TechBrief

The Advance Concrete Bridge Technology to Improve Infrastructure Performance Program's purpose is to advance the current state of practice for design and construction of post-tensioned bridge structures in the U.S.

Office of Bridges and Structures
FHWA-HIF- 20-041
February 2022

U.S. Department of Transportation
Federal Highway Administration

Methodology for Risk Assessment of Post-Tensioning Tendons

Introduction

Post-tensioned (PT) bridges have experienced a number of corrosion-related tendon failures in recent years. Both internal and external tendons have been affected by corrosion as a result of grout segregation, voids, and the intrusion of water and corrosive agents. Selection of effective strategies for corrosion protection during the design of post-tensioned bridges can mitigate the risks of corrosion damage during the service life of a bridge. FHWA developed a methodology for risk-assessment of PT tendons to assist designers and bridge owners in selecting effective strategies for corrosion protection (Link: Methodology Report). Neither the methodology nor risk assessment of PT tendons is required under FHWA regulations.

The report provides a suggested rationale for conducting risk assessment of Post-Tensioning (PT) tendons to aid designers in the selection of corrosion protection strategies for PT systems in bridges. The risk assessment is intended to help State Departments of Transportation (DOTs) as they prioritize the need for protective technologies and processes, considering the likelihood and consequences of corrosion damage (i.e., the risk) based on the attributes of specific PT system designs. This TechBrief summarizes the methodology developed in (Link: Methodology Report).

PT system attributes that can affect the likelihood of corrosion damage during the service life of a bridge are considered. These system attributes can include tendon profile, alignment and protection, the surrounding environment, and quality processes used during construction. The consequences of corrosion damage resulting in tendon failure are considered in terms of structural reliability, ease of tendon replacement, and the overall importance of a bridge.

Scope

The methodology described in (Link: Methodology Report) is applicable for assessing the risk of corrosion damage for PT tendons in bridge superstructures for the purpose of identifying appropriate corrosion protection strategies. The analysis is focused on electrolytic corrosion that commonly manifests as localized damage. The methodology is appropriately implemented for the analysis of individual tendons in a bridge.

Background

The PT risk methodology was developed using the procedures described in NCHRP Report 782, *Proposed Guideline for Reliability-Based Bridge Inspection Practices* [1]. The risk assessment process consists of estimating the likelihood of damage occurring, described by an Occurrence Factor (OF), and the consequences of that damage, described by a Consequence Factor (CF). The OF is analogous to a probability of failure or likelihood of an adverse event. The CF describes the potential impact of corrosion damage on safety, the cost of replacing a damaged tendon, and bridge importance.

Each of these factors can be estimated by analyzing key attributes of the bridge and tendon design that affect the likelihood of damage occurring and its consequences. For purposes of this document, risk is estimated as:

$$Risk = OF \times CF \qquad \text{Equation 1}$$

The risk calculated from Equation 1 provides a relative measure of the risk associated with a given set of attributes for a tendon. This measure of risk can be used to assess the need for action to reduce the likelihood of corrosion damage occurring during the service life of a bridge.

To identify the key attributes of bridge and tendon design that affect the risk of corrosion damage in PT tendons, FHWA formed a Reliability Assessment Panel (RAP) of experts in the design, inspection, construction, and maintenance of PT bridges. The expert elicitation procedures from Report 782 were used to identify key attributes of PT bridges that affect the likelihood of corrosion damage in tendons and its consequences. The attributes were ranked and used to form a risk model consisting of a quantitative scoring process, as described below, to provide an estimate of the OF and the CF.

The identified OF attributes were ranked qualitatively according to their impact on the likelihood of corrosion damage developing during the service life of a bridge. An attribute was ranked "high" if it is expected to have a significant impact on the likelihood of the corrosion damage, "moderate" for a relatively smaller impact, and "low" if it is expected to have minor or no impact. The attribute scoring was initially weighted according to its rank of High, Moderate, or Low as 20, 15, or 10 pts, respectively. Those attributes ranked as "low" impact on the likelihood of corrosion damage occurring in tendons were neglected due to the relatively small influence these attributes would have on the likelihood of corrosion damage.

Criteria were then developed to differentiate the RAP's scoring of a given attribute. Again, a High, Moderate, and Low scale was used, with "High" indicating a criteria or requirement that most increases the likelihood of damage to be assigned the maximum score (20 or 15 pts). The rank of "low" indicated a criteria or requirement least likely to increase the likelihood of corrosion damage and receiving a minimum score, typically 0. Criteria ranked as "moderate" were typically assigned 50% of the maximum score given the ranking of the attribute. For example, for the attribute of grout quality, a lower quality grout (e.g., Class A grout) is ranked as "High," and better-quality grout (e.g., Class C grout) was ranked as "low." In this way, higher scores indicate increased likelihood of damage occurring, based on the identified attributes and the rankings. Specific values for individual attributes were subsequently adjusted based on a sensitivity study and engineering judgment.

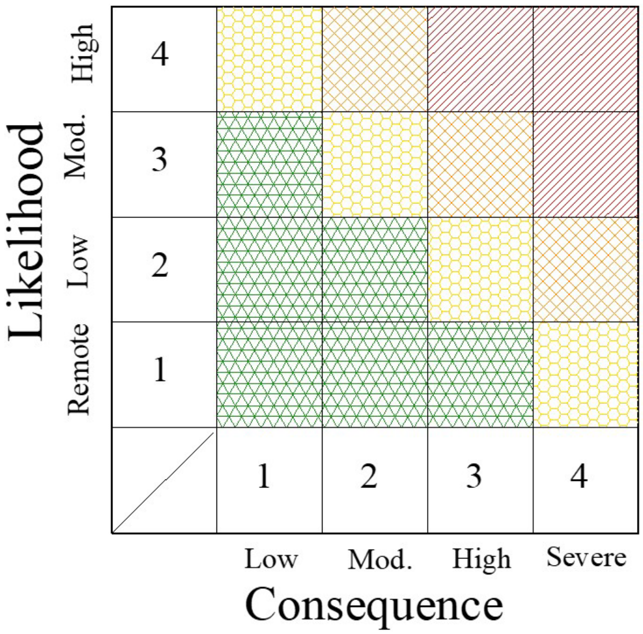
The values for each relevant attribute are assigned by rating the attribute according to the criteria developed. The results from each attribute are then summed and normalized to estimate the likelihood of damage, described by the OF:

$$OF = {\sum S_i}/{\sum S_0} \qquad \text{Equation 2}$$

where S_i is the score recorded for each attribute and S_0 is the maximum score for each attribute, such that the ratio is a value between 0 and 1. The CF is estimated in a similar manner.

The resulting OF and CF factors can be used in two ways to characterize the risk of corrosion damage in a tendon. The values can be used to place a particular tendon in the appropriate bin on a risk matrix such as that shown in Figure 1, or the product of the OF and the CF can be used to estimate a quantitative risk value on a scale from 1 to 100.

The OF and CF ratios can be used to locate the analyzed tendon on a risk matrix such as shown in Figure 1 by categorizing the likelihood (OF) and the consequence (CF). For the OF, categories of remote, low, moderate or high are used to characterize the likelihood, while categories of low, moderate, high, and severe are used to characterize the consequence for the CF. The factor for appropriate categories is determined by multiplying Equation 2 by 4, resulting in values on a scale from 0 to 4. For the OF, values between 0 and 1 are identified as "Remote," meaning the likelihood of damage is estimated to be remote, given the attributes and criteria. Values 1 or greater but less than 2 are ranked as "Low," and so on. The CFs are categorized in a similar manner. This approach provides a simple methodology for categorizing the likelihood of corrosion damage and its consequences by locating a given tendon in a particular bin on the risk matrix. Decisions regarding suitable actions are then based on the location on the risk matrix, with bins tending toward the upper right indicating higher risk and bins tending toward the lower left are lower risk.



Source: FHWA

Figure 1 Illustration. Example risk matrix showing likelihood and consequence levels.

The ratios can also be applied directly to provide a risk estimate on a continuous scale using the equation:

$$R = OF \times CF \times 100 \qquad \text{Equation 3}$$

where R is a relative risk value, or *risk factor*, on a scale from 1 to 100.

In either case, decisions based on the risk analysis are subjective and based on engineering judgment, and threshold values or ranges can be selected to support decision making. When using the risk matrix, individual bins are identified as different levels of risk as suggested by the different colors and patterns shown in Figure 1. When using a continuous scale from 1 to 100, threshold values can be selected to characterize the level of risk. Specific recommendations for characterizing the risk for tendons are described in the report (Link: Methodology Report).

Processes

The risk assessment conducted by the RAP identified damage mechanisms that can affect the likelihood of corrosion damage in PT tendons. The identified damage mechanisms are vulnerabilities of the design or construction process that have a significant impact on the likelihood of corrosion damage. The damage mechanisms identified by the RAP are shown in Table 1. The identified damage mechanisms included breaching of a duct or anchorage that would allow the ingress of water and corrosive agents into the duct. The quality of the construction and workmanship was also identified as affecting the likelihood of developing corrosion damage. The aggressiveness of the environment, the adequacy of the specification and detailing, the quality of materials used, and the potential for grout voids to form in the duct were each identified by the RAP, as shown in Table 1.

Table 1. Damage mechanisms identified by the RAP.

ID	Damage Mechanism
1	Breached duct or anchorage
2	Construction and workmanship quality
3	Environment
4	Inadequate specifications and detailing
5	Poor or improper materials
6	Grout voids

Attributes were identified that correspond to one or more of these damage mechanisms. These attributes are characteristics of the design, loading, materials, and construction processes planned for a given PT system.

The attributes identified were ranked according to their impact on the likelihood of corrosion damage as a result of the identified damage mechanism. Criteria were developed to differentiate the scoring of a given attribute based on the engineering judgment of the

RAP. Attributes that describe the likely consequence of a tendon failure due to corrosion damage were also identified and ranked.

Risk Model Attributes

The risk assessment process was used to identify and prioritize attributes that contribute to the risk of corrosion damage in tendons. The risk model described in (Link: Methodology Report) considers 19 separate attributes that are numbered A1 through A19 as shown in Table 2.

Table 2. Attributes and associated ranks identified by the RAP.

Attribute	No.	Attributes	Rank
PT Tendon and Profile	A1	Tendon Length	High
	A2	Tendon Vertical Profile	Very High
	A3	Tendon Curvature	Moderate
	A4	Profile Conflict Avoidance	Moderate
PT Tendon Joint and Closure	A5	Cold Joints, Precast Segments	High
	A6	Cold Joint, Cast-in-Place (CIP) Segments	Moderate
	A7	Closure Pours	High
PT System Materials and Components	A8	Anchorage Protection, Interior	Moderate
	A9	Anchorage Protection, Exposed	High
	A10	Venting Protection	High
	A11	Grout Material Performance	High
	A12	Materials Specification	Moderate
	A13	Venting	High
	A14	Use of Diablos	High
PT Installation Quality	A15	Construction Quality	High
	A16	Quality Assurance	Moderate
	A17	Grouting Procedures	High
Environmental	A18	Macro Environment	High
	A19	Micro or Local Environment	High

The attributes are organized into five categories for convenience as follows:

- *PT Tendon and Profile Attributes* describing design characteristics of the tendon being analyzed.

- *PT Joint and Closure Attributes* describing the attributes associated with joints between segments and the characteristics and number of closure pours traversed by the tendon.

- *PT System Materials and Components Attributes* describing the levels of protection provided at anchorages and vents, grout materials used, handling and storage of grout materials, location of vents relative to high points along a tendon, and the use of diabolos for external PT applications.

- *PT Installation Quality Attributes* describing the certification and specifications planned for construction and the procedures used to install grout.

- *Environmental Attributes* describing the ambient environment in which a bridge is to be constructed (macro-environment) and localized exposures to aggressive environmental conditions (micro- or local environment). The micro environment is used to characterize when a tendon anchorage is directly below an expansion joint or otherwise experiences localized exposure to water and corrosive agents.

The priority rank (i.e., High, Moderate) of each attribute is also shown in the table. Attributes ranked “Low” were not included in the model due to their relatively smaller impact on the likelihood of corrosion damage. Each attribute was assigned an alpha-numeric code (e.g., A1, A2, etc.) for organizational purposes.

Three attributes were used to characterize the consequences of corrosion damaged tendons as shown in Table 3. One describes the importance of tendons in terms of structural reliability, one describes the ease of replacement (i.e., potential cost), and one refers to the importance of the bridge itself in terms of the transportation network.

Table 3. Consequence attributes identified by the RAP.

No.	Attribute	Rank
C1	Tendon Importance, System Level	High
C2	Ease of Tendon Replacement	High
C3	Bridge Importance	Optional

Adoption of Current Specifications

The risk model considers the partial or total adoption of certain voluntary specifications that describe current state-of-the-practice for construction of durable post-tensioned bridges. The adoption of some or all portions of these specifications is known to vary among different bridge owners, with some owners adopting these specifications in full, while others may adopt only portions of the specifications or utilize owner-specified requirements that may differ. Implementation of these voluntary specifications may mitigate a number of attributes that contribute to the risk of corrosion damage in post-tensioned bridge construction implementing the risk model

The risk model is implemented by selecting the relevant attributes for determining the OF and scoring each attribute according to the information provided in the model. Analysis is conducted for a single tendon in a bridge; tendons with different attributes should be analyzed separately. Bridge design plans and specifications for the subject bridge are needed to determine the relevant attributes and the appropriate rating for each attribute.

The OF is determined from Equation 2 based on the summation of the relevant attributes. Attributes that are not relevant to a particular tendon design can be omitted from the analysis. The CF is determined from the three relevant attributes related to the system redundancy, the replaceability of the tendon, and the importance of the bridge.

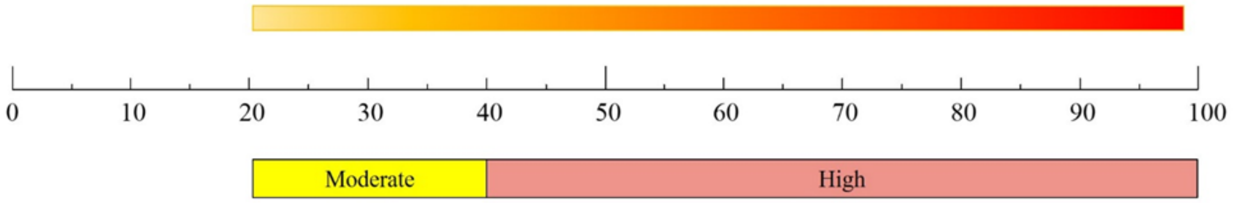
Based on the calculated values of the OF and the CF, the risk rating can be calculated according to equation 3 to determine the relative risk level for the tendon analyzed. Alternatively, the results may be plotted on a risk matrix, as described below. A spreadsheet format is suitable for implementing the model. Examples are provided in Appendix A of (Link: Methodology Report), which illustrate a spreadsheet application of the attributes for determining the OF and the CF.

Risk Levels

The risk model results in a relative score for the OF and the CF. The decision-making based on this output can be implemented using a risk matrix, in which the OF and CF are each categorized as one of four possible categories, and the risk level is assessed based on the bins in the risk matrix, shown in Figure 1.

Alternatively, a continuous scale from 1 to 100 can be implemented to estimate the level of risk based on Equation 3. Using this approach, the level of risk can be assessed using Figure 2. The figure illustrates an elevated risk range as risk factor scores increase based on the assessment process.

Risk mitigation or reduction strategies should be considered for tendons assessed to have certain levels of elevated risk. The following section describes common risk reduction and mitigation technologies that could be implemented to reduce the level of risk, though they are not required under FHWA regulations.



Source: FHWA

Figure 2. Chart. Example of risk levels based on 100-point risk scale.

Technologies for Preventing Corrosion Damage

This section describes available technologies for corrosion protection that could be implemented for PT tendons with elevated risk. The technologies have been divided into two groups, as shown in Table 4. This includes Mitigation Strategies that minimize the likelihood of corrosion damage in PT tendons uniformly, and Risk Reduction Strategies that can be implemented to reduce the value of certain attributes and thereby reduce the value of the OF. Relative measures of the cost and effectiveness of these technologies on a qualitative scale (Low, Medium, High) are also shown in Table 4.

The first group, Mitigation Strategies, describes technologies that could be implemented to minimize the likelihood of corrosion damage in PT tendons. These technologies may be considered when the risk level is very elevated due to design features that increase the susceptibility to corrosion damage. This includes Electrically Isolated Tendons (EIT), selection of corrosion-resistant strands (e.g., stainless steel strands), and use of corrosion-inhibitor in the tendon. Implementing these technologies in the design of PT systems may significantly reduce the risk of tendon failure due to corrosion damage.

The second group, Risk Reduction Strategies, describes technologies or choices that could be selected to reduce the numerical risk factor value by modifying various attribute values. Risk reduction strategies include changing attributes of the design that affect the CF, such as using replaceable tendons or increasing redundancy with additional tendons. Risk reduction strategies also include adding additional layers of protection, improving quality processes and fully implementing contemporary specification intended to protect tendons from exposure to corrosion materials. These technologies can be considered to reduce the overall risk profile and may be selected during the design process to improve the durability of the bridge.

The risk assessment methodology described in (Link: Methodology Report) is intended to provide a systematic approach to identifying when these risk mitigation and reduction strategies should be considered during the design phase for PT bridges. The risk assessment is intended to help DOTs as they prioritize the need for protective technologies and processes, with the goal of improving the durability of PT system designs through the appropriate implementation of corrosion protection strategies. More information on the risk assessment methodology can be found in (Link: Methodology Report).

Table 4. Corrosion protection technologies.

Strategy	Technology	Cost	Benefit
Mitigation Strategies	Electrically Isolated Tendons (EIT)	L	H
	Stainless steel strand	H	H
	Carbon fiber strand	VH	H
	Galvanized strand	M	M
	Corrosion-Inhibitor tendon impregnation	M	M
Risk Reduction Strategies	Replaceable tendons	M	H
	Increase number of tendons	L	M
	Full adoption of: PTI/ASBI M50.3-19 [1] PTI M55-1.19 [2]	L	H
	Enhanced QC/QA	L	H
	Vacuum-assisted grouting	L	H
	Include additional layers of protection	L	M
	Structural Health Monitoring	M	M

References

[1] G. Washer, M. Nasrollahi, C. Applebury, R. Connor, A. Ciolko, R. Kogler, P. Fish and D. Forsyth, "Proposed Guideline for Reliability-Based Bridge Inspection," National Academy of Sciences, Washington, DC, 2014.

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Research — This Technical Brief was developed as part of FHWA's Advance Concrete Bridge Technology to Improve Infrastructure Performance agreement. The Report is based on research cited within the document.

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Key Words — post-tensioning, strands, tendon, grout, corrosion, void, electrically isolated tendons.