Re Page B-84:

Q. With reference to Hydro's response to IC27-NLH in the 2007 Hydro Capital Budget, and specifically subsection (f) of that response, please update Hydro's response with respect to those recommendations that had not been followed or completed, namely R4, R6, R8 and R10.

A. IC27-NLH 2007 Hydro Capital Budget Question - R4

If the analysis identifies that a large number of poles need to be replaced then a separate study should be undertaken considering full refurbishment and/or upgrading or even building a new line before a capital program is launched.

R4 - Until now, Hydro has replaced a small percentage of the total pole inventory as part of WPLM program. Also, the poles replaced were not clustered in general. The need for a separate study was proposed to identify any large group replacement of wood pole line asset(s) such as insulators, conductors and poles and the merit of such large maintenance replacements against upgrading or building a new line section before a capital program is launched. Hydro has not yet encountered such a situation.

IC27-NLH 2007 Hydro Capital Budget Question – R6

Data to be analyzed to develop a "Replacement Criteria" for Wood Pole Lines based on a minimization of cost model as shown in Fig. 1.1. Some initial work has been completed as part of this study and this should be followed up further for validation of this model with additional field data.

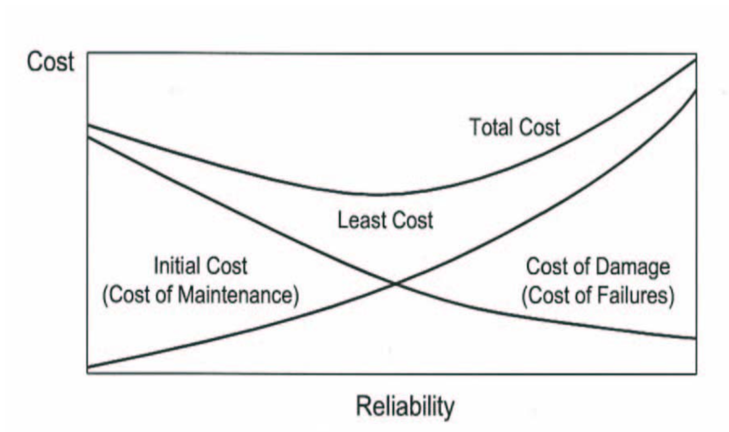


Fig. 1.1 – Optimum Cost Curve

R6 – The Transmission and Distribution (T & D) department has made considerable progress in the area of model development and has developed a methodology which can filter a large amount of condition based inspection data to provide a decision matrix for refurbishment /replacement of pole plant assets. The methodology uses a reliability based analysis and a paper was published in 2006 to describe the approach. The concept was well received during a presentation at the American Society of Civil Engineer's (ASCE) conference in Birmingham, Alabama. A copy of this paper is attached.

The work on model development will continue and the model will be improved as new data is available.

IC27-NLH 2007 Hydro Capital Budget Question – R8
In each year of this inspection program, a separate fund is allocated to do routine testing of components including the in-service wood poles of various ages to develop a long-term database. Hydro, in collaboration with MUN, has developed special benches to do this type of testing and this should be funded annually.

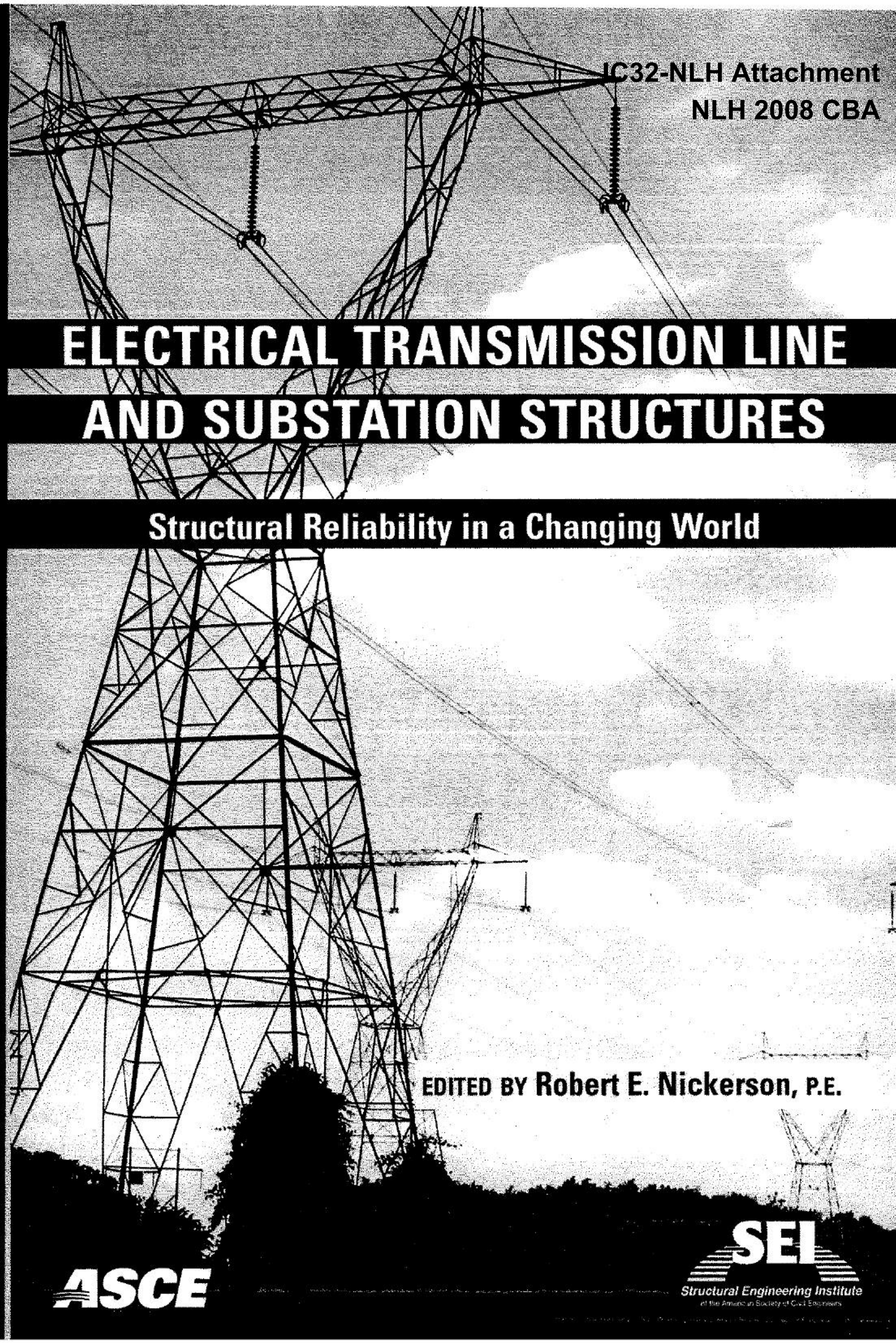
R8 - During the past few years, a number of full scale pole testing was done at the structural engineering laboratory of MUN and the strength data, identifying the degradation due to aging was used in analyzing the field data. This testing involves using large forces to bend the poles until they burst. MUN has indicated that the current setup for pole testing is not acceptable because it has concerns with respect to safety of pole testing in a confined environment.

T & D is currently in discussion with the Faculty of engineering to modify the test setup arrangement to mitigate the above issue and is expecting a proposal from MUN soon. Hydro is also in discussion with Memorial University of Newfoundland to fund a graduate student to support the long term R & D work with respect to non destructive testing.

IC27-NLH 2007 Hydro Capital Budget Question – R10
A working group be formed within Hydro's TRO Division, which should include one representative from each of Engineering, Operations and System Planning. The primary role will be to review the annual Engineering report on the inspection results and its recommendation to ensure that if any major line replacement is required in the future based on the data trend, Hydro will be able to plan this program in advance to avoid a large capital expenditure in any given year and distribute the resources in an even and timely manner.

R10 - Although T & D group discusses the various issues pertaining to the WPLM program with operations on a regular basis through monthly conference calls and a few "face to face" meetings, Hydro has not yet setup a formal Task group on WPLM program as it was outlined in the original proposal in 2003. This should be considered in 2007.

IC32-NLH Attachment
NLH 2008 CBA



ELECTRICAL TRANSMISSION LINE AND SUBSTATION STRUCTURES

Structural Reliability in a Changing World

EDITED BY **Robert E. Nickerson, P.E.**

ASCE

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Structural Engineering Institute
of the American Society of Civil Engineers

Condition Based Management Of Wood Pole Transmission Lines Using Structural Reliability Analysis

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Abstract

Newfoundland and Labrador Hydro (NLH) maintains approximately 2400 km of wood pole transmission lines operating at 69, 138 and 230 kV. During the past five years, NLH has developed a Wood Pole Line Management Program (WPLM). A framework for systematically analyzing a large volume of inspection data for wood pole transmission lines has been developed using the reliability based analysis technique. The method uses a "hybrid approach" where the uncertainties in load and strength values and the strength deterioration due to aging are taken into account with the condition rating of each pole and structure to develop a condition matrix table. The methodology is presented with particular application to a section of a HV transmission line with various methods of mitigations.

Introduction

Newfoundland and Labrador Hydro operates a high voltage network system that consists of forty-one (41) wood pole transmission lines. These lines consist of approximately 26,000 transmission size poles of varying ages, with the maximum age being 41 years. Almost two-thirds of transmission pole plant assets fall into two age categories; approximately 34% are at or over 30 years, and another 31% are 20 to 30 years old. The remaining asset age is less than 20 years old.

Historically, NLH's pole inspection and maintenance practices followed the traditional utility approach of sounding and visual inspection only. The earlier program was time based, with 20% of a line inspected in each year. It is well known in the literature that poles become extremely susceptible to fungi and/or insect attack as the preservative retention level depletes over time. Figures 1 and 2 present two types of damage: (i) damage due to rot and (ii) damage due to Carpenter ants.

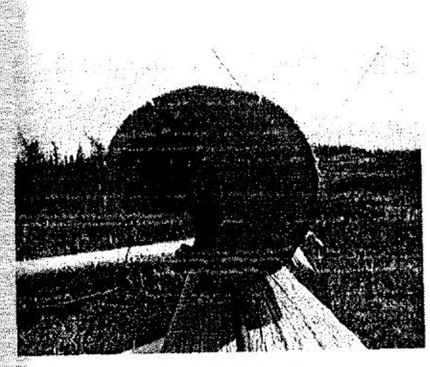


Figure 1. Pole Rot Damage

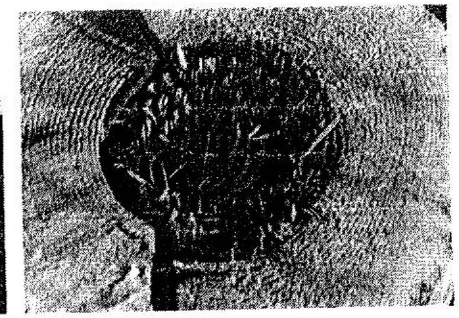


Figure 2. Carpenter Ant Damage

In 1985 and 1998, NLH decided to take core samples on selected poles to test for preservative retention levels. NLH also collected data on pole decay. The results of these tests raised concerns regarding the general preservative retention levels in wood poles. Between 1998 and 2003, additional coring and preservative testing confirmed that there were a significant number of poles that had preservative levels well below the threshold level required to maintain the reliability of these lines. During this period, a large number of poles were replaced because the preservative level had lowered to the point that decay had advanced and the pole was no longer structurally sound. Figure 3 presents the measured retention levels (averaged) for Southern Yellow Pine (SYP) poles for the lines located on the eastern part of Newfoundland. The poles were originally treated with pentachloropheonol and were installed in mid-60's. Figure 4 presents the rejected pole population plotted in terms of asset retirement curve known as IOWA curves (Winfrey, 1937). These curves are used widely in industrial asset retirements. A 50-year curve (Type R4) was chosen for pole plant assets in validating the rejected pole data for various age groups. The data correlation is good. These inspections and the validated IOWA curve data for a number of lines confirmed that NLH needed a more formal wood pole line management program to ensure that future maintenance program is well managed.

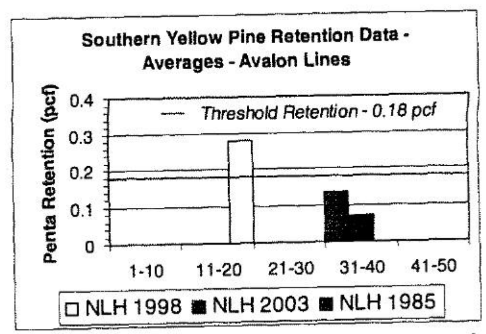


Figure 3. Southern Yellow Pine Preservative Retention Data

Scope

This WPLM program (Haldar, 2004) covers the on-going management of forty-one (41) wood pole lines across Newfoundland and Labrador. The primary objective of the program was to address three specific items. These are: (1) inspect, test and treat 26000 poles and associated line components such as conductor, hardware, insulator over a 10 year period (2) develop and implement an electronic data collection system to ease the field data collection and subsequent data analysis and (3) develop a general reliability based methodology using a "*hybrid*" approach. The result of the conventional structural reliability analysis is used with the field inspection data to assess the consequence of a specific failure mode with particular reference to strength deterioration with increasing line age.

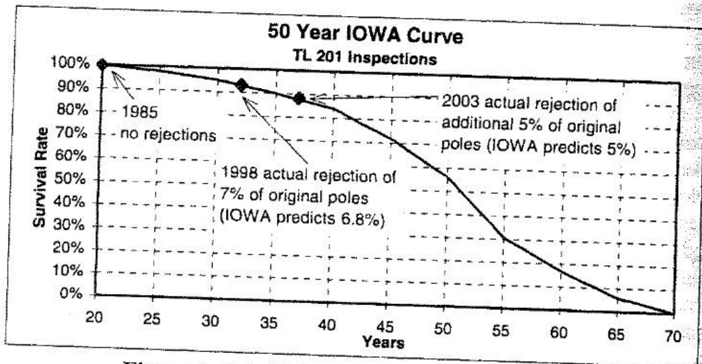
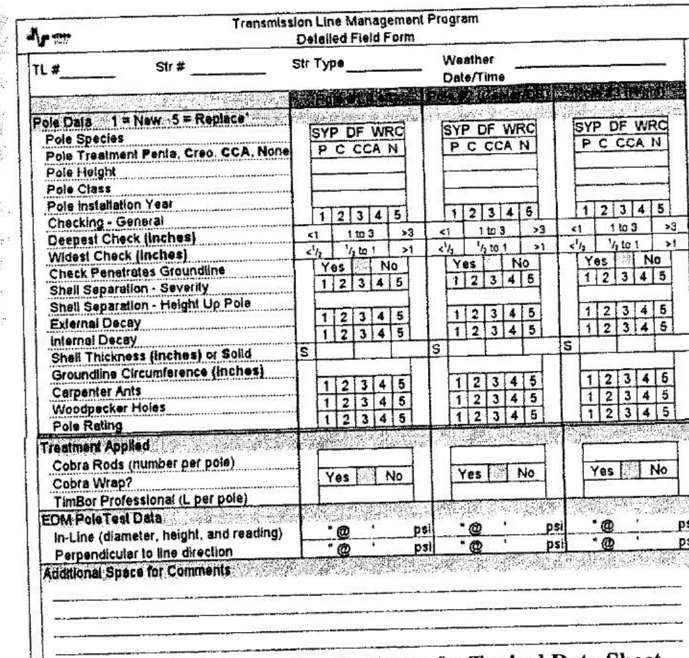


Figure 4. Pole Rejection Data –IOWA Curve

Database Development

As part of the WPLM program, the requirements of an electronic data collection system, and a storage database to archive the inspection data, which would allow for easy retrieval for subsequent analysis, were identified. A detailed inspection form was developed to collect the field information for each line component. This included structure, conductor, hardware, insulator and guy arrangements. Each main component was further broken down into various subcomponents and information was collected with specific questions for the overall condition assessment. For example, the structure as a major component was broken down into poles, cross braces, knee braces and cross arms. Figure 5 shows a typical data sheet for pole inspection. ESRI Canada was retained as a consultant to develop the software and to procure the compatible hardware for the electronic data collection program. So far, NLH has collected inspection data for 4755 structures along with other line components and they have been archived in the system.



Transmission Line Management Program
Detailed Field Form

TL # ______ Str # ______ Str Type ______ Weather ______ Date/Time

Pole Data 1 = New 5 = Replace			
Pole Species	SYP DF WRC	SYP DF WRC	SYP DF WRC
Pole Treatment Penta, Creo, CCA, None	P C CCA N	P C CCA N	P C CCA N
Pole Height			
Pole Class			
Pole Installation Year			
Checking - General	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Deepest Check (inches)	<1 / 1 to 3 / >3	<1 / 1 to 3 / >3	<1 / 1 to 3 / >3
Widest Check (inches)	<½ / ½ to 1 / >1	<½ / ½ to 1 / >1	<½ / ½ to 1 / >1
Check Penetrates Groundline	Yes / No	Yes / No	Yes / No
Shell Separation - Severity	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Shell Separation - Height Up Pole			
External Decay	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Internal Decay	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Shell Thickness (inches) or Solid	S	S	S
Groundline Circumference (inches)			
Carpenter Ants	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Woodpecker Holes	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Pole Rating	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Treatment Applied			
Cobra Rods (number per pole)			
Cobra Wrap?	Yes / No	Yes / No	Yes / No
TimBor Professional (L per pole)			
EDM PoleTest Data			
In-Line (diameter, height, and reading)	" @ ' psi	" @ ' psi	" @ ' psi
Perpendicular to line direction	" @ ' psi	" @ ' psi	" @ ' psi

Additional Space for Comments

Figure 5. Pole Inspection Sections of a Typical Data Sheet

Reliability Based Condition Assessment Methodology

Reliability Based Inspection (RBI) and maintenance program is primarily based on the failure mode evaluation and assessment (FMEA) of each component under a given loading scenario and strength and subsequent evaluation of its consequence on the system. In this approach the line is treated as a system.

Reliability analysis is based on the assumption that the strength as well as the effects of all loads on the line or on its components are random variables and can be defined completely by their respective probability distributions. The respective strength distribution can be developed based on the sample test data set or can be obtained based on published data of similar pole age groups and exposures. The loading parameters are normally wind velocity, ice thickness and their combinations and are converted to loads and load effects through appropriate transfer functions. The load distributions could be lognormal or non-normal. The shaded area in Figure 6 measures the failure probability. In structural analysis, this can be measured in terms of a "beta value" (β), which is directly related to the failure probability (Melchers, 1996). For example, a β value of 1.282 represents 10% failure probability while a β value of 1.645 implies 5% failure probability. The higher β value indicates a lower failure probability.

Once the failure probability is assessed under a specific loading scenario, the risk can be calculated by simply multiplying the failure probability by the consequences of the failure expressed in dollars.

Figure 6 depicts the overall mechanism (process) of assessing failure probability when an asset (line, component etc.) is exposed to both the variations of load effects as well as the strength. Variation of strength is not only inherent to the original design mean strength (for example SYP with 8000 psi) but also it is applicable to the time dependent strength value at any discrete time point as shown in Figure 6. Actual rate of deterioration is not necessarily smooth as shown in the figure but can be evaluated reasonably well if we collect the strength data at discrete time points such as 10, 20, 30 and 40 years respectively. Initial failure probability will be low and most lines will have an acceptable factor of safety. As deterioration process progresses over time, the capacity, R (t) in Figure 6 will start to decrease and at some point, it could be less than the load effect thus initiating a failure within the service life (40 to 50 years).

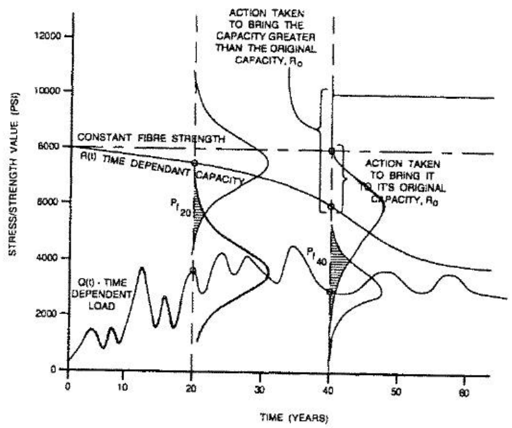


Figure 6. Time Dependent Aging Problem in Reliability Analysis (Modified After Schueremans, 2003)

Stress Strength Interference

Figure 6 depicts the interference of load and strength diagrams at age 20 years and 40 years respectively. For example, to illustrate how to assess this failure probability at age 20 years, the shaded area indicated as " $p_{f,20}$ " is an estimate of the failure probability assuming we know the distributions of load effects and strength at this point. The strength values can be obtained by carrying out full-scale tests for in-service poles removed from the site or by collecting field data based on non-destructive evaluation (NDE) using POLETEST equipment (EDM, 1997), provided

the NDE prediction is reasonably good. This should be done based on appropriate calibration (correlation). Some of the difficulties in doing this calibration will be discussed later. As a further illustration at age 40 years, the strength deteriorates further. The shaded area " $p_{f,40}$ " depicts the measure of failure probability at age 40, which is much greater than " $p_{f,20}$ ".

Figure 6 also depicts that as the structure loses its capacity because of the strength deterioration below some threshold value, it may be necessary to bring the capacity to its original installed level R_0 by appropriate intervention (mitigation). It may even be necessary to increase the capacity to a new level greater than the original capacity, R_0, by extra reinforcement such as adding guys, stubbing at ground level, adding bracing, etc. These graphical illustrations are based on the assumption that load effects remain constant over the entire service life. However if the load effects (design loads) change over the service life (Haldar, 1997), then the measure of " $p_{f,40}$ " will be amplified further (Figure 7).

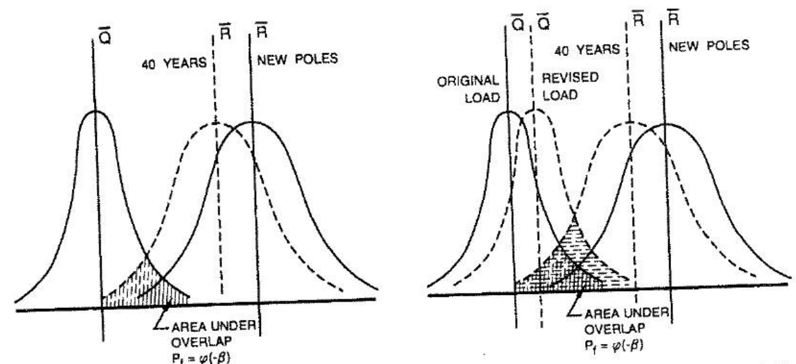


Figure 7. Effect of Strength Reduction and Load Revisions During Service Life

Reliability Assessment Of A H-Frame Structure Under Wind Only Case

Figure A1 in the APPENDIX depicts a typical 230 kV wood pole H-Frame structure that is cross-braced and knee braced to support the conductor loads due to wind and ice. The structure may experience three possible failure modes under various load combinations. These are: (i) pole bending, (ii) pole buckling and (iii) knee brace failure under vertical load. Let us assume a simple transverse "pole bending" failure mode due to wind only. In this situation the bottom of the cross brace is the "weak link" and the distribution of moment value should be compared with respect to the current strength distribution value at this point. A lognormal distribution is used here to simplify the calculation process and the details of the β-value computation are presented in the APPENDIX. For non-normal load effects, the computation process is more involved (Haldar, 2006).

Strength Model

To develop the strength distribution of the in-service poles of various age groups, a number of poles were tested at Memorial University of Newfoundland (MUN). Figure 8a depicts the MUN test set up. Since the test program has a limited sample size it was decided to correlate the full-scale test data with NDE data obtained by POLETEST (EDM, 1997). Figure 8b presents the data collection in the field using POLETEST. Figure 9 depicts the full scale and the predicted data (NDE) obtained from MUN test. The uncertainty in the prediction is introduced through two factors: (i) model error and (ii) data error due to finite sample size. However to develop a general methodology for calibration of various full-scale test data against POLETEST data, one needs to assess the quality of the dataset (correlation) and its influence on the prediction interval.

In statistical data analysis, the degree of predictability will often depend on the quality of the dataset (mutual dependence between full scale test data and the NDE data) and this is often measured by the statistical correlation coefficient, R^2. The correlation value was low. This raised concerns with respect to the prediction interval reported in the literature in terms of strength cut off limit in the POLETEST manual. (EDM, 1997). A further literature search revealed that similar observations with particular reference to poor correlation were also reported by Wright (1992) for SYP data. Figure 10 presents this data.

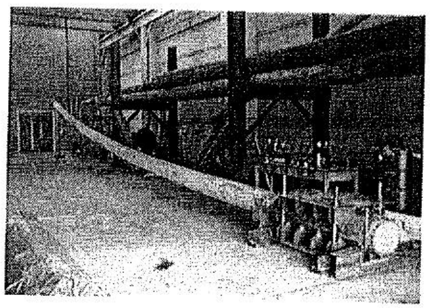


Figure 8a. MUN Test Setup

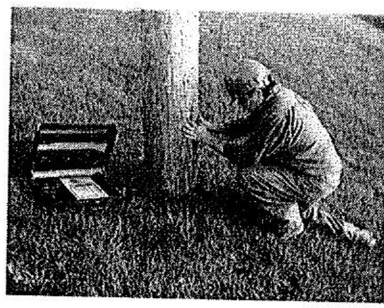


Figure 8b. POLETEST in Use

Since the data correlation was poor, it was decided to use directly the full-scale test data in the reliability calculation with particular reference to strength model for a specific pole age group. However NDE data analysis is still under study and the full results will be published in the near future.

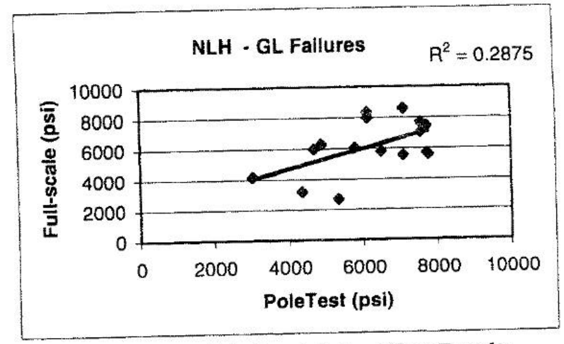


Figure 9. Predicted and Actual Test Results

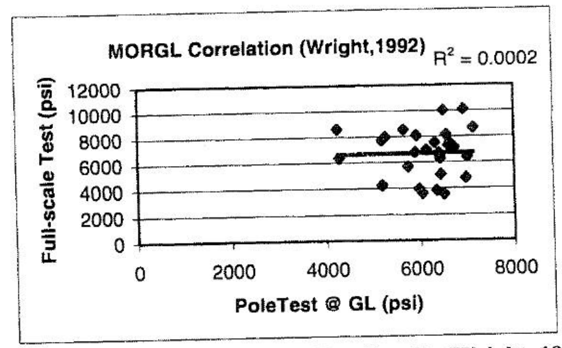


Figure 10. Predicted and Actual Test Results (Wright, 1992)

Development Of Condition Matrix Based On Field Data

This section will describe a logical approach to the development of condition matrix where the structural reliability analysis information of each pole (β-Value) is used with the condition rating obtained from the field inspection (Figure 5). Each pole is also tested for NDE information. If the pole has shell separation problem or other localized problems, this NDE information may not be available. The retention level data is collected for 10% of the pole population inspected. Additional retention data collection is mandatory if a pole is ranked 3 or above. After a careful evaluation of the data for each pole, which includes sounding information, retention level data as well as shell rot, pole decay, etc, a revised ranking is established as per Table 1.

Table 1. Overall Condition Ranking For Line Component

Pole Condition	Rank	Action
Severe	5	Emergency (Safety Issue) –Immediate mitigation, possible replacement
Poor	4	Requires Analysis and possible mitigation within next year
Fair	3	Requires analysis (possible mitigation) and monitoring
Good	2	No Immediate Action Required (Good for next inspection cycle)
New (Less than 10 years)	1	No Immediate action required

This revised ranking could be higher than the field rating taking into account the additional comments of the inspector. This revised ranking is later used against the β value for each pole obtained from the reliability analysis (APPENDIX) to derive an overall condition matrix for a specific failure mode. A β value of 2.0 - 2.5 is usually targeted as threshold. Similar condition matrix can be developed for all other primary failure modes for each line component such as cross arm, cross braces, conductor, etc. Let us assume that we have inspected a number of poles on a line. By using the above approach, one can derive four possible outcomes. Table 2 presents these outcomes.

Table 2. Condition Matrix Showing Inspection Versus Analysis Outcomes

Condition Matrix	Inspection	
Analysis	**Outcome 1** Condition Rating –Low β - High	**Outcome No.2** Condition Rating -Low β -Low
	Outcome No.3 Condition Rating -High β -High	**Outcome No.4** Condition Rating -High β - Low

Figure 11 presents the analysis results of a 230 kV line. Only a section of a line is included here, which consist of 60 pole inspection data. The analysis shows that 33 poles out of 60 poles inspected do not require any immediate actions. The remaining 27 poles do require some further actions. Outcome 4 requires actions to mitigate the problem of 3 poles

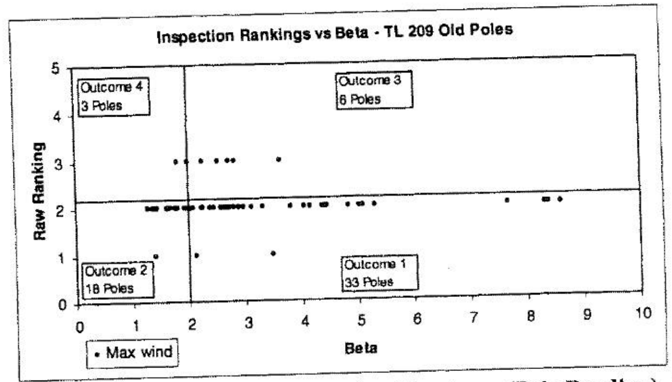


Figure 11. Summary Plot For Suspension Structures (Pole Bending) –Beta Values Versus Condition Ranking

The specific mitigation action can vary depending on the failure mode. If a pole has lost fiber strength considerably, one can add guys to support the pole or replace the pole completely. Obviously adding few guys would be a much cheaper option compared to the full replacement of the pole. If the problem is specific at the ground line, stubbing should be considered to attain a more cost effective solution. Similarly, if the analysis shows that the top portion of the pole where the knee brace arrangement is placed is exposed to decay, steel collars may be added to increase the strength. Figure 12 shows some decision chart outlining the above approach. The above 3 poles required additional guy supports. These poles will be monitored and will be re-evaluated within two years.

Conclusions

A framework for systematically analyzing a large volume of wood pole transmission line inspection data has been developed using the reliability based analysis technique. The method uses a hybrid approach where the uncertainties in load and strength values and the strength deterioration due to aging are taken into account with the condition rating of each pole to develop a condition matrix table. This matrix table provides four possible outcomes for future mitigations. Although the method is presented for "pole bending" failure mode, it is also equally applicable to other failure modes such as vertical failure mode of the cross arm or buckling failure mode of the angle and/or dead end structures.

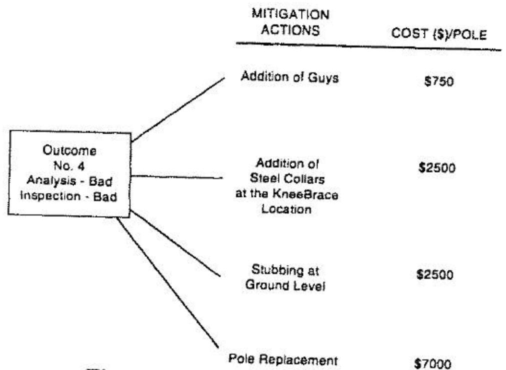


Figure 12. Mitigation Approach

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APPENDIX A

Estimation Of β - Value For Pole Bending Analysis Under Wind Load

Figure A1 presents a typical H-frame structure (knee braced and cross braced) of height, H_G above the ground line. The failure point is assumed to be below the cross brace level. The point where the bending moment is zero (contraflexure point) is first determined. The bending moment at the bottom of the cross brace level, M_C, is also determined from the maximum shear at the point of contraflexure. This moment is a function of the many parameters that depend on conductor diameter, ϕ_{Top} (diameter at the pole top), ϕ_b (diameter at the bottom of cross brace), ϕ_C (diameter at the zero bending moment point), ϕ_G (ground line diameter), H_{BT} (distance between the contra flexure location and pole top), H_{BC} (distance between the point of contra flexure and the bottom of the Cross brace), G_f (gust factor), V (annual wind speed) and t_{ice} (annual ice thickness) respectively.

The limit state function at any time is LS = $R_{M_c}(t)$ - M_C, where $R_{M_c}(t)$ is a time dependent function that relates strength over time. Failure indicates that LS ≤ 0.0. $R_{M_c}(t)$ can be evaluated at discrete time points of the pole plant assets from inspection, test etc. It is expressed as $R_{M_c}(t) = \sigma_{Fibre}$ (t) x Z_{M_c}(t) where Z_{M_c} (t) = $(\pi/32)$ $[\phi_C(t)]^3$ is the section modulus and σ_{Fibre} is the fiber strength at any time point. Again both σ_{Fibre} and Z_{M_c} are time dependent.

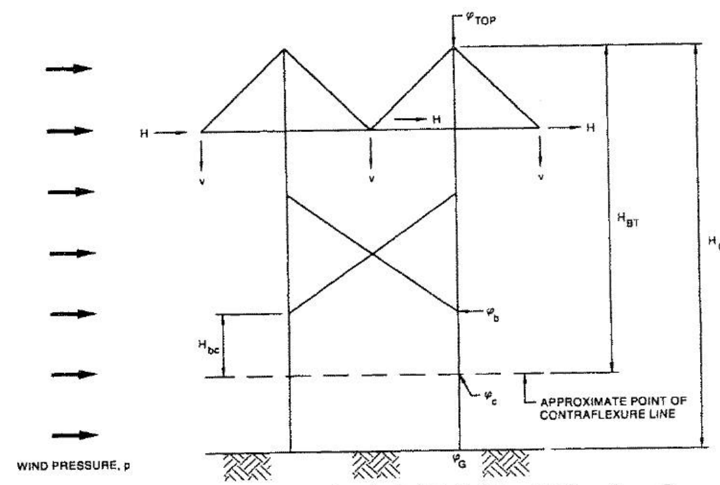

Figure A1. H-Frame Structure – Analysis Model For Estimating β

Based on our own test data, we find that σ_{Fibre} drops to a point from the initial average value significantly and then remains in steady state condition beyond 35 years. On the other hand the section modulus, Z_{M_c} can continue to drop due to rot and/or carpenter ant damage unless some actions are taken early enough to arrest the situation (probably through treatment with some additional cost) or putting collar to increase the section modulus. The load effect M_C is calculated based on annual values of wind speed, ice thickness and their combinations. The mean and the variance of the load effects are computed and the time dependent reliability index, $\beta_{M_c}(t)$, is obtained as (Melchers, 1996)

$$\beta_{M_c}(t) = \frac{Ln\{\frac{\overline{R}_M(t)}{\overline{M}_C}[\frac{(1+COV^2{}_{M_c})}{(1+COV^2{}_{R_c})}]^{0.5}\}}{\sqrt{Ln[(1+COV^2{}_{M_c})(1+COV^2{}_{R_c})]}}; \qquad [A1]$$

where COV of R_{M_c} and M_C define the coefficients of variation for load effects and strength respectively.