EXTERNAL LOADING OF HIGH VOLTAGE PYLONS

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Resume

This contribution is devoted to issues of long term safe service of high-voltage pylons, which are loaded during service by variable loading with simultaneous acting of external environment. There were proved the procedures ensuring that the limit state will not occur during the period of technical life and the service will be safe for a long time. A draft of diagnostic procedures was elaborated, applied in suitable inspection intervals, following from the analysis of failure risks. The maintenance and repair procedures, assuring the safety of service until next inspection are planned on the basis of application of analytic methods of dynamic fracture mechanics. This procedure of controlled ageing is designed for the new and serviced pylons as well. The controlled ageing at the same time prolongs the technical life of structure with a high measure of safety. Residual life can be determined in each phase of pylon life. Controlled ageing allows saving high economic values at spending considerable lower costs for inspection and maintenance.

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1. Introduction

The construction of high-voltage lines transmitting 110 kV, 220 kV and 400 kV started in Europe in the 40-ties of the past century. Most of original pylons are in service till present days Fig.1.

Fig. 1. Pylon for 2x400 kV (48 years old).
(full colour version available online)

Replacement is actually performed only for the reason of pylon breakdowns. Pylons are loaded by random loading processes. Breakdowns usually occur due to icing, strong side wind and/or by combination of both. Gusty wind causes the galloping of ropes. In general, four types of dynamic loading occur which are caused by unfavourable weather conditions. These are: aeolian oscillations of ropes, galloping oscillation of ropes, dynamic impact at shedding of ice from the rope and detachment of whirls on the pylons and insulators, Fig.2.

Danger of sudden breakdown occurs at resonance, when the loading frequency is equal as the own frequency of pylons. Breakdown of one pylon used to be the initiator of the so-called domino effect - a progressive breakdown of greater number of pylons.

2. Response to external loading

The rate and dynamics of external loading cause a response in the critical points of structure by damage cummulation. In the first phases this is an event without visible signs on material

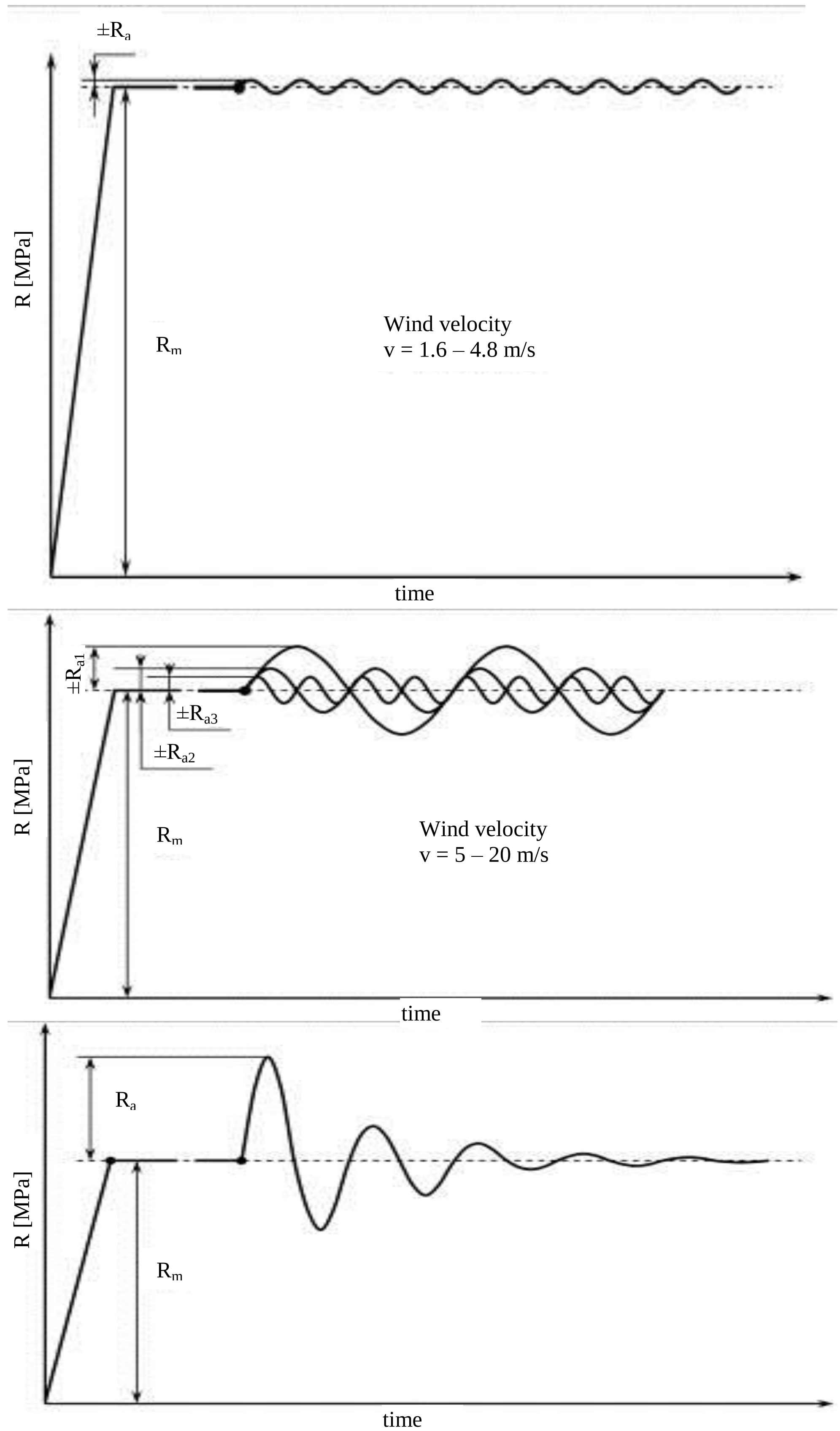

Fig. 2. Loading by aeolian oscillation, galloping oscillation and by impact.

surface, when the incubation phase of fatigue failure on the level of structure and substructure (crystals) takes place, mainly by growth in density of dislocations. This stage of development of fatigue cracks is usually affected by the stress concentration from notches and also by residual stresses, mainly in the zone of welded joints. After incubation stage of fatigue process, the stage of fatigue crack growth follows. The damage process terminates by sudden rupture of the remaining cross section. In case of existence of surface defects (crack, lack of fusion, cold lap etc,) the incubation phase is abandoned and the entire process of fatigue consists only in the fatigue crack growth.

By the Griffith – Irwin (1957) [1] theory, the main criterion for fracture of a structure and/or its part consists in attainment of the critical crack size ac. At this size of crack, the limit state would occur by mechanism of brittle or mixed brittle-ductile fracture. Regarding the fact that fracture occurrence should be avoided, the admissible crack size must be smaller than the critical, what is expressed by the safety coefficient m1. The admissible length of crack at the end of safe life is az = ac : m1.

The structures dynamically loaded in service may be loaded either by high-cycle fatigue, strain (low-cycle) fatigue or by irregular fatigue loading [2]. Theoretical background for determining the growth rate of fatigue cracks is sufficiently mastered at present. For crack growth rate at high cycle fatigue, the Paris – Erdogan (1963) [3] relationship is used, whereas for the strain fatigue the Manson – Coffin’s (1954) [4] relationship is applied and at irregular fatigue, the cumulative hypotheses are employed, whereas the most widely used seems to be the Palmgren – Miner’s (1945) [5, 6] criterion in conjunction with Wöhler´s (1858) [7] curve.

Present direction in the field of design, manufacture, service, repairs and liquidation of structures is governed by the approaches making use of the theoretical and practical knowledge of the „Fitness For Service – FFS“ approach. (This method was conceived and developed within IIW - International Institute of Welding, in Commission XV – „Design, analysis and fabrication of welded structures“ (1990). This methodics at present became the contents of Commission X – Structural Performances of Welded Joints – Fracture Avoidance. Documents from this field are accessible on the web site: www.eurofitnet.org.

The „fitness for service“ theory may be used actually in all fields of fabrication and service of metallic but also non-metallic (plastics, composites, ceramics, concrete etc.) structures and products. Application of this theory in fabrication and service of metallic structures is schematically shown in Table 1.

The limit state may occur from several reasons, for example from the material loss of the bulk structure, caused by corrosion. Material degradation may occur due to ageing, distortion of crossarms and due to defect growth by fatigue process, most often by loading caused by the sharp atmospheric influences.

3. Risk based inspection

At present, there are many important high-voltage lines in the age, when the life of pylons is approaching and/or it has already reached the design life. Therefore it is necessary first of all to eliminate in maximum possible measure the dangerous states and risks leading to possible formation of limit state in pylons and at the same time to secure the diagnostics of all pylons older than 40 years.

Repairs and maintenance of pylons are mostly performed just by partial interventions, either of greater or smaller extent and these are performed on the basis of empiric professional judgements. The methods suitable for assessment and continuous diagnostic monitoring of real technical state of pylons during their life has not been developed nor introduced up to now. Neither relevant methods

Table 1

Modules of „FITNESS FOR SERVICE“ approach.

Safety and service reliability	Structure design	Structure fabrication	Assessment during life	Analysis of limit states
Information needed for assessment	Information about service during life	Rate and type of loading	Mechanical properties of material	Extraordinary effects
Possible failure modes	Fracture (brittle, ductile)	Distortion (plastic collapse)	Fatigue	Corrosion
Integrity criteria	Critical defect size	Residual life	Categorisation	Passportisation
Application	Creation of databases	Utilisation of databases	Controlled ageing	Economic studies

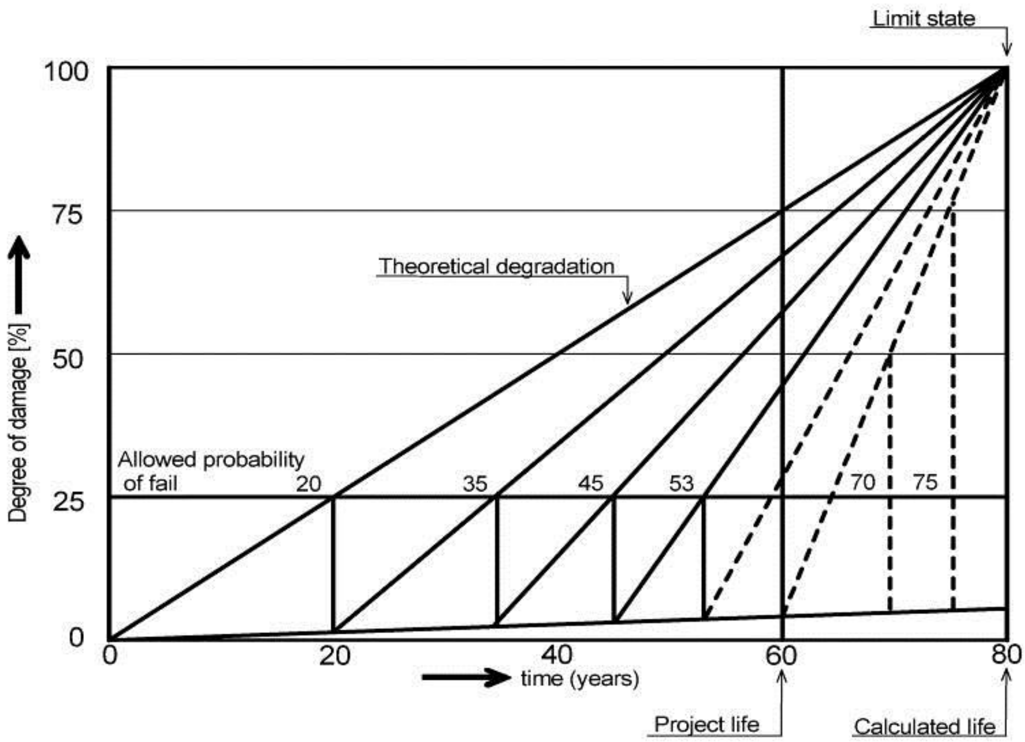

Fig. 3. Intervals of structure inspection by the Risk Based Inspection theory.

Table 2

The system of diagnostic measurements.

	Diagnosed subject					
Material sampling	General visual inspection	Direct NDT inspection				
Mechanical tests	Surface corrosion UTT	Inspection of critical points				
Metallographic studies	State of surface protection ET	VT	UT	ET	MT	PT
Chemical analysis	Distortion of crossarms	Residual stresses				
Transition temperature	State of bases	Local hardness				
	Results of diagnostics					
	Proposal for maintenance and repairs					

for determination of residual life, that would be generally accepted and binding, were elaborated. Since there is considerable disunity in opinions how to proceed in individual cases, it is necessary to elaborate a knowledge-based solution of diagnostics, procedures for maintenance and repairs as well as for replacement of pylons and/or entire lines.

Optimum solution of maintenance and repairs supposes determination of suitable inspection intervals. Their determination follows from the analysis of damage risks - RBI (Risk Based Inspection) [8], as shown in Fig. 3. The structure must be capable to tolerate the failures formed between the two inspection intervals. Thus, in spite of existence and growth of damage caused by corrosion and/or dynamic loading, the structure must be safe and functional up to the next planned inspection. Determination of interval of diagnostic inspections directly depends on the admissible probability of failure.

4. System of diagnostic measurements

Diagnostics is aimed at an objective determination of factual state of pylon material from the viewpoint of its damage during the service. Modern non-destructive and destructive diagnostic methods used for determination of factual degree of pylon damage allow to attain a complex picture about the internal and external defects in the critical cross sections, as well as the measure of material damage due to ageing. The scheme of system for diagnostic measurements of condition of high-voltage pylons is shown in Table 2.

5. Life of pylons

The diagnostics evaluates the actual state in damage of individual pylons. All pylons of a line and/or a line section need not to belong to the same category of assessment from the viewpoint of their damage. Based on assessment criteria, the extent of damage is assessed in five degrees, whereas the first degree represents a non-damaged pylon and the fifth degree represent a pylon in emergency condition. The intermediates comprise: slightly, moderately and considerably damaged pylon. The damage degrees are schematically shown in Fig. 4. It is necessary to determine the residual life of the most damaged pylons at least in the period when the fourth degree of pylon damage was observed. This is necessary for perspective planning of partial or complete replacement of a line after exhausting the residual life of pylons. The pylons in the fifth damage degree are not suitable to serve and must be immediately replaced.

The damage process of steel structure of pylons progresses in the course of life separately in its individual components (corrosion, ageing, defect growth, distortions of crossarms etc.) but the resultant effect of damage is represented summarily. The degradation process is governed by actual physical and chemical laws, which allow to predict their expected further development, as also seen in Fig.4. Thus, a real possibility to determine the supposed residual life of pylon structure is created. The individual degradation effect preserve certain specific features, therefore it is necessary to analyse the individual degradation effects separately.

The overall final assessment of a pylon must be considered by the highest individual degree of damage achieved for the whole set (the weakest link of a chain is decisive). Similarly at a line assessment, the most damaged pylon in the individual section (between two reinforcing pylons) is decisive. The residual life may be determined for each individual pylon, however it is recommended to determine it just for the most damaged pylon in each section.

6. Residual life

Residual life generally depends on the state in structure damage, on acceptable damage level and on the supposed service conditions in the course of time from diagnostics performance till the end of safe life. Four significant modes of damage may occur on pylon structures which alter during the course of life and affect the residual life of a pylon:

- material ageing,
- corrosion,
- fatigue crack growth,
- distortions of crossbars.

Determination of supposed residual life is an engineering problem, which solution consists of an unimpeachable estimation of time during which the pylons may be utilised and met requirements for service safety. Residual life of pylons is thus considered till termination of a safe service and not up to reaching the emergency (limit) state. Each of the mentioned damage modes may separately cause the termination of service period, due to exceeding the critical damage size (CDS). The time courses of assessment properties can be obtained on the basis of long-term monitoring of individual damage modes. This allows to achieve the life function of studied property. At individual damage modes, attention should be mainly paid to the following two issues:

- course of the life function at individual damage modes,
- critical degree of degradation (CDS) of an actual damage.

Regarding the fact that the development of individual damage modes, as well as the admissible degree of degradation mutually differ, since they are of different physical or chemical essence, it is necessary to approach to individual damage modes separately. For determination of residual life a graphical course of individual damage modes was plotted with marking the critical size of each individual damage, as shown in Fig. 5. The courses and also critical sizes of damage were obtained experimentally on the pylons, fabricated of steel grades S235 J2 and S355 J2.

6.1 Material ageing

Degradation mechanisms of material ageing are given by the way of its manufacture, mode and rate of loading, environment, where the material is situated eventually by temperature changes during the service [9]. Actual manifestation of ageing is measurable either by observing the growth in transition temperature and decrease in upper shelf energy at impact bend test and/or by reducing the critical defect size at fracture toughness test, as shown in Fig. 5 – ageing. For steel type S235 J2 the CDS is achieved at TT= +10°C and for steel type S355 J2 at TT= +5°C.

6.2 Corrosion

Depth corrosion on material surface at transition of web to concrete may even reach the depth of several millimetres. The corrosion loss directly weakens the carrying cross section of web and creates thus the nuclei for fatigue cracks at dynamic loading [10, 11]. Fig. 5 – corrosion shows the course of development of surface corrosion loss during the life, where the critical degradation degree CDS is being expressed by the value of surface corrosion loss in 3 mm size (depth) for the steel grade S235 J2 and 2 mm for the steel grade S355 J2.

6.3 Fatigue crack growth

The instantaneous crack depth is determined from the diagnostic measurements and it is then plotted to diagram of fatigue crack growth dependence on time Fig. 5 – fatigue. The critical value of fatigue crack size – CDS (crack depth) is 7 mm for the steel grade S235 J2 and 5 mm for the steel grade S355 J2.

6.4 Distortion of crossbars

In case of distortion of crossbars it is necessary to introduce the stability condition, which was proposed and proved by the results of diagnostic measurements. Number of pylon crossarms is usually around 140 (up to first crossbeam height). Stability condition states, that the number of distorted crossbars would not

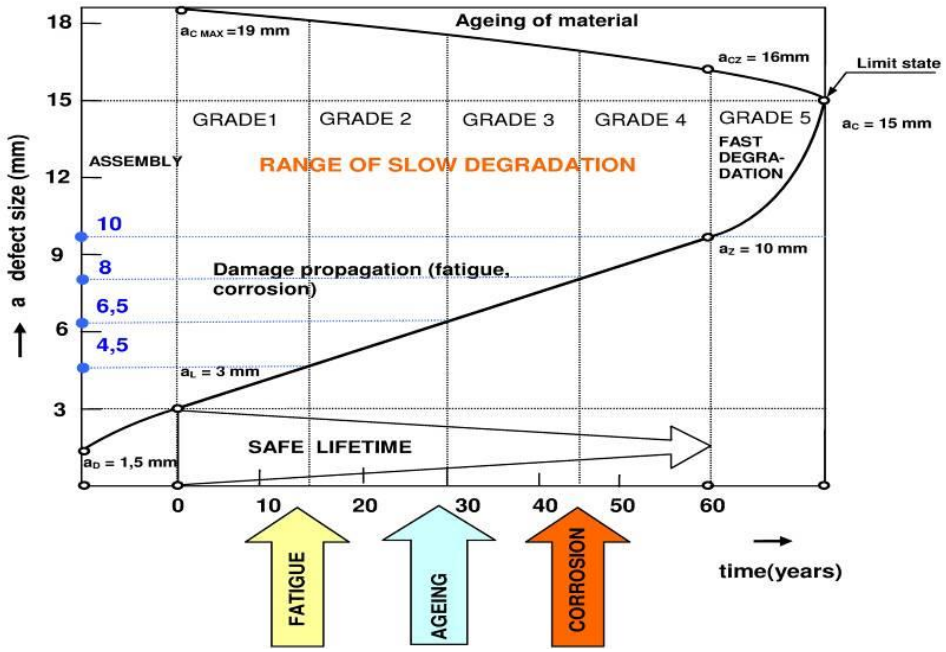

Fig. 4. The course of life and the degrees of pylon damage.
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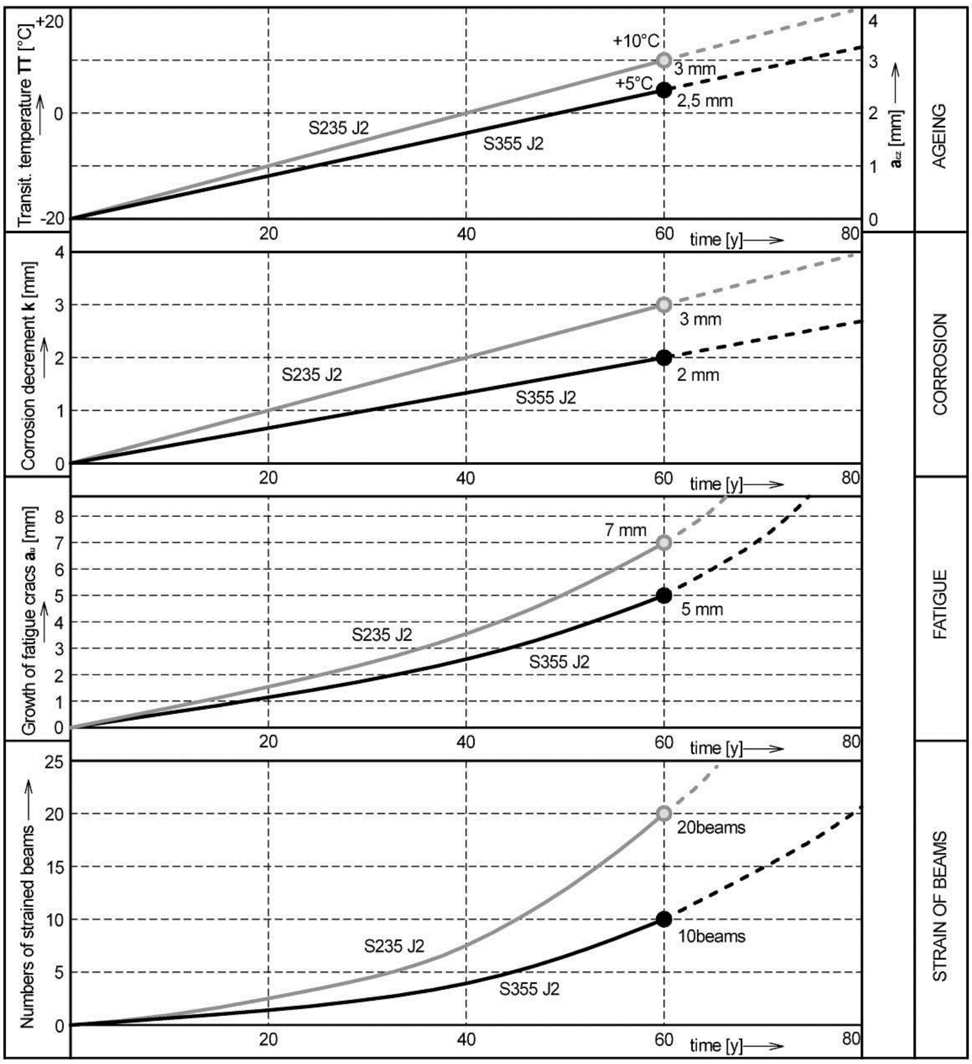

Fig. 5. Determination of residual life of pylons.

exceed 15%, thus not more than 20 crossbars for the pylons fabricated of steel grade S235 J2. For pylons of steel grade S355 J2, the stability condition accepts only 10 distorted crossbars, owing to their slenderness. It was shown that the time course of distortion of crossbars is not linear. Therefore for determination of residual life it is necessary to use the courses shown in Fig.5 – distortion of crossbars (strain of beams).

Residual life is in individual cases determined in such a manner that a point with the measured damage size is plotted on the degradation curve. Residual life is then determined as the time from that point on the curve up to the end of life (60 years). The shortest of the observed lives is then considered for the real residual life.

At plotting the dependencies of damage development, the starting point was the design life 60 years and the computing life 80 years. As proved by practice, the real development of damage is individual and in principle differing from the predicted, eventually calculated development. This lays higher importance on diagnostics of damage development in the set intervals. From RBI theory it follows, that the diagnostics terms (inspections with subsequent maintenance) would be most suitable in intervals 20, 35, 45, and 53 years. In close linkage with inspection, the removal of found damages and imperfections must follow. In this way the operator introduces the system of a controlled ageing of pylons with the aim to prolong the time of their safe service.

7. Controlled ageing

Integrity of pylons must be ensured continually. The quality systems have introduced the principle of responsibility of manufacturer and operator for the safety of product, in our case the lines of high-voltage during the entire period of their technical life. This requirement may be ensured by the method of controlled ageing of pylons. Principle of controlled ageing consists in the fact that a complex diagnostics with subsequent maintenance (eventually also repairs) of all defective points is performed in the intervals defined in advance [12, 13]. After such action the structure gets to its „initial“ state. However, the material degradation caused by ageing will remain a permanent change that cannot be removed. These intervals are determined by the RBI (Risk Based Inspection) method, as shown in Fig. 6.

Controlled ageing has a direct effect upon two most important performance criteria, namely the service reliability and Life Cycle Costs (LCC). However, also time of safe service is prolonged. On the side of expenditures, the costs for diagnostics, maintenance and repairs are involved, whereas on the side of savings a prolonged time of safe life of pylons is obtained. Practice has shown that the cost for controlled ageing is considerable lower, than the savings obtained by prolonged time of safe service with postponing of new investment.

8. Passportisation and database of pylons

Precondition for introduction of system of controlled ageing consists in creation of passportisation of pylons. Each pylon has its passport with given all basic data necessary for further analysis in the course of life, as shown in Table 3. In the course of life also other data are gradually added to these basic ones, obtained from the inspection diagnostics measurements, as seen in Table 4. The proposals for maintenance and repairs of individual pylons are then derived from these data.

System for creation of databases follows from passportisation. Individual lines were put into service at different time. It is quite apparent that all input data will not be available for the older line sections. However, this is by no means an obstacle for creation of databases of actual present state. A database is actually a defined set of passports with all relevant data for performing the analyses of actual state and plans of maintenance, repairs and/or reconstruction. It also allows performing the economic analyses,

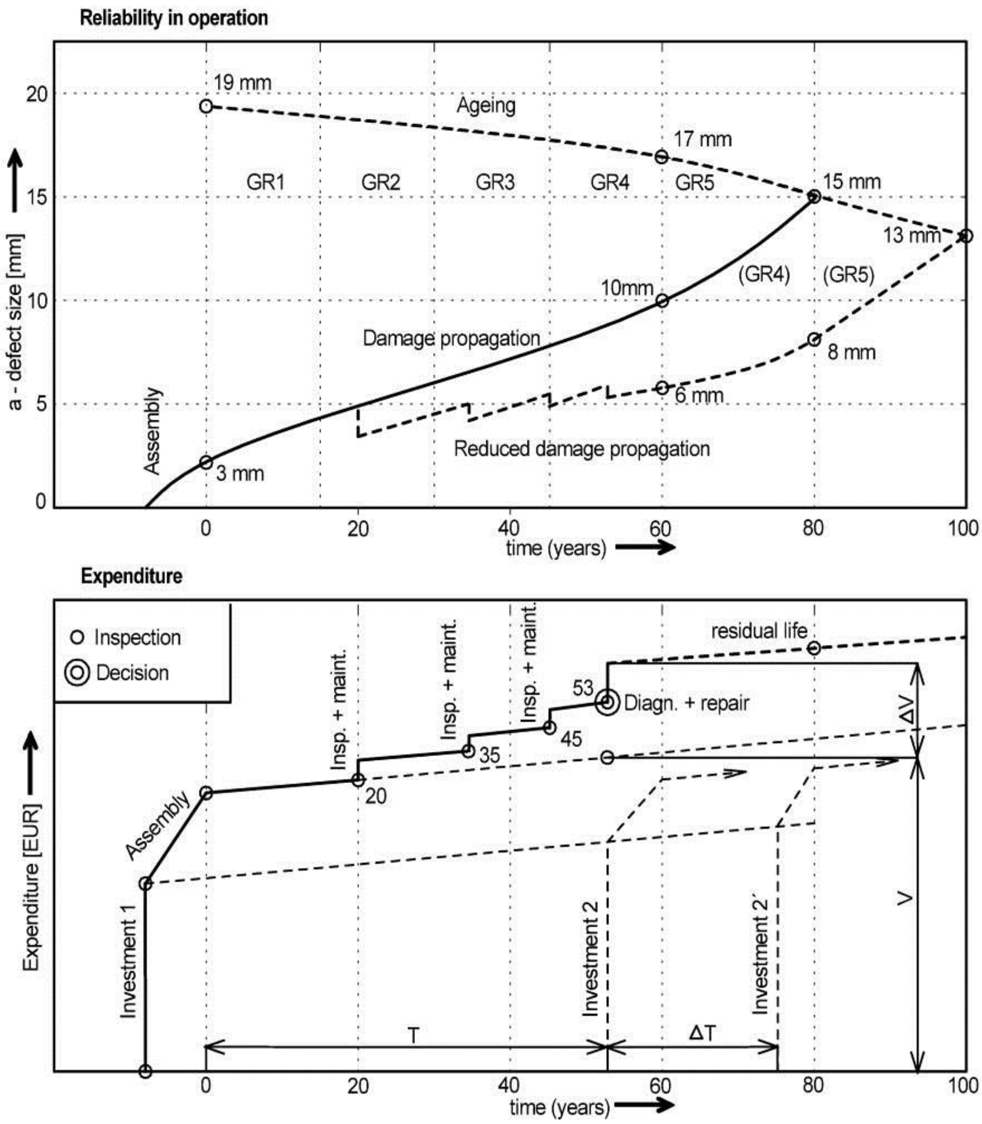

Fig. 6. Course of controlled ageing and data analysis.

Table 3

Main data in passport

Fabrication and putting to service	**External effects in the region of location**	**Realised repairs and maintenance**
Locality (map)	Temperature range, icing zone	Replacement of crossarms or other parts (splice bars etc.)
Line designation	Band of precipitation	Replacement of accessories
Pylon designation	Band of wind speed	Replacement of ropes
Drawing documentation	Maximum windstorm degree in the region	Replacement of insulators
Static calculation - standard	Landslides	Renewal of paints
Date of pylon erection	Seismic effects	Removal of scrub, soil
Date of putting into service	Area of infestation – industry	Repair of foundations
Pylon material	Area of infestation – chemistry	Other repairs
Used joints: welds/bolts	Other effects	Other maintenance
Filler metal Other data	Notes	Notes

Table 4

Degree of pylon degradation determined by diagnostic measurements (record).

Pylon identification		Footing Profile of webs Profile of crossbars		Date of measurement
Measurement method	Inspected object on the pylon	Measured location	Observation - finding	Suggested precautions
VT	Webs Joints of webs Expansive corrosion Crossbars - distortion Eccentricity Surface corrosion State of surface protection Defects of welded joints Defects of bolted joints Defects of foundation Surroundings – scrub			
ET	Paint thickness			
MT	Defects of joints			
PT	Defects of joints			
UTT	Corrosion loss			
UT	Volume defects			
Category of pylon damage			**Residual life**	

either short-term or perspective ones as well. Database contains in electronic form, besides the passports also all input data from inspection protocols, results of mechanical and metallographic tests, results of chemical analyses and also complete photo documentation from the diagnostic measurements and tests. All tests and measurements must be performed by an authorised institution. Database is continually completed with all data connected with the service of pylons, as the results of diagnostic measurements, significant climatic effects occurring during the life line, realised maintenance operations, renovation of paints, removal of scrub, repair of foundations, replacement of insulators, replacement of ropes, repairs and other interventions into the line.

9. Discussion and conclusions

Research of life of pylons in high-voltage lines has shown the possibilities for realisation of repairs, maintenance and replacement on the basis of knowledge approach. In some cases of loading of carrying pylons it is necessary to perform also other non-standard tests, as for example fatigue tests, tests of crack growth rate, determination of fracture toughness, tensometric (strain rate) measurements, rigidity measurements and detection of resonance frequency of a pylon. It is advantageous, when a continuous material testing during entire life is considered already at fabrication and installation of pylons. In such a case, the so-called reference specimens are fabricated, which are then located on new pylons. At extraction of test specimens, the carrying part of pylon need not be damaged, because this reference material is used for the tests.

In order to assure the service reliability, as well as the optimum economical usage of transmission system, it is advisable to elaborate and implement the program of controlled ageing of transmission system [14, 15]. This will then allow to monitor and assess the effect of service and degradation processes on individual components of transmission line, to observe the trends in changes of their state and to accept early the precaution measures for removing and/or moderating the causes of ageing. The program of controlled ageing is one of preconditions allowing to prolong the residual life of transmission system. Starting point of setting up such program consists in passportisation and creation of databases, set on the basis of a complex diagnostics.

Finally it must be emphasised that determination of residual life is neither cheap nor simple. This supposes introduction of a system for observing the „life“ of pylons starting with design up to discarding from service (decommissioning). This concerns mainly the passportisation and creation of databases, including the diagnostics. This will result in current knowing of the residual life of pylons and thus also possibility of a continuous decision-making and optimisation. The knowledge of other parameters, service reliability and safety as well as material for economic analyses creates an added value to determination of residual life. This is realised by the „fitness for service“ [16] approaches, by which it is unacceptable to let a structure in service up to formation of a limit state. Integrity of pylons is decisive. And it is guaranteed up to the end of life, however with the exception of extraordinary events, which cannot be predicted neither prevented.

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References

[1] G.R. Irwin: J. Appl. Mech. (Trans. A.S.M.E.) 24 (1957) 361-364.

[2] A. Hobbacher: Recommendations for Fatigue Design of welded Joints and Components, Doc. IIW-1823-07, 2007.

[3] P. Paris, F.Erdogan: J. Basic Eng. 85(4) (1963) 528-533.

[4] L.F. Coffin: Trans. ASME 76(6) (1954) 931-950.

[5] Z. Hashin: A Reinterpretation of the Palmgren – Miner Rule for Fatigue Life Prediction, Technical Report NO. 1, University of Pennsylvania, Philadelphia, Pennsylvania, 1979.

[6] S.H. Crandall, W.D. Mark, G.R. Khabbaz: The Variance in Palmgren – Miner Damage Due to Random Vibration, MIT Cambridge, Massachusetts 1962.

[7] A.Z. Wöhler: Zeitschrift für Bauwesen 8 (1858) 641-652.

[8] J. Sinay: Risks of technological equipment Technical University of Košice, Košice 1997.

[9] I. Hrivňák: Welding and Weldability of Materials, Slovak Technical University, Bratislava 2009.

[10] The Fitness for Purpose of Welded Structures, Doc. IIW/IIS – STT -1157-90, 1990.

[11] P. Polák: Corrosion Cracks Propagation Velocity, Welding Research Institute, Bratislava 1998.

[12] L.L Schreir: Corrosion, George news Ltd., London 1963.

[13] D. Daniš: AT&P J (10) (2005) [Available online: http://www.atpjournal.sk/buxus/docs/atp-2005-10-55.pdf].

[14] www.frost.co.uk

[15] www.hempel.sk

[16] M. Koçak: Welding in the World 51(5-6) (2007) 94 – 105.