes that the loss of tensioning force is a result of relaxation of the steel only. This means that the shrinkage of the concrete due to processes such as crystallisation of new phases and drying is excluded. The consequence is that the results should be considered as being on the conservative side.

Since the beginning of the 1980ies, Vattenfall Research and Development AB has performed laboratory testing of post tensioning wires, which has been removed from the containments of the reactors at Forsmark and Ringhals. The tests have been repeated approximately every tenth year for each containment, in order to verify that the wires still met the initial requirements.

Collation of measurements through the years, especially for the Ringhals 2, has led to the suspicion that the fracture elongation tends to increase simultaneously as the 0,2 limit and fracture strength may have increased. Measurements on site of the remaining tensioning force have shown that the force in some of the tendons is near 80 % of the initial tensioning force. This is a deviation, which should be followed up specifically for Ringhals 2, but the phenomenon as such is as well of interest for reactor containments in general.

A literature study has been made and the measurements of remaining tensioning force made on site has been used to find out something about what is to be expected in the future. Very little can be found in the literature concerning long term properties but by using data from previous measurements of the mechanical properties, it is found that the elongation limit of some of the tendons is decreasing. The differences in the other two mechanical properties; yield force and maximum force, are too small to be verified. The study of the remaining tensioning force revealed that the only tendons as a group to lose tensioning force pronouncedly are the horizontal tendons of Forsmark F2 and all tendons of Ringhals R2.

When re-tensioning is carried out it may be a good idea to put spacings only on those tendons on which a low tensioning force has been measured. There is otherwise a risk of stressing the tendon to a larger force than the initial with rapid loss of tensioning force, the first time after the re-tensioning. Over-tensioning may plasticise the wire and thereby impair the relaxation properties.

List of content

Energiforsk

1 Introduction and background

1.1 INTRODUCTION

Since the beginning of the 1980ies, Vattenfall Research and Development AB has performed laboratory testing of post tensioning wires, which has been removed from the containments of the reactors at Forsmark and Ringhals. The tests have been repeated approximately every tenth year for each containment, in order to verify that the wires still met the initial requirements. Collation of measurements through the years, especially for the Ringhals 2, has led to the suspicion that the fracture elongation tends to increase simultaneously as the 0,2 limit and fracture strength may have increased. Measurements on site of the remaining tensioning force have shown that the force in some of the tendons is near 80 % of the initial tensioning force. This is a deviation, which the owner of Ringhals 2 is managing, but the phenomenon is of interest when other reactors are concerned.

Some work has been carried out previously concerning the loss of tensioning force and the role of the concrete structure together with the tendons, /1//2//3/. The purpose of the post tensioning tendons is that the tensioning system is designed to counterbalance the tensile forces from the design pressure. There are two different tensioning systems in use, the BBRV[1]-system and the VSL[2]-system /3/. The tendons in the BBRV-system consist of a large number of single wires and are used in Ringhals 2 to 4 and Forsmark 3. The tendons in the VSL-system consist of a number of strands, which are stretched by pulling directly in the strands and are used in Forsmark 1 and 2.

1.2 SCOPE

The scope of the project covers finding answer to the following questions:

- How does the material structure and properties change with the long times involved and what are the mechanisms, which causes the changes;
- Has the properties of the steel, such as 0,2 % limit, elongation limit, repeated bending test values etc. changed in a noticeable way and what can be expected in the future;
- Is it from the tendon materials characteristics possible to carry out a re-tensioning of the tendons without problem or is it desirable to re-tension to a lower force than the initial?

The scope covers finding ways to present and analyse the data from the measurements of the tendon forces from all the containments, and when that was made.

1.3 INCLUDED

This project is focused on collation of experiences and finding out what can be found using the tendon materials data already available.

Included is a review of a large number of documents from both Forsmark and Ringhals that have been made available to the project.

[1] System named after the developers Birkenmaier, Brandestini, Ros and Vogt
[2] Vorspann System Losinger

Included is also a literature survey of pertinent data bases and material from search on the internet and Vattenfall Research and Development AB:s reports.

1.4 EXCLUDED

The steel tendons are stressed to high loads in post tensioning and are therefore prone to relaxation. The project assumes that the loss of tensioning force is a result of relaxation of the steel only. This means that the shrinkage of the concrete due to processes such as crystallisation of new phases and drying is excluded. The consequence is that the results should be considered as being on the conservative side.

Excluded are experimental details, but such work could be part of a follow-up study.

Excluded are conclusions on the impact that the long-term stability of tendons would have on reactor containments, since such would need taking into account other influencing factors but the relaxation of the steel.

2 The metallographic background

Post tension wires are made of carbon steel, which is treated thermally, and mechanically in order to obtain the desired low relaxation and low creep rates. This section contains a short version of the metallography, which is needed for some understanding of the relaxation process.

As is understood from the designation carbon steel, these steels contain iron (chemical designation Fe) and carbon (C). They may also contain minute quantities of other elements, which have specific effects during the thermal treatment. The mixing of carbon in an iron melt result in homogenous solution of carbon in the iron, but during cooling the steel (Fe+C) behaves in a way which from the beginning may not appear to be logical. The steel first solidifies to austenite, still with a homogenous distribution of carbon in the austenite grains. As the steel cools, ferrite grains begin to form and they keep growing and increasing in number. Ferrite in contrary to austenite can only dissolve minute quantities of carbon and therefore the carbon content increases in the austenite grains as more and more of the structure is made of ferrite. At the temperature 738 °C, the remaining austenite, which now contains 0,8 % C transforms; but not to ferrite, which is unable to dissolve the carbon. Instead it transforms into another structural constituent called pearlite. The pearlite grains consist of ferrite and a compound of iron and carbon called cementite (Fe_3C). The cementite is distributed in the shape of colonies of parallel plates.

Figure 2.1 is of a ferrite – pearlitic microstructure. Each white or dark area is a grain, surrounded by a grain boundary. The ferrite is white and the pearlite dark, because the distances between the lamellas of the pearlite are too small to be resolved under the optical microscope.

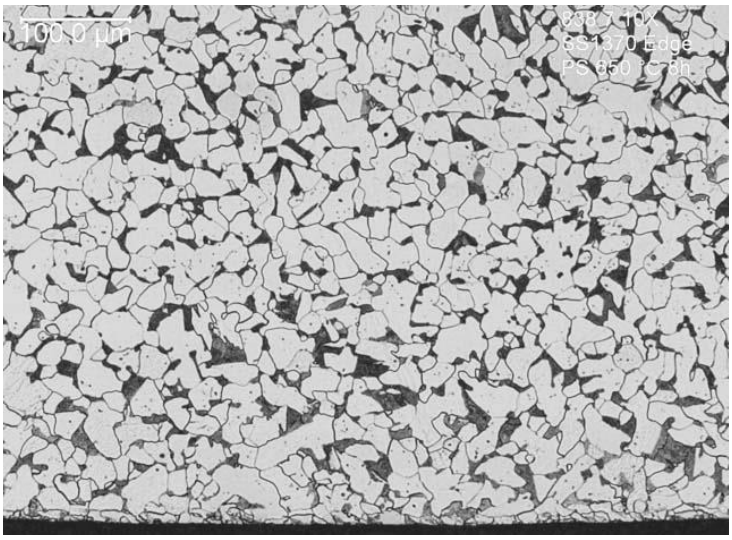

Figure 2-1 Ferrite-pearlite microstructure with approx 20 % pearlite (dark areas) / 4 /.

The hardness and strength of the carbon steels increases with increasing carbon content, as now can be understood, by the increasing amount of pearlite in the microstructure. The carbon content must however be below 0,8 %, otherwise the cementite forms grains by itself and the pure cementite is brittle. Therefore, if higher strength is needed it has to be achieved by some other means. One way of doing this is to cool the steel more rapidly. By doing so the pearlite becomes finer which increase the strength.

A process called patenting is often used for wires, whereby the wire is heated in a furnace and rapidly quenched in a bath of air (in earlier days molten lead) resulting in an extremely fine pearlite. The wire is thereafter drawn through dies with smaller and smaller holes until the right diameter is obtained. The drawing destroys the original structure, but increases the hardness due to deformation, which in turn increases the dislocation density (figure 2.2). Post tensioning wires are often heat treated to reduce the relaxation rate by stabilization, whereby the wire is rapidly heated to a relatively low temperature for an as short time period (0,5 – 2 s) and then cooled (figure 2.3. The difference in stress-strain behaviour is explained as differences in the distribution of residual stresses over the cross section /5/, but it is the author’s opinion that other mechanisms may be involved.

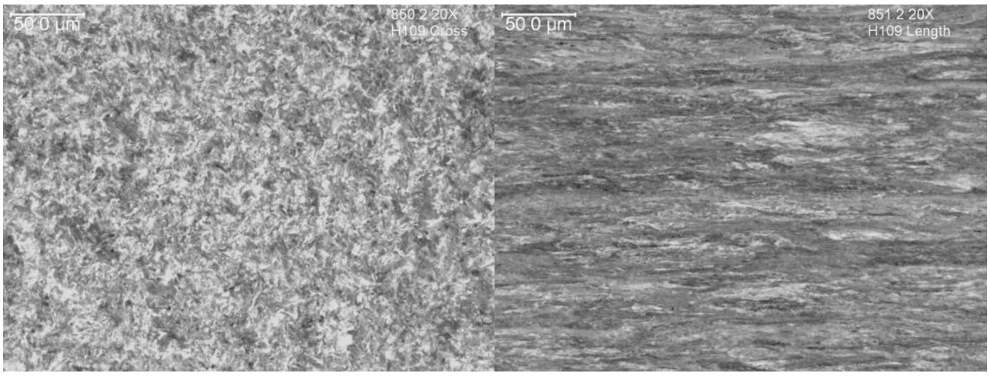

Figure 2-2 Cross sectioning to the left and longitudinal sectioning of fabricated post tensioning wire at high magnification. Nothing remains of the original microstructure /4/.

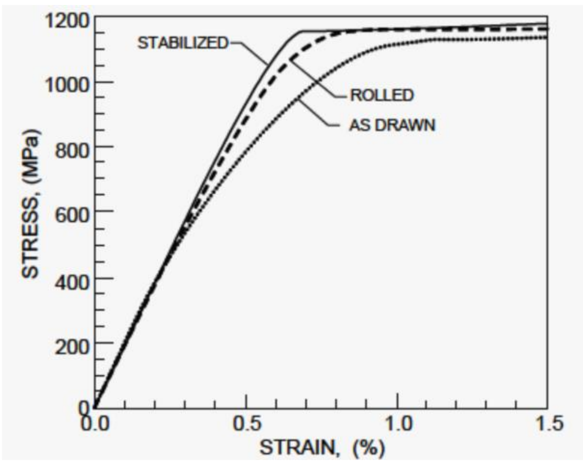

Figure 2-3 Difference in stress-strain behaviour for different treated wires /5/.

2.1 THE DEFORMATION OF STEEL

There are basically two different types of deformation; elastic and plastic. Elastic deformation means that the object or as in this case the wire elongates linearly in proportion to the stress according to Hookes law $\sigma = E*\varepsilon$. where σ is the stress and ε is the elastic strain. The proportionality constant E is called elastic modulus or Youngs modulus depending on the circumstances. The elongation is not permanent and disappears on off-loading. This type of deformation makes common springs work. Plastic deformation is a permanent deformation under load and remains after off-loading. Plastic deformation is brought about in wire drawing, rolling, deep drawing of plates, stamping of coins etc. In a common tensile test of post tensioning wires, the two regions are easy to identify, see figure 2.4. Note that the vertical scale is in the applied force and not the stress, but they are in this case interchangeable. When the strand is tensioned in use, the applied force is often around 70 % of the rated fracture strength or approximately 125 kN for the wires in the figure. This is at a smaller force than a one that causes plastic deformation.

A closer look at the region with elastic deformation reveals that the plotted line is not perfectly straight even if it is close to being that. The slight curvature during loading is largely due to creep at high stress and pure creep is one extreme of two time dependent deformation processes. The other one is pure relaxation. The following is an attempt to explain what is happening in the steel during plastic deformation.

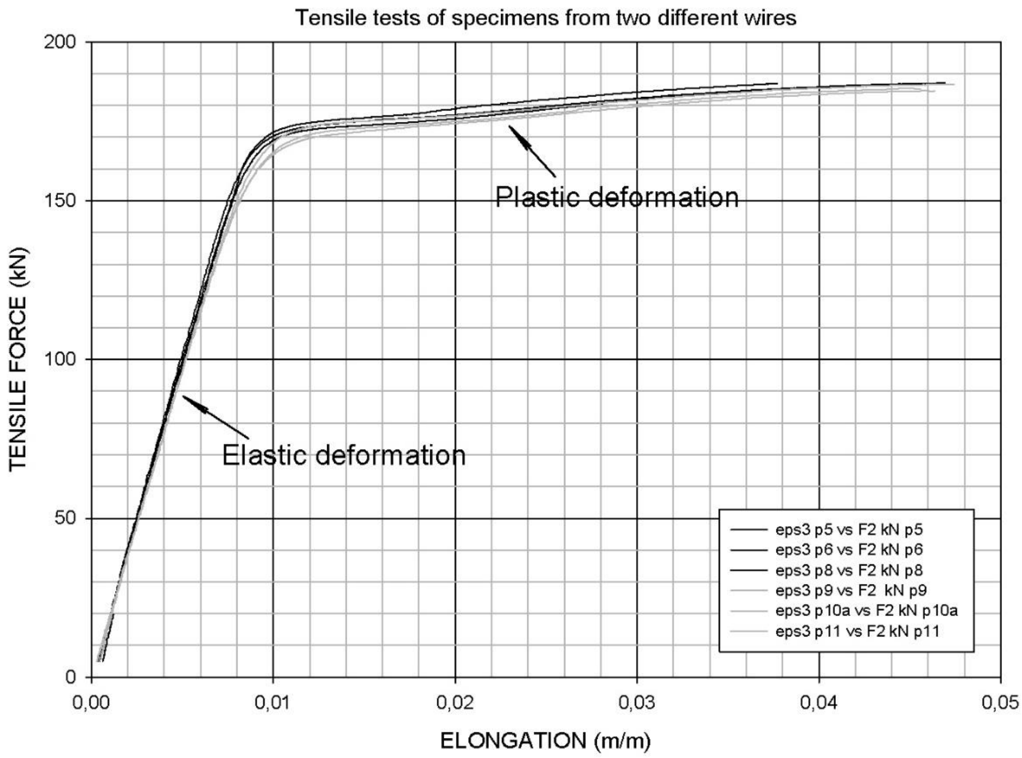

Figure 2-4 Force-elongation graph showing the relationship between applied force and elongation (strain)/4/.

In the crystal structure there are types of faults, which are called dislocations and they have to be there due to thermodynamic reasons, even though the amount is influenced by heat treatment and deformation. The easiest dislocation to understand is probably the edge dislocation, see fig 2.5. The edge dislocation is an atomic plane, which lacks continuation. Due to the elastic stresses from the disturbance of the atomic positions large force fields are generated around the dislocation. Much less force is needed to move the dislocation one atom position than to move all atoms simultaneously one position in a crystal plane. Figure 2.5 also shows a dislocation movement due to shear stress. Whenever a dislocation has passed completely through a grain, it is deformed the minute distance of an atomic spacing. So, the dislocation goes all the way through the grain and the grain is deformed. A dislocation can easily be moved almost without resistance. Other dislocations, stress fields from dissolved foreign atoms, particles, grain boundaries etc. are obstacles to the movements. Increasing temperature decreases the energy barrier for dislocation movements; this is called thermal activation. All plastic deformations in steel, including relaxation, with the exception of brittle fracture involve dislocation movements en masse.

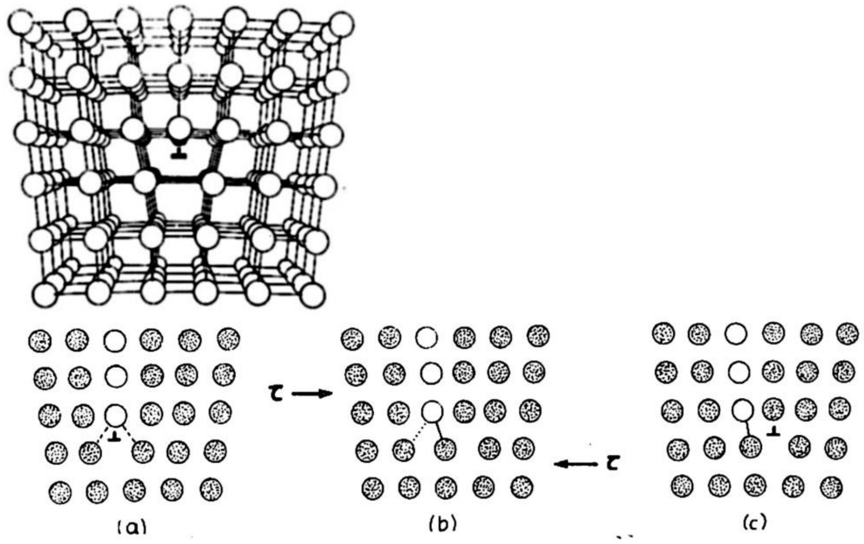

Figure 2-5 Edge dislocation in the crystal (top). Movement of the edge dislocation under applied shear stress (bottom) /6/.

2.2 CREEP AND RELAXATION

Creep is defined as elongation under constant load and relaxation is defined as loss of stress during constant elongation. The mechanisms for creep and relaxation in the material are the same and depend on the previously described thermally activated dislocation movements, with some differences.

Creep is the elongation during constant load or stress often during moderate loads, such as 20 – 40 % of nominal tensile strength. There are three stages of creep (figure 2.6). The primary stage is characterised by a continuously decreasing creep rate, the secondary stage by a more or less constant creep rate and the tertiary stage by an increasing creep rate.

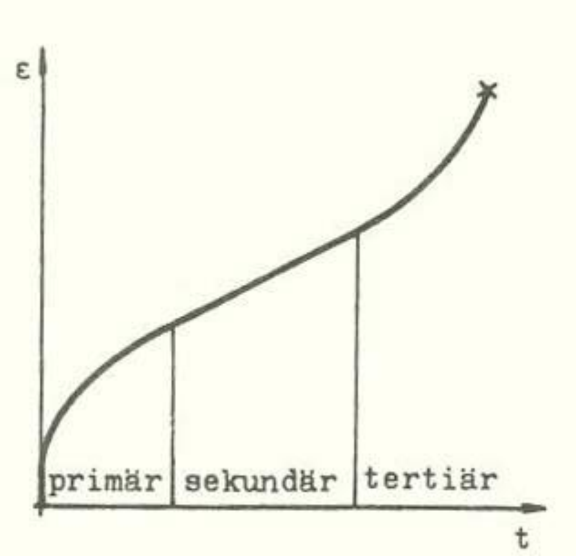

Figure 2-6 The three different stages of creep. The figure shows high temperature creep, which is the most commonly treated case in the literature. At lower temperature, there may not be a tertiary stage/6/.

The models can be described using mathematical formulas. The elongation in the first and second stage is according to the formulas $\varepsilon = a*\log t$ (logarithmic creep), where "t" is the time and "a" is a constant, or $\varepsilon = a*t^b$ (power law creep). Figure 2.7 is an example of the results from a precision measurement of creep of an aluminium alloy overhead conductor, measured at room temperature and 40 % of the rated tensile strength. The creep in this case is according to the power law creep equation.

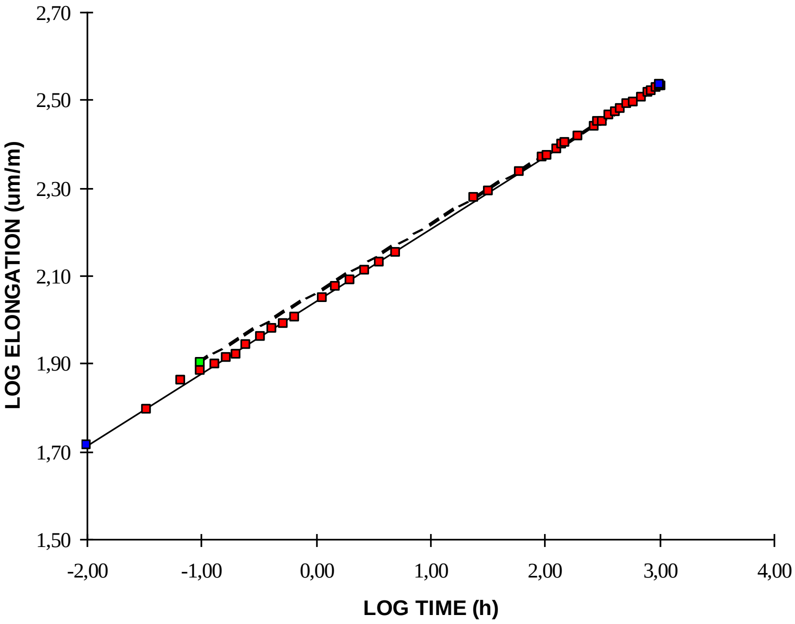

Figure 2-7 Precision creep measurement of an overhead conductor, showing the usefulness of logarithmic scaling /4/.

With relaxation is understood the loss of tensioning force during constant elongation, often during high loads, such as 60 – 80 % of nominal tensile strength. Contrary to creep, no stages are mentioned in the literature but both equations are used as for creep:

R = a*log t

R = a*t^b

Where "a" and "b" are constants

The logarithmic equation gives a linear relationship between linear force, or relaxation and the logarithm of time (see fig 2.8). It is always decreasing. The power law equation gives a linear relationship between the logarithm of force or stress and the logarithm of time. Depending on the constants it can be either increasing or decreasing. When relaxation data are presented it appears that the power law equation is preferred, see fig 2.9.

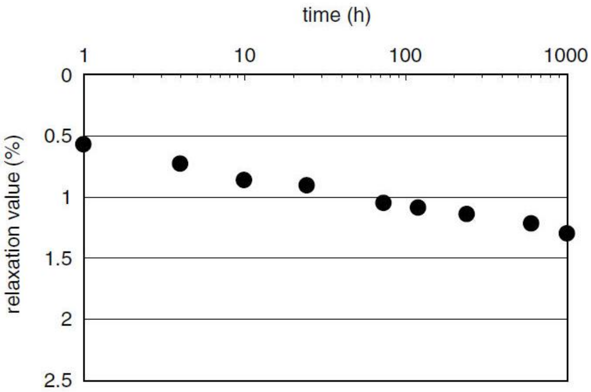

Figure 2-8 Relaxation test results for USP strand. The authors of this paper have used lin-log scaling in this relaxation plot/7/.

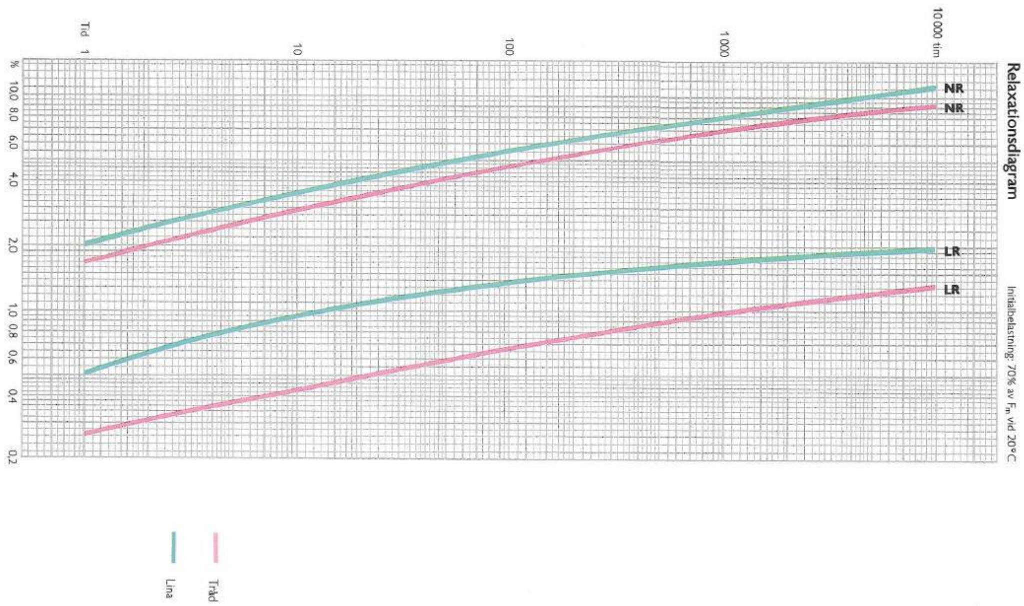

Figure 2-9 Log-log graph of the relaxation of post tensioning wires. The curves are calculated so no measurements are plotted/8/.

A relaxation loss of force of 10 % does not mean that the wire has become 10 % longer. The total region of the elastic elongation is only 0,5 – 1 % of the total length of the sample. A relaxation of 10 % therefore corresponds to a much smaller elongation than that. Using the results from tensile testing, it is found that with fracture strength of 50 kN, 10 % loss corresponds to the elastic elongation at 0,7*0,1*50=3,5 kN, i.e., an elongation less than 0,07%.

It was mentioned earlier that the mechanisms for creep and relaxation are thermally activated, which means that the rate of creep or relaxation changes rapidly with temperature. Figure 2.10 shows the simultaneous effect of initial load and temperature. The relaxation curves for 20 °C has a marked knee at 80 % load, where relaxation rate increases rapidly. The position of the knee shifts to lower load for higher temperatures because the increasing temperature means that less stress is needed to activate the new high relaxation rate process to the right in the graph.

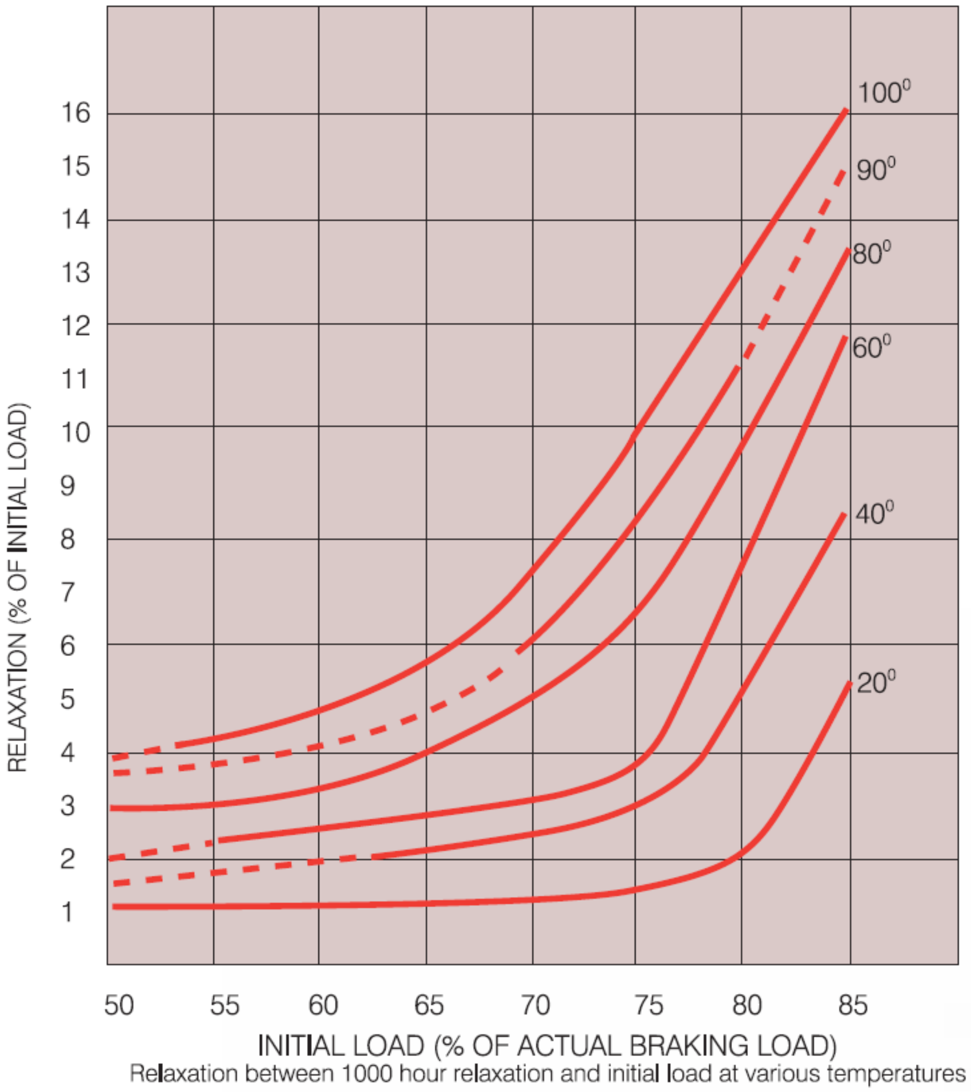

Figure 2-10 The figure shows the relationship between the three parameters relaxation, initial load and temperature for a low relaxation strand/9/.

2.3 RE-TENSIONING

When re-tensioning is carried out it may be a good idea to put spacings only on those tendons on which low tensioning force have been measured. There is otherwise a risk of stressing the tendon to a larger force than the initial with rapid loss of tensioning force, the first time after the re-tensioning.

This is pointed out in reference /10/ from which the diagram in figure 2.11 is taken. Over-tensioning may plasticise the wire and thereby impair the relaxation properties. If it on the contrary, would have been beneficial for the relaxation properties, the wire producer would already have used the method.

Initial Jacking Force (kips)	Initial Percent of Ultimate Load (%)	Residual Load at 72 Hours (kips)	Percent Stress Loss At 72 Hours (%)
34	82.3	26	23.5
28	67.8	27	3.6

Figure 2-11 The effect of overstressing according to ref. /10/.

3 Evaluation of loss of tensioning force

3.1 SOURCES OF LOSS OF TENSIONING FORCE AT SYSTEM LEVEL

There are two main sources of loss of tensioning force during the lifetime of the confinement. Even though the concrete is not tensioned during the first year, processes such as crystallisation of new phases and drying may result in some shrinkage of the concrete. The steel tendons are stressed to high loads in post tensioning and are therefore prone to relaxation.

The observed relaxation in post tensioned concrete can be divided into two major components; the relaxation of the steel tensioning wires and the shrinkage of the concrete. The major contributor to the shrinkage of the concrete is drying shrinkage, which is a process by which the cement past loses water to the surrounding /11/ /12/. The process may continue for many years depending on the thickness of the concrete, temperature and humidity /13/. The major drying shrinkage takes place during the first years and may continue for many years /13/. The two most important properties of the concrete which affects the drying shrinkage are the water content and the aggregates. The total drying shrinkage is probably due to the common character seldom discussed in the literature, but some values can be obtained from sources such as internet, Wikipedia organization information and company information and reports discussing other topics. The drying shrinkage is according to these in the range of 0,2 – 0,5 mm/m /14/.

An estimate of the importance of the drying shrinkage can be made by assuming that at least one third of the shrinkage has taken place before the tensioning is applied and the final shrinkage is in the lower half of the interval. The remaining shrinkage will then be 2/3 of 0,3 mm/m = 0,13 mm/m.

For a steel wire the elongation at 70 % of the fracture load is approximately 0,7 %. The length change due to the shrinkage of the concrete will equal 0,013 % of the length of the tendon. This means that the remaining stress in the tendon will be 70 – 1,7 = 68,3 % of the fracture load of the tendon. It is therefore uncertain which the sources to small differences in the measured tensioning forces are.

Examples of non-major processes contributing to the loss of tensioning force are thermal effects and settlement in the fixtures of the tendons, and redistribution of load between the individual strands by higher relaxation rate in the most strained ones.

The relaxation component of the measured reduction in tensioning force due to the steel cannot within this project be separated from other components. The obtained reduction in tensioning force is therefore a sum of contributing processes, i.e., the different influencing components are not possible to separate without using force data only.

In the following the loss of tensioning force is treated as a result of relaxation of the steel only.

3.2 ASSESSMENT OF TENSIONING FORCE OF TENDONS

The tensioning force of the tendons are measured first at the installation of the tendons and thereafter are the tensioning force measured on some of the tensioning tendons in several years interval. The tendons tested are different each time so that there is no tendon on which the relaxation has been re-measured more than once but after different time after installation. In some cases openings have been made in the containment and the tendons reinstalled and re-tensioned.

The force is measured using a hydraulic jack, which lifts the anchor-plate and when the plate lifts, the slope of the relation between force and displacement changes. The force at which this happens is determined from the set of force and displacement data.

The hydraulic jacks used for this operation are calibrated within 2 % of the applied force. There are however several sources of error, such as friction and deformation of the concrete.

3.3 ANALYSIS OF TENSIONING FORCE DATA FROM FORSMARK AND RINGHALS

Miss Johanna Spåls at Ringhals and Mr Lars-Erik Berglund at Forsmark have supplied most of the tensioning force data for this analysis. In addition, results have been used from prior investigations available at the laboratory Älvkarlebylaboratoriet[3].

Data from three sets of tendons; vertical horizontal and dome are compared with each other as well as the same type of tendons from other containments. Dot plots are used for exploratory data analysis (EDA) purposes, which give a presentation that is visually easy to interpret. The single dot plot shows the amount of data points, the symmetry of the distribution and how large the scatter is. When more than one dot plot is presented in the graph, the data is easily compared in a way which is easy for the reader to understand.

The widely used standard deviation is purposely avoided when possible. The standard deviations sometimes used in a routine fashion, even when testing of hypotheses is not intended or even possible. The major obstacles for a meaningful statistical analysis are the small and varying number of observations and what appears to be the case – the variation in the width of the scatter. The standard deviation is also influenced by happenstance data and there is a risk that the large scatter is bigger than the prediction.

When many points are plotted, it is not possible to separate all dots. Therefore, the sample size n is usually stated for each set of measurements.

The initial tensioning forces for each of the containments are plotted in the first graph (see for example Figure 3.2). The procedure of tensioning the tendons is to load the tendons, lock them and release the hydraulic jack, after which some rapid settlement takes place in grips and other loaded parts. The initial scatter is therefore much larger than the 2 % the hydraulic jack is calibrated within. An error in the calibration will not affect the scatter, but it will instead introduce a systematic bias on all values.

Other sources of scatter are the determination of the discontinuity point on the measured force – displacement relationship, which marks the tensioning force of the tendon, friction, and movements of the tendon. The accuracy and repeatability of the complete measurement has not been found.

[3] For details on data source, contact that the author.

The graphs that follow are ot plots of the remaining force in % of the initial force of the tendon plotted along the Y-axis and the measurement as group plotted along the X-axis (see for example Figure 3.3). This means that the different measurements are evenly spaced along the X-axis, regardless of when the measurement actually was made. Each dot represents the measured remaining force at the inspection expressed as percent of the initial force. The initial force is automatically excluded from the graph, because it will always be 100 %. The different types of tendons; vertical, horizontal and dome are plotted in individual graphs.

In the graphs it is easy to see the differences between different measurements and if those differences are obvious or not as well as their relation to the scatter. Due to simple chance, a measurement on few tendons may result in values falling closer to each other than a measurement with a larger number of values. This is sometimes referred to different effects of happenstance data.

In the reports concerning the containments/1//2//3/, the lowest acceptable remaining tensioning forces have been calculated. These values, when compared to the initial tensioning force represent approximately 82 % of the initial tensioning force. It is therefore of interest to see if there is a tendency for the remaining tensioning force of the group of tendons to fall to the vicinity of 82 % in the near future.

3.4 METHOD FOR TREND ANALYSIS OF DATA FROM TENSIONING FORCE MEASUREMENTS OF TENDONS

A method was developed to enable trend analysis of the tensioning force data of tendons. Being the first of the reactors studied, the containment of reactor 2 at Ringhals was studied more extensively than the containments of the other reactors.

The mean values of tensioning force data were obtained by calculating the mean of the individual percent losses for each measurement occasion. This reduces the variance of the mean values, compared to first adding the individual values and then subtracts the means.

Regression analysis was performed by fitting a line to the obtained means. The distance between the observation and the fitted line, the residual, is sometimes understood as measure of the systematic deviation of the individual observation or error of the model if the residuals vary systematically. The standard deviation of the means, the standard errors, are around 1 % and can therefore explain the major part of the scatter of the mean values around the regression line. Treatment of variances etc was omitted on purpose (see Appendix 1). Only the regression line will be plotted, but it must be remembered that it may not be a perfect representation.

The regression should be made and displayed using log-log scaling on the x and y axis for the analyses. The x-axis displays time as log (hours) from the initial tensioning. A shortcut is to only use the year for the inspection and subtract the year for the initial tensioning and transform the difference into hours. The error introduced by this process is small in comparison to other errors.

The drawback of using logarithmic scales is that the time-scale of the graph is difficult to comprehend.

3.5 EVALUATION OF TENSIONING FORCE DATA FROM RINGHALS 2

3.5.1 Remaining tensioning force

The scatter of the initial tensioning force is considerable, but no systematic differences are apparent between the three different groups of tendons, see figure 3.1. The maximum difference of the values is 13 % of mean for the dome tendons. This means that the scatter is of the same size as the distance to the lower limit for the measured tensioning force see figure 3.2. The sizes of the groups, *n* which represents the number of tendons in the graphs, are very different for different types of tendons.

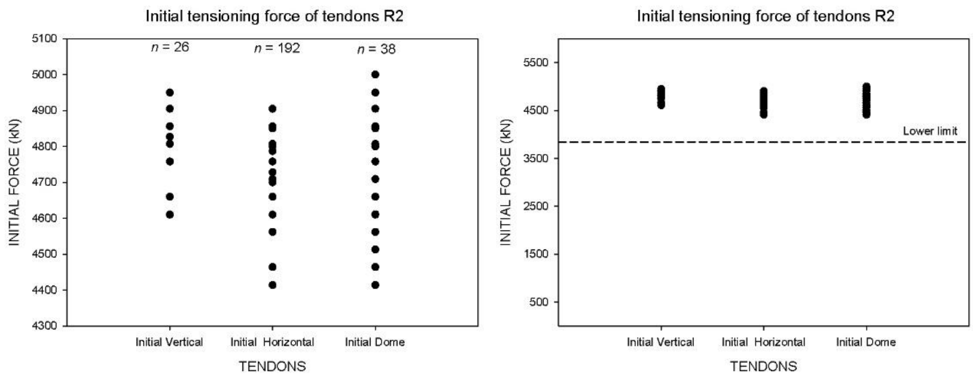

Figure 3-1 Dot plots of the initial tensioning force for the three types of tendons. The distance in force between the initial tensioning force and the lowest accepted limit is shown in the right graph.

The dot plots of the remaining force of the vertical tendons are shown in figure 3.2. Most of the loss of tensioning force takes place during the first two years, after which the mean force of the tested tendons is 88 % of the initial. There is a tendency of losing a further 5 % until present. The tendons were re-tensioned 1989 due to exchange of the steam generator and it resulted in some increase of the tensioning forces. As for the vertical tendons most of the loss in tensioning force of the horizontal tendons takes place during the first two years, with 86,4 % remaining 1975. Another 3 % may have been lost until present, but the tendency is not immediately apparent and the variation is much larger than the difference.

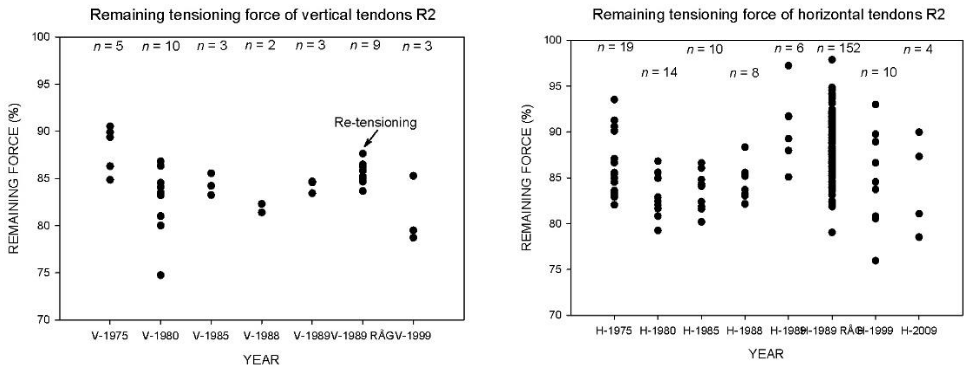

Figure 3-2 Remaining force of individual vertical and horizontal tendons. The re-tensioning 1989 resulted in some increase in tensioning force in both vertical and horizontal tendons.

The dot plots of the remaining force of the dome tendons are shown in figure 3.3. As for the vertical tendons most of the loss in tensioning force takes place during the first two years, with 90 % remaining 1975. Another 6 % have been lost until present according to the mean values. No tensioning loss is apparent after 1980.

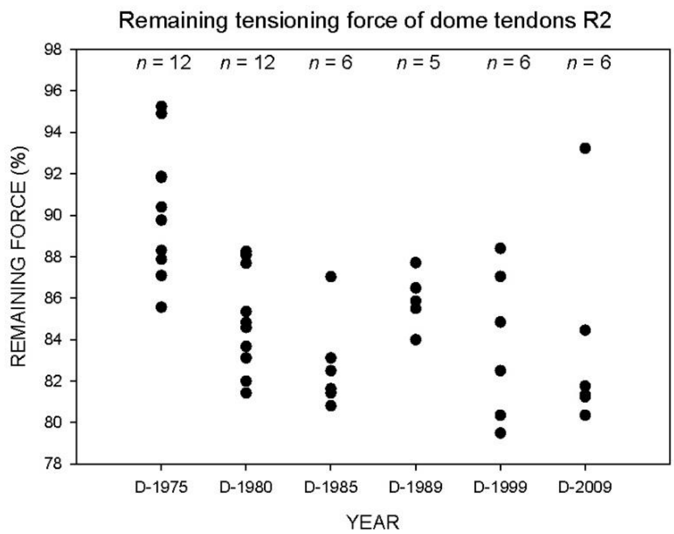

Figure 3-3 Remaining tensioning force of individual dome tendons. Re-tensioning was not carried out so no increase in tensioning force can be seen.

3.5.2 Prediction of relaxation based on trend-analysis

The mean values for the three different sets of tendons are shown to the upper left in figure 3.4. In this graph, the difference between the initial tensioning force and the rest of measurements is very obvious. The re-tensioning of the tendons, which took place in 1989 may have increased the remaining force by up to 5 percentage units. The results of the regressions in the other graphs of the same figure can be seen in table 3.1. The re-tensioning was carried out on vertical and horizontal tendons. All three regression lines have a small negative slope, which indicates that tensile force is lost over time. The remaining tensioning force data from three different sets of tendons were evaluated by linear regression.

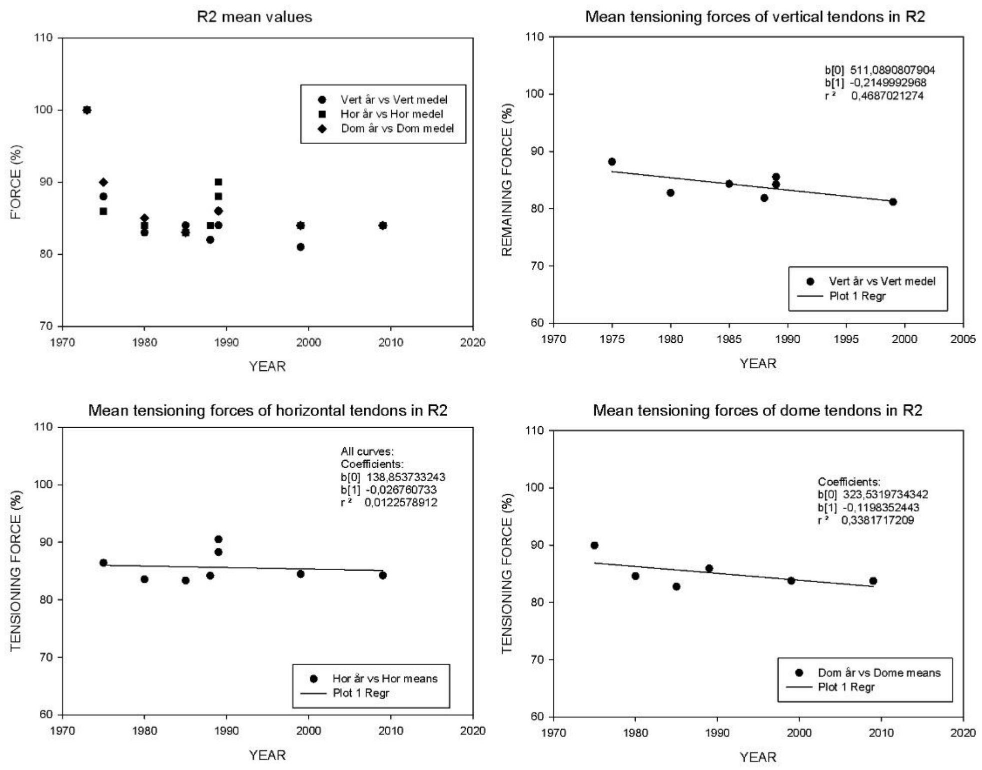

Figure 3-4 Clockwise from upper left: All mean values of the remaining tensioning force for the tendons in Ringhals 2, regression using a lin-lin graph for vertical, dome and horizontal tendons respectively.

Table 3-1 Linear regression to the formula y = b(0) + b(1) · x for prediction of relaxation.

	Intercept	Slope	Calculated force (%)	
Tendon	**b(0)**	**b(1)**	**2030**	**2050**
All measurements, linear plot				
Vertical	511,1	-0,215	74,6	70,3
Horizontal	138,9	-0,02676	84,5	84,0
Dome	323,5	-0,1198	80,3	77,9
Year 1989 values exempted				
Vertical	572,6	-0.2463	72,7	67,8
Horizontal	131,3	-0,02360	83,4	83,2
Dome	322,3	-0,1193	80,1	77,8
Log-log plot				
Vertical	2,074	-0,03096	79,0	78,3
Horizontal	1,963	-7,329E-3	83,4	83,2
Dome	2,049	-0,02416	81,6	81,0
Only un re-tensioned tendons				
Vertical	2,069	-0,02979	79,3	78,6
Horizontal	2,037	-0,02379	79,8	79,2
Dome	2,049	-0,02416	81,6	81,0

Removing the re-tensioning of 1989 does not reduce the scatter, see figure 3.5. The last values after 1989 are in fair agreement with the values obtained before 1989 and can therefore be a sign of renewed rapid loss of tensile force.

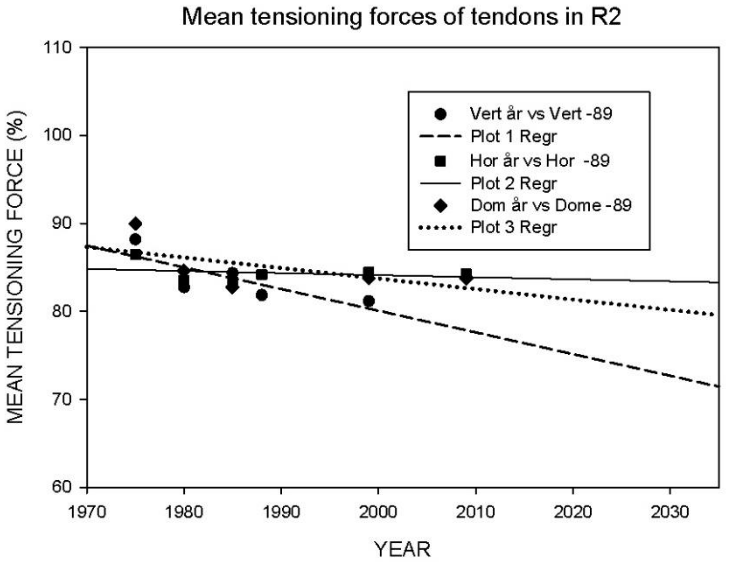

Figure 3-5 All three regressions in one graph with the 1989 observation of re-tensioned tendons removed plotted in linear scale. The largest slope can be found for the vertical tendons.

The graphs were made into log-log graphs according to one of the relaxation models, see fig 3.6. This time the results are more coherent. Finally log-log diagram of the tendons, which had not been re-tensioned, were made, see figure 3.7. The results of this analysis is somewhat unexpectedly in agreement with the re-tensioned tendons, see table 3.1.

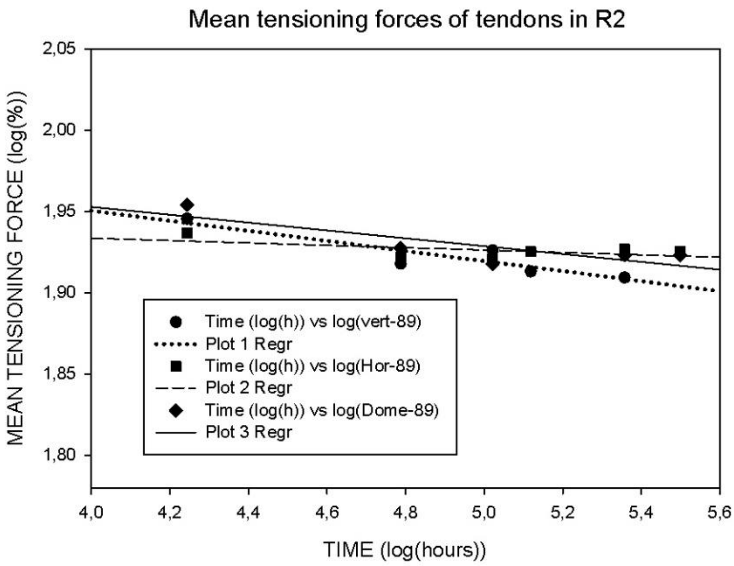

Figure 3-6 Plot of remaining tensioning force for all the three sets of tendons with the 1989 observations removed.

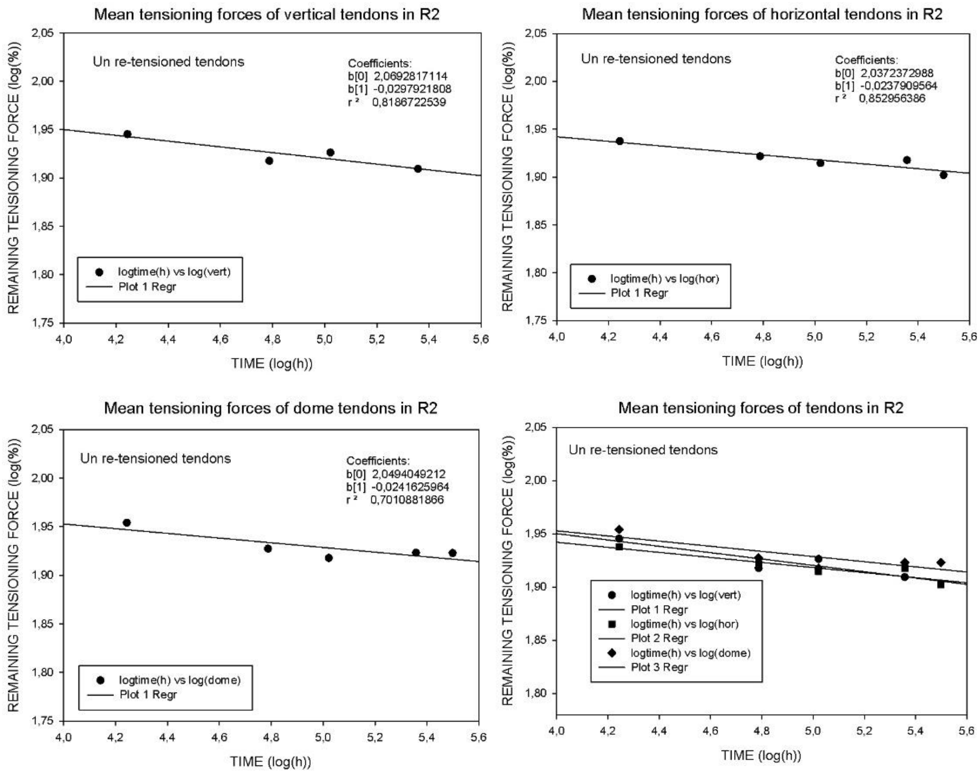

Figure 3-7 Linear regression of the un-retensioned tendons of Ringhals R2 plotted in log-log scale.

3.6 EVALUATION OF TENSIONING FORCE DATA FROM RINGHALS 3

The initial tensioning of the horizontal tendons were the largest and varied between 4611 and 5003 kN, which is 8 % of the mean value.

Larger scatter is found for the re-tensioned REX-horizontal tendons for which the scatter was 15 % and the measured forces varied between 4202 kN and 4871 kN, see figure 3.8. The scatter of the re-tensioning — REX in the figure — was at least 50 % larger than for the original tensioning. One very low observation of 4113 kN was found among the vertical re-tensioned tendons.

Approximate values for the limit forces in % were calculated using the mean of the tensioning force. The distance to the limit is of the same proportion as the scatter of the individual values.

The remaining tensioning force in all three groups of tendons shows little or no relaxation after the initial loss of tensioning force. Instead all measurements indicates that it within the limits of the measurements remains between 90 and 95 % or the initial tensioning force, see figure 3.9.

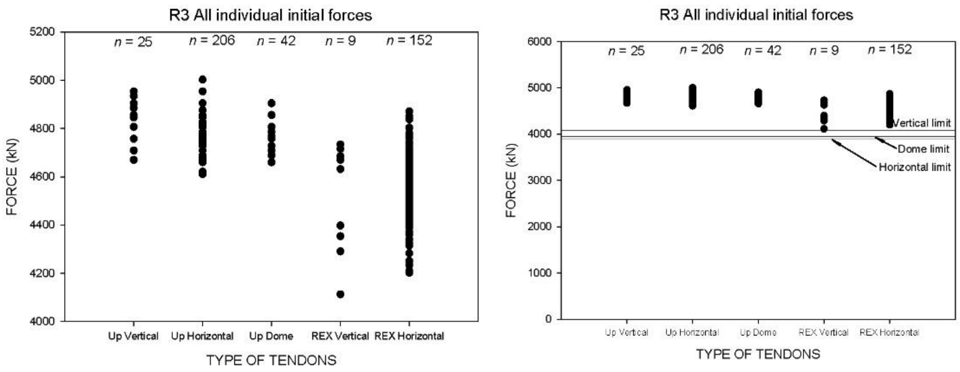

Figure 3-8 Initial tensioning forces of the tendons in Ringhals R3.

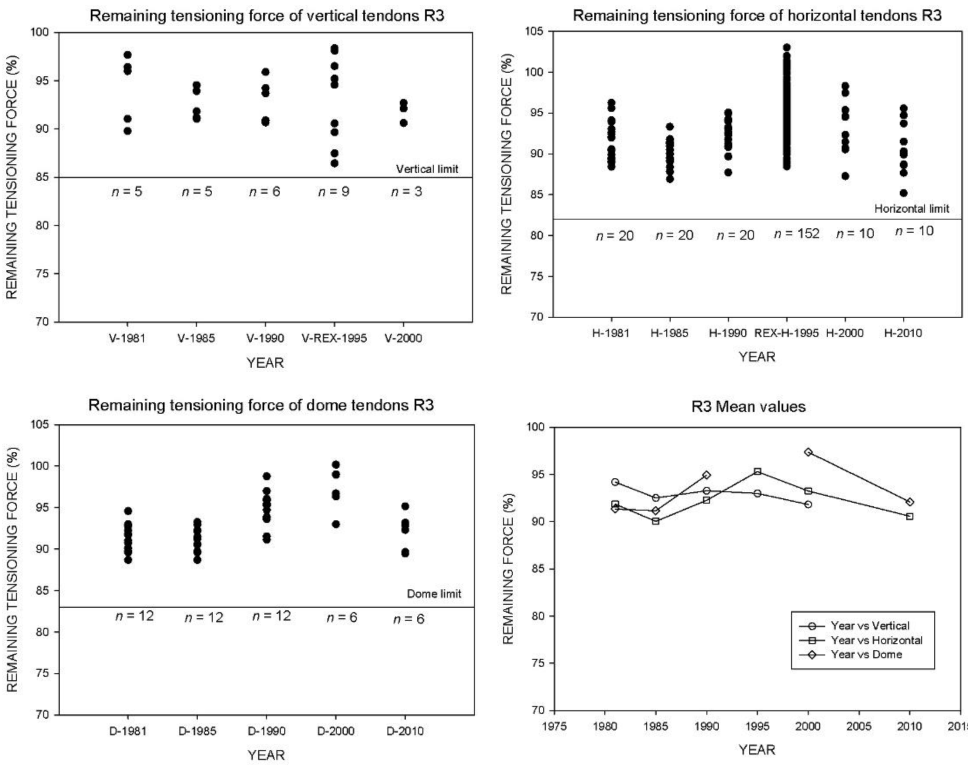

Figure 3-9 Remaining tensioning force of the tendons in Ringhals R3. The mean remaining tensioning force is shown in the bottom right graph.

The regression analyses give little or no support for the hypothesis that tensioning force is lost. The vertical tendon however, show a small negative slope which indicates that tensioning force is lost, see figure 3.10.

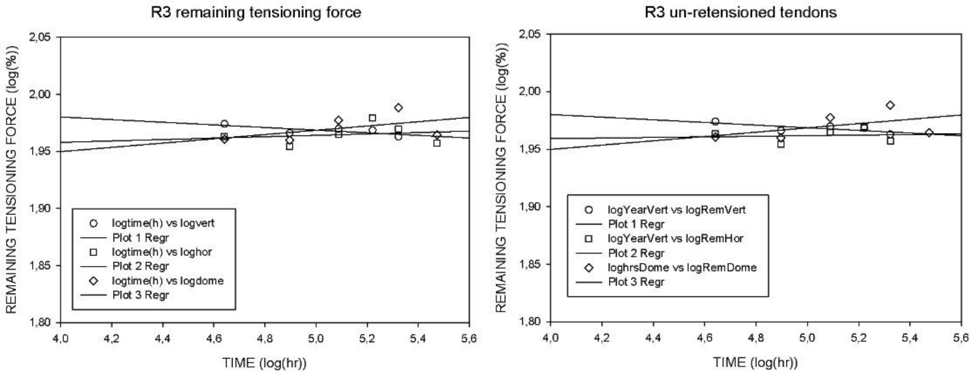

Figure 3-10 Regression analyses of the tendons in Ringhals R3. The vertical tendons show a small negative slope. The results are very similar irrespective of whether the re-tensioned tendons are included or not.

3.7 EVALUATION OF TENSIONING FORCE DATA FROM RINGHALS 4

The scatter of the observations of the initial tensioning forces was 4 % for vertical and dome tendons and twice that for the horizontal tendons. In the first graph, see fig 3.11, it can be seen that two outliers are responsible for the larger width of the scatter. The *n* for the horizontal tendons is however much larger than for the other type of tendons so it is possible that the difference is due to the different sample size.

When studying the graphs of the remaining forces, see figure 3.12, there are two features, which are obvious. The measurements of the horizontal tendons 1986 resulted in comparatively low forces and in particular, the observations of the dome tendons have outliers towards the low force side. Note that for some of the measurement occasions, the sample size *n* is very small.

The linear regression results in regression lines with very little slopes. Calculated remaining forces for the horizontal tendons, which have the biggest slope, results in 91,7 % for the year 2030 and 91,3 % for 2050, see figure 3.13.

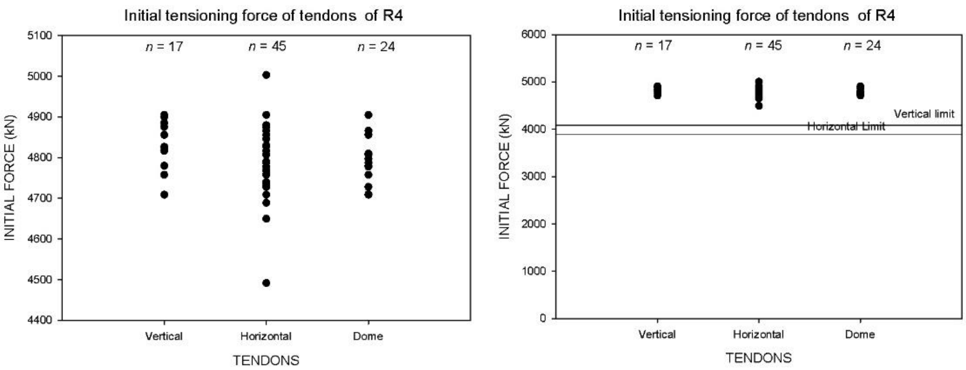

Figure 3-11 Initial tensioning forces of the tendons in Ringhals R4.

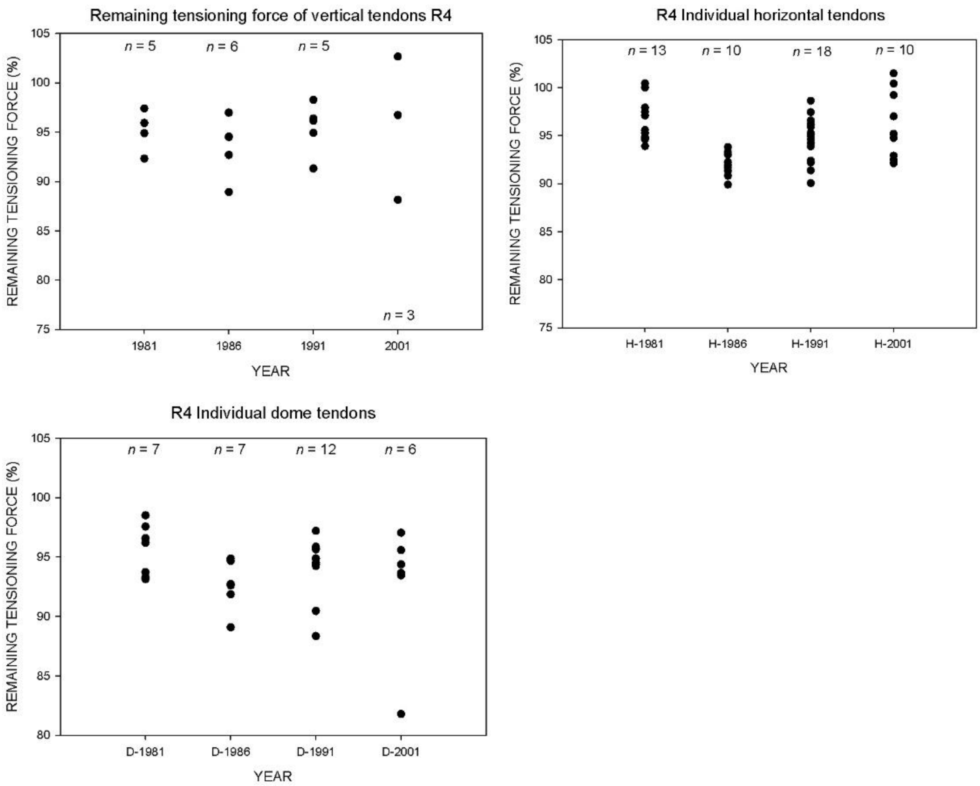

Figure 3-12 Remaining tensioning forces of the tendons in Ringhals R4.

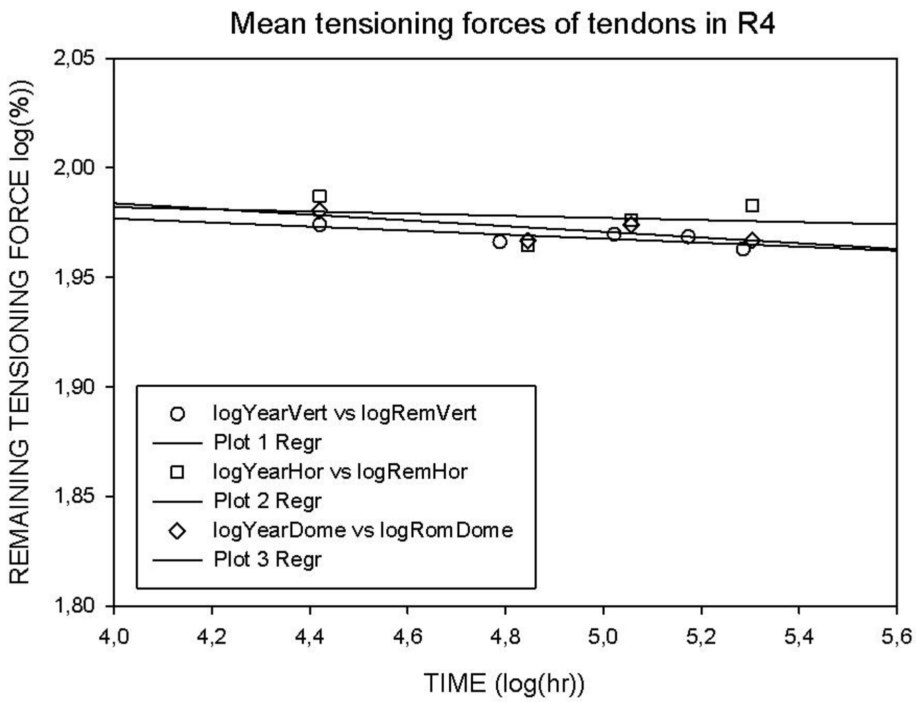

Figure 3-13 The regression lines of Ringhals R4 are very close together.

3.8 EVALUATION OF TENSIONING FORCE DATA FROM FORSMARK 1

The initial tensioning forces of the vertical tendons are larger than for the horizontal tendons. The initial tensioning force of the vertical tendons ranged between 2234 and 2458 kN and of the horizontal between 1847 and 2280 kN, so there exists a pronounced difference in initial tensioning force. The range is 9 % of the mean for the vertical tendons and 22 % for the horizontal. The graphs of the remaining tensioning force shows that there is no obvious loss of tensioning force, which is also shown in the graph of the regression analysis, see figure 3.14. Also, note the low values of the remaining tensile force for the year 1982.

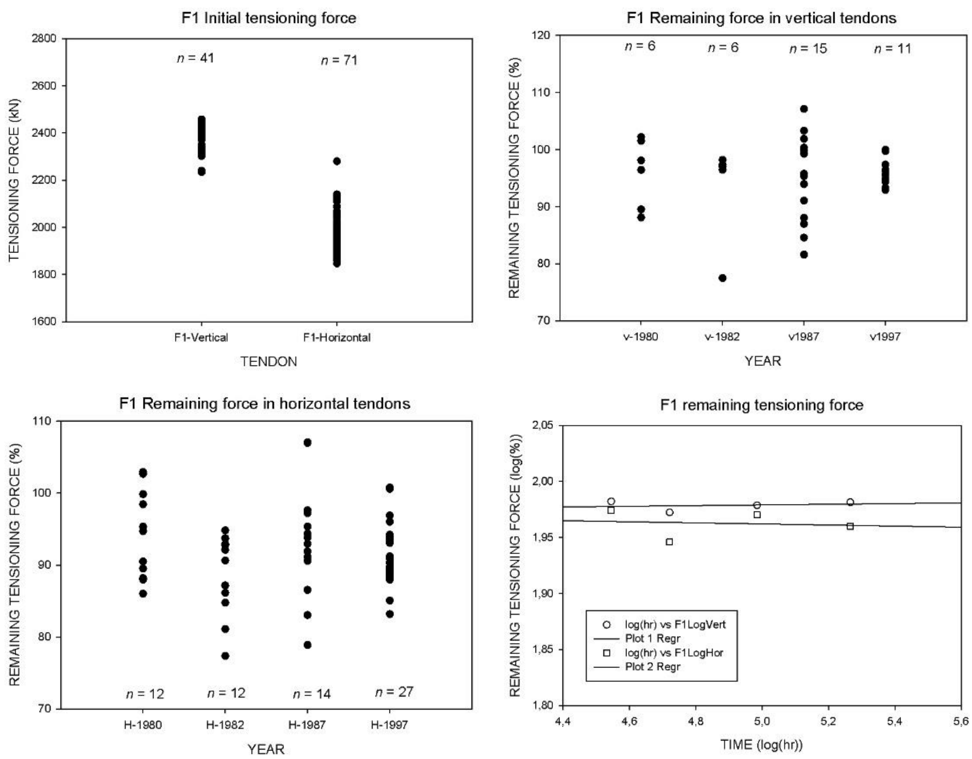

Figure 3-14 Graphs showing dot plots for initial tensioning forces, upper left, remaining tensioning force, upper right and lower left and regression at lower right.

3.9 EVALUATION OF TENSIONING FORCE DATA FROM FORSMARK 2

The initial tensioning forces of the tendons are larger for the vertical tendons than for the horizontal, see figure 3.15, which is as for the tendons of Forsmark 1. The initial tensioning forces of the vertical tendons ranged from 2130 kN to 2549 kN and from 1996 kN to 2252 kN for the horizontal. The range is 18 % of mean for the vertical tendons and 12 % of mean for the horizontal.

The graphs with the dot plots shows no obvious loss of tensioning force after the initial loss, but the dot plots of the remaining tensioning force show pronounced loss of the tensioning force with time. This is also manifested in the regression analysis of the mean values for the remaining tensioning force. Despite this loss is not greater than that, the mean of the remaining tensioning forces will be 72,2 % in 2030 and 70,2 in 2050.

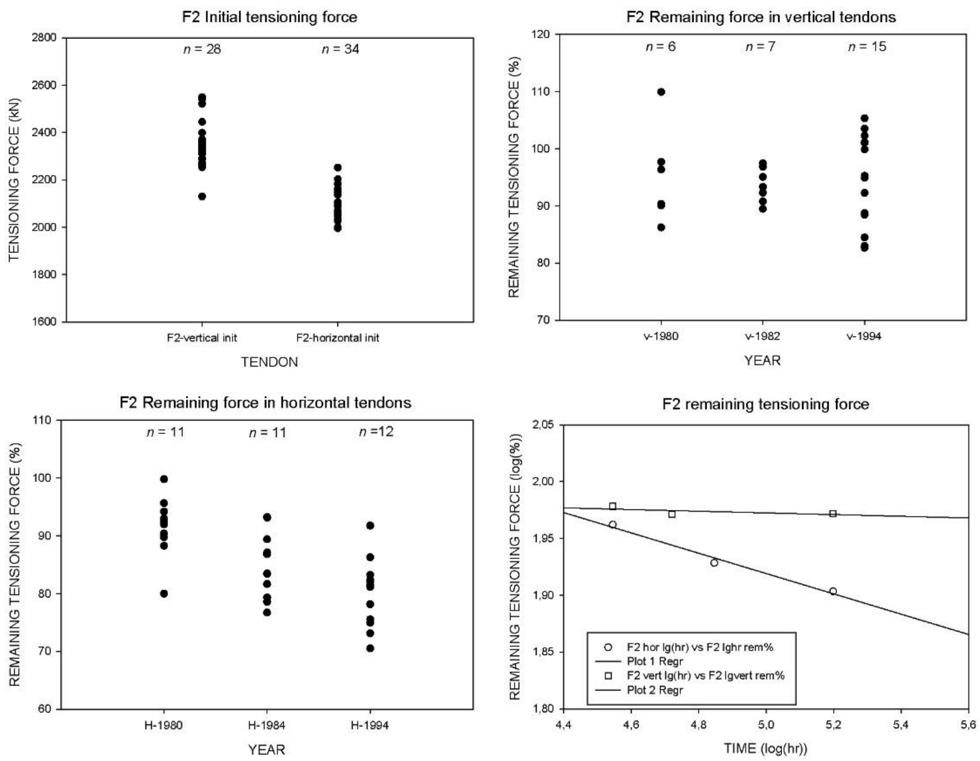

Figure 3-15 Graphs showing dot plots for initial tensioning forces, upper left, remaining tensioning force, upper right and lower left and regression at lower right. Note that the horizontal tendons, loses tensioning force in all measurement occasions.

3.10 EVALUATION OF TENSIONING FORCE DATA FROM FORSMARK 3

The initial tensioning forces differ from the ones of Forsmark 1 and Forsmark 2 in the way that there is no obvious difference in the initial tensioning forces between the vertical and the horizontal tendons. The initial tensioning forces of the vertical tendons ranged from 4690 kN to 5000 kN and from 4805 kN to 5050 kN for the horizontal. The range is 5 % of mean for the vertical tendons and 6 % of mean for the horizontal tendons and there is no loss of tensioning force after the initial loss of force, see figure 3.16.

A regression analysis was made using the 2010 measured forces for Forsmark F3 and it was found that those individual values were in good agreement with the regression of mean values, see figure 3.17. The scatter of the slopes is natural when not means for a larger number of observations are used.

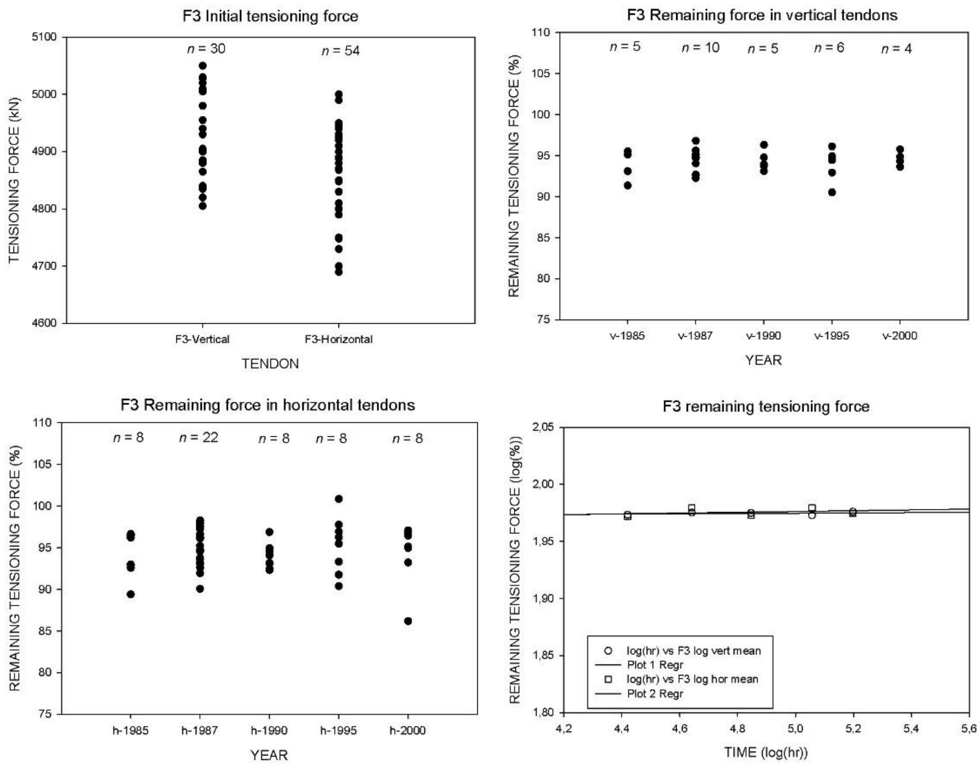

Figure 3-16 Graphs showing dot plots for initial tensioning forces, upper left, remaining tensioning force, upper right and lower left and regression at lower right. Not the slightest loss of tensioning force after the initial can be seen.

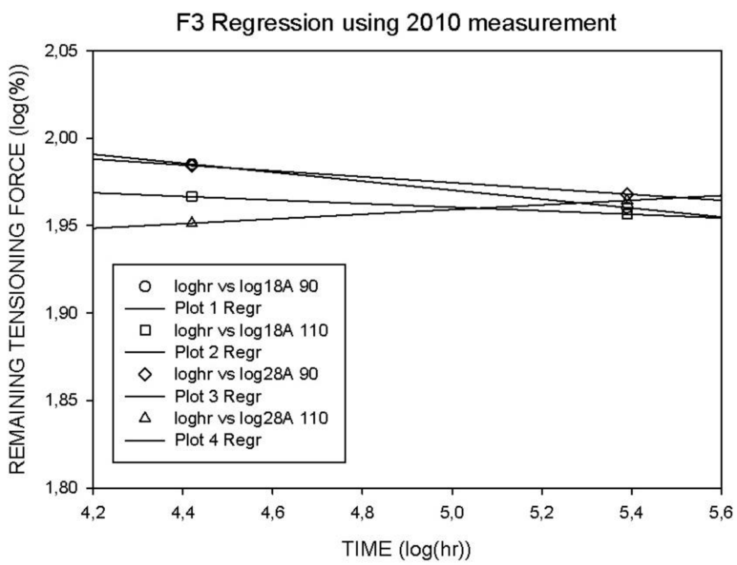

Figure 3-17 Regression using measured forces in 2010.

4 Evaluation of mechanical properties

4.1 INTRODUCTION

Vattenfall Research and Development AB has in the past decades performed several tensile tests on single wires as well as 7-wire strands from reactor containments at Forsmark and Ringhals. The tests are done every 10th year for each containment having non-grouted tendons in order to control that the wires and strands fulfill requirements regarding their mechanical properties. The tests presented below are from the nuclear power plant blocks Ringhals 2, 3 and 4, and Forsmark 3.

In the very beginning, which standard to use was an unsettled question. The Swedish standard for wires SS 14 17 57 4th edition was in force until 1987-04-01 and tests have carried out according to this standard. The fourth edition was only a preliminary standard and was replaced by the 5th edition.

Single wires have also been tested according to specifications acquired from the producer. The properties, which were determined were: elastic modulus, yield strength defined as the force which resulted in 0,2 % permanent deformation, $F_{0,2}$, the maximum force during the test, F_m, the elongation limit, ε_g. and the relation $F_{0,2}/F_m$. The requirements were a little lower in the preliminary standard for $F_{0,2}$, F_m, and ε_g.

The methods to perform the tests have been developed. In the beginning an extensometer was used with 250 mm gauge length up to 1 % and for the continued deformation the displacement of the grips was plotted. Strain gauges glued on the wire have also been used.

Today, a measuring system with 0,01 mm resolution and usually the values displayed in 0,1 mm resolution is used with a gauge length which can be varied up to the distance between the grips but usually is 2 m. The elongation can also be recorded to fracture. This method has made it possible to compare force-elongation curves between different wires and between different positions on the wire in detail, which, has shown that some ∅ 6 mm wires starts deforming at 30 kN and does not seem to have a functioning stabilization, see figure 4.1. In this figure one of the wires starts deforming already below 30 kN and the deformation at the same load is up to 0,04 % units larger than for the other wire. Note that in the graph, both wires have the same elongation limit and F_m. Hardness measurements results in lower hardness for the H114 wire than for the D41 wire.

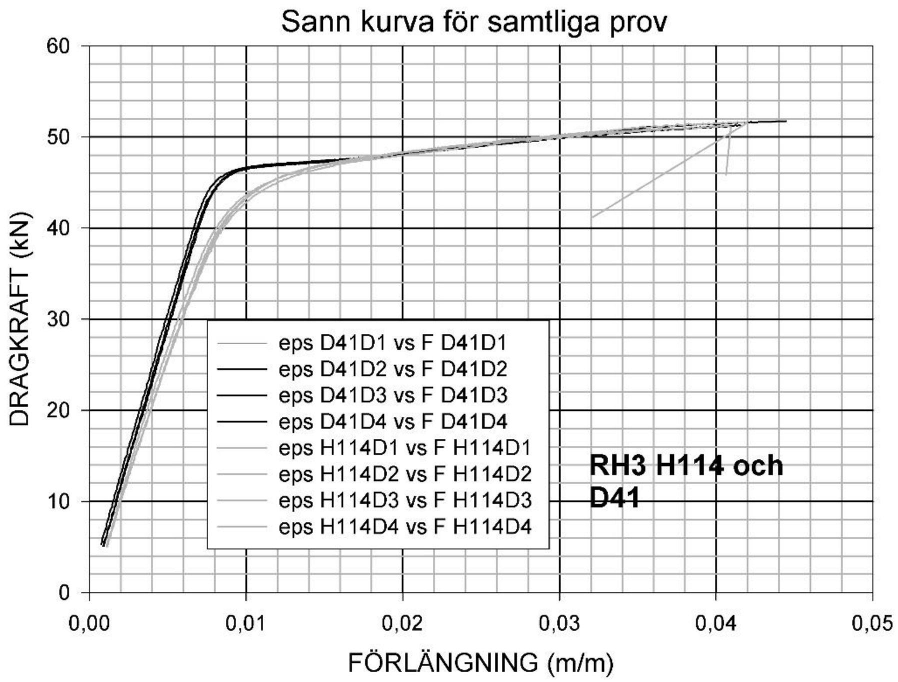

Figure 4-1 The graph shows different force elongation curves for two different wires. The stabilization of the H114 wire may have been destroyed or was not correct from the beginning.

4.2 EVALUATION OF DATA FROM TENSILE TESTS AT RINGHALS AND FORSMARK

In the following, the acquired values for yield force; maximum force and elongation limits from the repeated tensile measurements are evaluated to find trends. It should however be noted that when the measurements are performed, usually only one wire of each type is tested even if up to four tests are reported. Tensile tests specimens are cut from each end and one in the middle with one specimen in reserve from the middle.

The scatter is due to variations in the properties between the different specimens and between wires when tests performed at different years is compared. Wires of different types are treated individually. The data are for ∅ 6 mm single wire. Usually a scatter of one or two kN is considered very small – The accuracy of the tensile testing machines are for instance usually not better than 1 %.

The 0,2 % yield strength of the wires seems to be decreasing in the Forsmark 3 containment but that is probably only due to the first values, which are from as-delivered wires prior to tensioning, see figure 4.2. The wires from the dome tendons of Ringhals 2 seem to have a true increase in yield force when the individual values are compared with the regression line.

In the graphs for the maximum force, see figure 4.3, it can be seen that Forsmark 3 continues to show a downward trend and the Ringhals 4 an upward trend towards increasing maximum force. The Ringhals 2 and 3 does not show any clear trend.

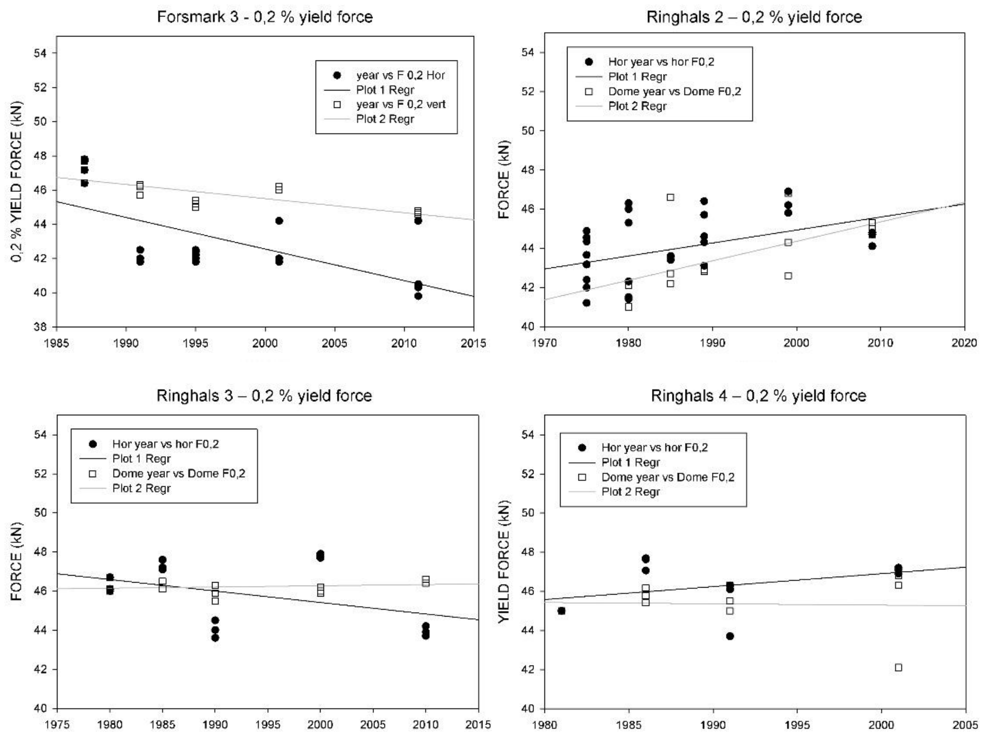

Figure 4-2 Trend analysis of the measured 0,2 % yield forces.

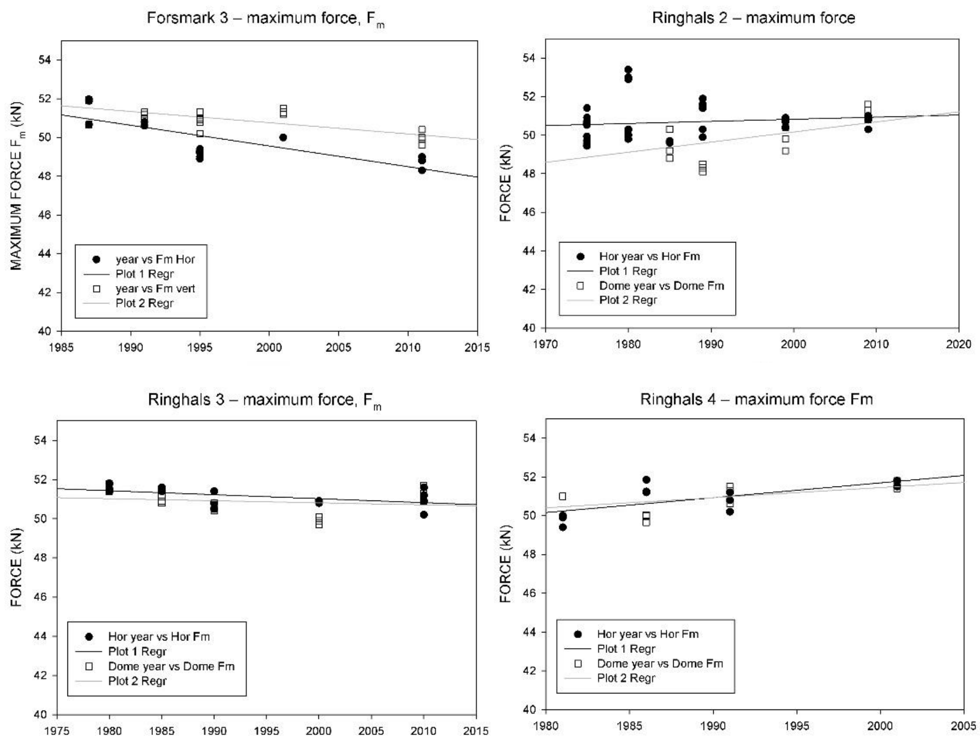

Figure 4-3 Trend analysis of the measured maximum forces.

The values for the elongation limit from the Ringhals 2 have large scatter, see figure 4.4, but even when the 1999 values are removed, the trend seems to be towards lower elongation limits, as is also the case for Forsmark 3 and Ringhals 3, but not to the same extent.

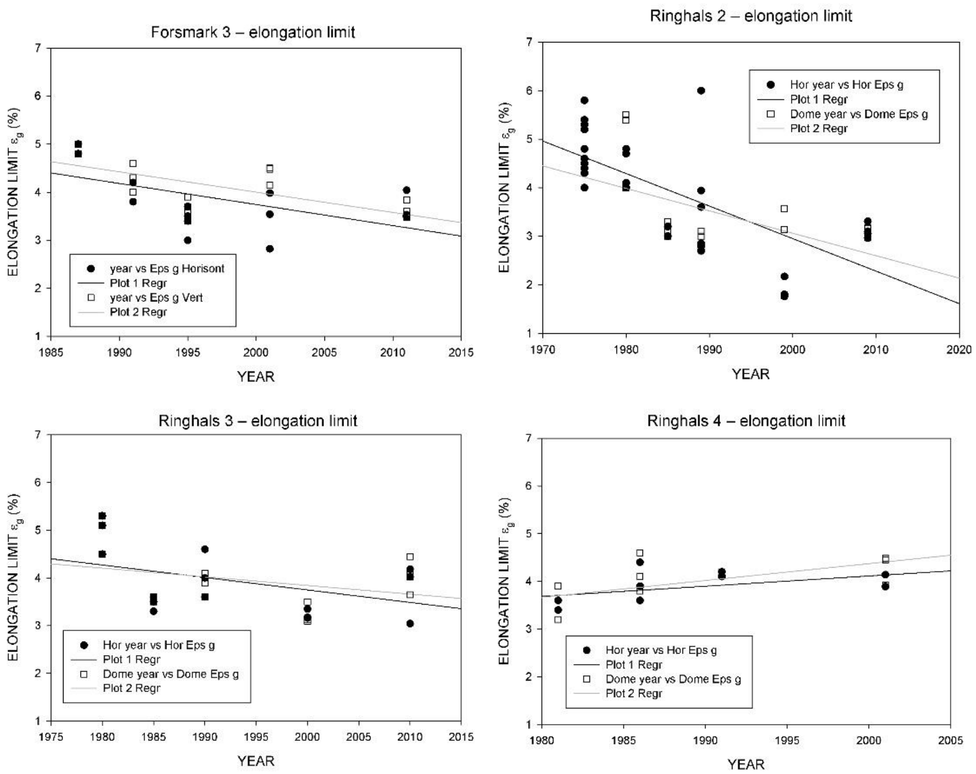

Figure 4-4 Trend analysis of measured elongation limits.

5 Conclusions and recommendations

5.1 CONCLUSIONS ON LOSS OF TENSIONING FORCE WITH TIME

The measured tensioning forces acquired in the inspections at Ringhals and Forsmark were analysed. Certain loss of tensioning force of tendons over time is something that is expected by the nuclear power plant ageing management.

A method has been developed, based on several different approaches, for visualisation and trend analysis of tensioning force data sets.

The scatter of the measurements of initial tensioning force is of equal proportion as the acceptable loss of tensioning force. The results show that majority of the loss of tensioning force takes place between initial tensioning and the first inspection. After the initial loss of tensioning force, most types of tendons have such small loss of tensioning force that it cannot be separated from the random scatter and measurement uncertainty. There are exceptions however:

- All three types of tendons in Ringhals R2 as well as the horizontal tendons of Forsmark F2 show loss of tensioning force with time.
- The horizontal tendons at Ringhals 4 show slight negative slope of the regression line, but still have 91 % of the initial tensioning force 2050 (see table 5.1). That negative slope is also so small that a line representing no change of the force will be within the confidence limits of almost any confidence interval.
- The horizontal tendons of Forsmark F2 show a loss of tensioning force with time down to around 70 % (see table 5.1). Further investigations are needed to clarify if this actually would be the case.
- A regression analysis was made using the 2010 measured forces for Forsmark F3 and it was found that those individual values were in good agreement with the regression of mean values.

Table 5-1 Projections into the future of the tensioning force losses for the tendons with largest loss of tensioning force.

	Intercept	Slope	Calculated force (%)	
Tendon	**b(0)**	**b(1)**	**2030**	**2050**
Ringhals R4				
Horizontal	2,035744	-0,0129886	91,7	91,3
Forsmark 2				
Horizontal	2,36595	-0,089369	72,2	70,2
Only un re-tensioned tendons Ringhals R2				
Vertical	2,069	-0,02979	79,3	78,6
Horizontal	2,037	-0,02379	79,8	79,2
Dome	2,049	-0,02416	81,6	81,0

All-in-all, the evaluation shows that some tendons, when tensioning forces are compared, are losing tensioning force more quickly than other tendons from other containments. Due to how these values are obtained, the variations can be considerable, which has been shown.

5.2 CONCLUSIONS ON MECHANICAL PROPERTIES OVER TIME

By performing tensile tests it is possible to see differences between individual wires and sometimes, different positions on the same wire. However, it must be kept in mind the analysed data sets also contain influence from other system parameters (e.g. creep of the concrete). This means that no precise conclusions can be made.

As for the loss of tensioning force of tendons over time, certain changing mechanical properties over time is as well something that is expected by the nuclear power plant ageing management. Investigations such as presented here are needed in order to assess that property changes are not greater than what can be acceptable.

From the analysis of measurements over time the following conclusions can be made:

- An overall, and expected, obvious trend is that the elongation limit of the tendons is decreasing.
- The tendons in Ringhals R2, and possibly also Ringhals R3 and Forsmark F3, have pronounced losses in elongation limit. However, the loss is still within acceptable limits.
- For the other two mechanical properties, yield force and maximum force, the measured data sets show no changes over time.

5.3 RECOMMENDATIONS

High-precision creep tests

The author recommends that high-precision creep tests are carried out on both ex-serviced and new wires in order to clarify what is to be expected of the performance in the future. The creep test can be considered as a relaxation test in which the tensioning force is continuously being adjusted to the initial force. Such a test can answer questions such as:

- How much deformation, which can be translated to creep or relaxation, is there already in the wire?
- Will the rate of creep or relaxation decrease or increase with time?
- What happens if a stabilized wire is accidentally tensioned to plastic deformation?
- Are there differences in the creep or relaxation properties expressed as different creep equations?

Re-tensioning study

A closer study of the re-tensioned wires should be made. There are indications - for instance in the Ringhals 2 measurements of the remaining tensioning force - that the effect of re-tensioning is lost quite quickly.

It is recommended that, when planning re-tensioning of tendons, to take into account that individual cables can have a large spread in remaining tensioning force. Re-tensioning should only be considered for those cables that have low measured tensioning force, i.e., *not* the approach to re-tension all cables of a certain kind. The reason for this is that the strands have already been permanently deformed trough relaxation, with some strands more so than others. There is thus the risk that a re-tensioning results in a higher relaxation rate, than the otherwise at controlled condition expected small relaxation. Certain strands could then after re-tensioning have high loss of tensioning force, or corresponding deformation. The author thus recommends that re-tensioning is made to a tensioning force corresponding to the force measured at the first inspection after installation.

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Appendix 1

A. Motivation to the omission of variances (Section 3.4)

Sometimes graphs can be found in the literature with fly-legs attached to the plotted symbol, representing the standard deviation of the distribution and if the author finds it to large – the standard deviation of the mean. More correct is to use confidence interval for the regression line and prediction interval for the observations. A 95 % confidence interval defines within 95 % probability where the regression line is. A prediction interval of 95 % defines with 95 % probability the values between which the observations can be found.

An example is shown in figure A.1. Both the confidence and the prediction intervals are narrower at the centre of the amount of observations. Two observations are outside the prediction limits, which is in agreement with 5 %. The confidence interval rapidly gets wider when predictions are made outside the observations in the graph. Therefore,

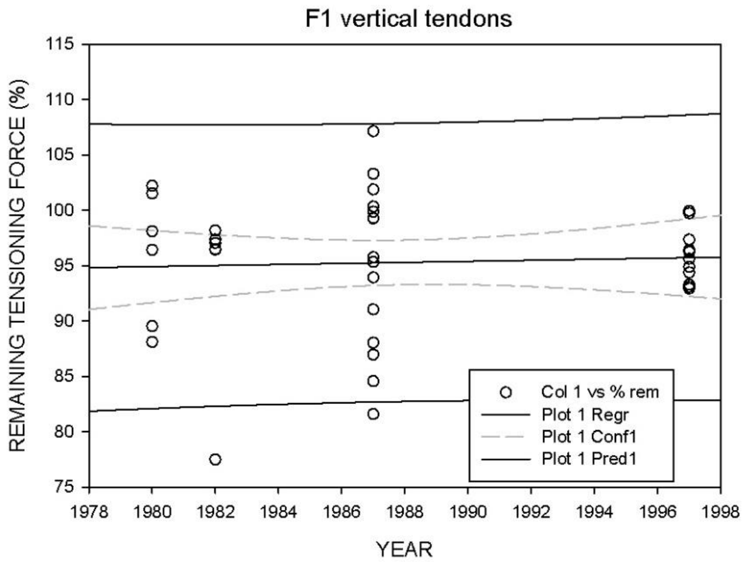

Figure A.1: An example of linear regression with 95 % confidence interval for the regression and 95 % prediction interval for the observations.

LONG TERM STABILITY OF TENDONS AND POST TENSIONING WIRES

The tendons and post tensioning wires are an important part of the design of the reactor containment. Material properties and structure of the wires and tendons change over time in a post tensioned design, and it is important to investigate the long term performance. This project is based on a literature study and data from long term measurements from surveillance data from reactor containments in the nuclear power plants Ringhals and Forsmark.