RESEARCH REPORT
External Research Program

Investigation Protocol for Evaluation of Post-Tensioned Buildings

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INVESTIGATION PROTOCOL
FOR EVALUATION OF POST-TENSIONED BUILDINGS

Report for
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SUMMARY

Investigation protocols for the evaluation of buildings with unbonded post-tensioned reinforcement are described. The high strength steel strands used in the post-tensioned construction are susceptible to corrosion. The corrosion is not likely to be evident from visual inspections. Special techniques and expertise are required to assess unbonded post-tensioning systems.

Evaluations can have many different objectives. The client and consultant should identify and agree upon the purpose of the investigation and end objectives. The consultant must recognize business influences and risk tolerance of the client when defining the scope of the investigation. Clients need to resolve the conflicting objectives of minimizing the investigation costs and reducing uncertainties in predicting future performance.

Planning of the investigation should begin with a review of available documents such as drawings, specifications, construction records, and previous reports. Prior to deciding on the scope of testing, a preliminary design review should be conducted to assess the overall robustness of the design, identify the most critical areas and potential problems one should look for on site. A preliminary visual inspection should be performed to confirm occupancy loads, identify obvious deviations from the original design, and note areas with signs of distress that would warrant special investigation. Accessibility, physical constraints and any other requirements that impact the testing program should be identified. Building areas should be grouped according to their exposure to moisture and the associated risk of moisture access to strands. A reasonable number of strands should be sampled in each exposure group with inspection recess locations selected to maximize the likelihood of finding problems, if there are any.

Site work includes chipping of concrete to expose strands by contractors experienced with this work. The tension in every strand length exposed for testing should be assessed by the screwdriver penetration test. This may be supplemented by: quantitative tension measurements on selected strands using the cut-wire or deflectometer methods; extraction of selected strands for full-length inspection and metallurgical tests; humidity measurements within the sheaths; and analysis of contaminants with the sheath. The extent of fieldwork and testing depends upon the client's requirements and the initial test results. If the initial findings lead to uncertain or ambiguous conclusions, the scope may need to be expanded to increase the level of confidence.

Test results should be evaluated by an engineer with experience in the design and assessment of buildings with unbonded post-tensioning. Significant judgment must be exercised when interpreting the results obtained at inspection recesses, as they may not reflect overall conditions. Causes of detected strand tension deficiencies should be confirmed. The tolerable tendon loss ratios (portion of tendons that can be lost without compromising safety) should be determined. Prediction of future performance should be based on information obtained for the particular structure and the potential for future moisture access to the post-tensioning system.

Reporting should incorporate format and nomenclature consistent with that used in the consulting industry. Background information and details of previous test/repair programs should be included. Test results should be clearly presented for differing areas throughout the structure. Repair and maintenance recommendations should identify areas of immediate concern, implications for future performance, and monitoring requirements.

Continued monitoring is required where testing has identified a potential for future deterioration of the post-tensioning system. The building should be visually inspected and strands should be rechecked for tension on a periodic basis. The time between such inspections should be short enough that ongoing deterioration is unlikely to reduce the structural strength to critical values between inspections. An acoustic monitoring system has been developed which can identify strand breakage as it occurs. This system can reduce the uncertainty in predicting strand breakage and timing of repairs.

Many different repair options exist, if strand breakage compromises the safety of the structure. Preventative maintenance measures such as waterproofing of anchors and slab surfaces, and systems that purge moisture from within the tendons may be warranted in some cases.

RÉSUMÉ

Il est question des protocoles d'investigation relatifs à l'évaluation des bâtiments avec armature non adhérente de précontrainte par post-tension. Les câbles d'acier de résistance élevée qui s'utilisent dans de telles constructions sont sujets à la corrosion. Pourtant, la corrosion n'est pas évidente lors d'inspections visuelles. Des techniques et compétences particulières sont requises pour évaluer l'état de l'armature non adhérente précontrainte par post-tension.

L'évaluation peut poursuivre de nombreux objectifs différents. Il y va de l'intérêt du client et du consultant de caractériser l'objet de l'investigation et les objectifs ultimes, et d'en convenir. Pour sa part, le consultant doit tenir compte des influences d'affaires et de la tolérance au risque du client au moment de définir la portée de l'investigation. De son côté, le client doit régler les objectifs conflictuels qui consistent à réduire les coûts d'investigation et l'incertitude des prédictions entourant la performance future.

La planification de l'investigation doit commencer par la vérification des documents disponibles, tels que dessins et devis, dossiers de construction, et rapports précédents. Avant de décider de la portée des essais, une première vérification conceptuelle doit permettre d'évaluer la solidité générale de l'ouvrage, de désigner les endroits critiques et les problèmes possibles à rechercher sur les lieux. Une inspection visuelle préliminaire doit permettre d'établir le nombre d'occupants, de trouver les anomalies évidentes par rapport au concept d'origine, et de noter les endroits montrant des signes de dommages importants, qui justifieraient une investigation particulière. Il faut régler la question de l'accessibilité, des contraintes physiques et de toutes autres exigences influant sur le programme d'essais. Les aires du bâtiment devront être groupées selon leur exposition à l'humidité et le risque que l'humidité parvienne jusqu'aux câbles. Un nombre raisonnable de câbles doivent être échantillonnés dans chaque groupe d'exposition et les regards d'inspection choisis de façon à optimaliser la probabilité de trouver les problèmes, s'il y en a.

Les travaux sur place confiés à un entrepreneur possédant de l'expérience pertinente doivent permettre d'exposer des câbles. La tension de chaque longueur de câble exposé pour les besoins d'essais doit être évaluée au moyen du test de pénétration d'un tournevis. On pourra en outre procéder à des mesures quantitatives de la tension de certains câbles selon la méthode du fil découpé ou à l'aide d'un déflectomètre; extraire certains câbles pour en inspecter toute la longueur et effectuer des test métallurgiques; mesurer l'humidité à l'intérieur des gaines, et analyser les contaminants de la gaine. L'étendue des travaux à pied d'oeuvre et des essais dépend des besoins du client et des résultats d'essais initiaux. Si les premiers résultats aboutissent à des conclusions incertaines ou ambiguës, la portée des travaux pourrait devoir être accrue pour raffermir le sentiment de confiance.

Les résultats d'essais se doivent d'être évalués par un ingénieur possédant de l'expérience dans les domaines de la conception et de l'évaluation des bâtiments précontraints par post-tension. Il faut faire preuve de beaucoup de jugement lors de l'interprétation des résultats obtenus à l'endroit des regards d'inspection, puisqu'ils pourraient ne pas indiquer le véritable état général. Les causes de la tension déficiente notée des câbles devront être confirmées. Le coefficient de perte tolérable des câbles (fraction de la perte ne risquant pas de compromettre la sécurité) devra être déterminé.

La prédiction de la performance future devra être fondée sur les renseignements recueillis à l'égard du bâtiment particulier et de la possibilité éventuelle que de l'humidité parvienne jusqu'aux câbles de précontrainte par post-tension.

Le rapport devra suivre le mode de présentation et la nomenclature qu'utilisent les consultants, en plus de contenir des données documentaires et des précisions sur les programmes d'essais ou de réparations précédents. Les résultats d'essais devront être présentés clairement selon les différentes aires du bâtiment. Les recommandations en matière de réparations et d'entretien devront cerner les endroits méritant une attention immédiate, établir les répercussions sur la performance future et les besoins de contrôle.

Un contrôle continu s'impose lorsque les essais indiquent la possibilité de détérioration future des câbles de précontrainte par post-tension. Le bâtiment doit faire l'objet d'une inspection visuelle et la tension des câblés vérifiée périodiquement. Le délai séparant ces inspections doit être suffisamment court pour que la détérioration ne réussisse pas à amener la solidité structurale à des valeurs critiques entre les inspections. Un système de contrôle acoustique permet de déceler la rupture des câbles lorsqu'elle se produit. Ce système peut réduire l'incertitude quant à prédire la rupture des câbles et le choix du moment d'effectuer les réparations.

Il existe de nombreuses options de réparation différentes, si la rupture de câbles compromet la sécurité du bâtiment. Dans certains cas, des mesures d'entretien préventif portant notamment sur l'imperméabilisation des ancrages et des dalles, ainsi que sur les dispositifs éliminant l'humidité à l'intérieur de l'armature, peuvent être justifiées.

Protocole d'investigation pour l'évaluation de bâtiments précontraints par post-tension

Sommaire

Plus d'un milliard de pieds carrés d'ouvrages en béton comportent une armature non adhérente précontrainte par post-tension en Amérique du Nord. En général, les ouvrages ainsi réalisés affichent une bonne tenue en service à la condition que l'humidité ne puisse pas parvenir jusqu'à l'armature non adhérente précontrainte par post-tension. Par contre, les bâtiments construits de cette façon requièrent des techniques d'évaluation particulières pour éviter d'établir un mauvais diagnostic pouvant mener à des réparations contre-indiquées, coûteuses, voire inutiles. En revanche, de sérieux problèmes de sécurité peuvent passer inaperçus si le programme d'évaluation ne permet pas de reconnaître les problèmes particuliers des systèmes de précontrainte par post-tension. Le présent document vise à mieux comprendre les exigences techniques particulières de l'investigation et de l'entretien des bâtiments comportant une armature non adhérente. Il est destiné à venir en aide aux ingénieurs, aux maîtres d'ouvrage et aux spécialistes de l'immobilier qui doivent composer avec de tels bâtiments.

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1. INTRODUCTION

1.1 Background

There is more than one-billion square feet of concrete structures which utilize unbonded post-tensioned reinforcement in North America. In general, these buildings perform well provided that moisture access to the unbonded post-tensioned reinforcement is avoided. However, buildings constructed in this manner do require special evaluation techniques to avoid misdiagnosis that can lead to inappropriate, expensive, or unnecessary repairs. Alternatively, serious safety issues may be left undiscovered if the evaluation program fails to recognize the unique issues related to unbonded post-tensioning systems. The purpose of this document is to provide an understanding of the unique technical requirements for investigation and maintenance of buildings with unbonded tendons.

Unbonded post-tensioned reinforcement consists of high strength steel strands which are coated with a layer of grease and inserted into plastic sheathing. The complete assembly including steel strand, sheathing, and anchors is described as a tendon. Tendons are laid out on the formwork and supported on wire chairs of varying height. After the concrete is placed and allowed to gain strength, the strands are tensioned at one or both anchors using a hydraulic jack. After tensioning, protruding strand lengths are cut and a grout plug is typically placed over the anchors.

Corrosion and breakage of unbonded post-tensioned strands has occurred in many structures as a result of moisture penetration into the tendons. The high strength steel strands are particularly susceptible to corrosion. Problems have been observed in post-tensioning systems built prior to the late 1980's, after which time new systems were introduced with improved waterproofing and durability. Moisture ingress and strand corrosion have been encountered to varying degrees in buildings, depending upon factors such as sheathing type, service environment, and moisture entry prior to or during construction. Many buildings have performed well while the others have required multi-million dollar repair programs.

Unbonded post-tensioned strand corrosion and breakage usually will not be externally evident, even though the amount of strand breakage may be extensive. An investigation program involving selective exposure and testing of strands is necessary to assess safety, predict the likelihood of future strand breakage, and decide whether monitoring or repair is required. Inspection can be costly and disruptive, and repair even more so. The management and engineering considerations are typically to minimize disruption, minimize cost of inspection and monitoring, maximize the time between repair cycles (optimize repairs), and to provide adequate assurance of the building's safety and serviceability.

Durability concerns regarding unbonded post-tensioned reinforcement were first identified in the 1980's. Since that time, investigation protocols have evolved over time as project experience increased and the level of knowledge in the consulting community grew. This document represents a summary of this experience.

1.2 Objectives

This document is written with two different reader groups in mind.

First, it is intended that this document be a guide for owners, property managers, and others with an interest in real estate, to develop consistent standards and expectations for the assessment and maintenance of unbonded post-tensioned structures. Non-technical readers will gain an understanding of the unique characteristics of unbonded post-tensioned reinforcement that make buildings with unbonded tendons unlike other types of buildings.

The second intent of this protocol is to assist the Professional Engineer in the planning and execution of an appropriate evaluation program for a structure containing unbonded post-tensioned tendons.

In order to satisfy the above objectives, this document is intended to:

- identify factors that have contributed to the wide range in performance of unbonded post-tensioning systems,

- recognize business influences and risk tolerance of building owners and other stakeholders in defining investigation scope,

- outline currently available investigation techniques,

- suggest appropriate investigation sampling sizes for different building types,

- define contents of typical reports,

- provide general comments on restorative and preventative maintenance options.

1.3 Scope

This document outlines the steps that should be followed in the investigative process and provides recommendations for the maintenance and restoration of structures containing unbonded post-tensioned reinforcement. Suggestions regarding the type and extent of testing that should form part of a complete condition survey are presented while bearing in mind that different stakeholders may require differing levels of reporting detail.

This document has been prepared by consultants familiar with performing condition surveys of post-tensioned structures and represents their opinions regarding the procedures that may be employed in the evaluation process.

1.4 Organization of the Document

The format of this document reflects the recommended thought process to plan and undertake the investigation of unbonded post-tensioned buildings as follows:

1. Establish the client's requirements. The intended use of the information collected will be important in determining the scope of the investigation.

2. Planning and performance of the investigation program. Recommended procedures for the interpretation of field results are presented along with comments regarding the use of the information to predict future performance of the structure.

3. Preparation of reports summarizing findings. Suggested format and content of reporting is outlined with a view to consistency within the consulting community.

4. General information is provided regarding the monitoring, maintenance and restoration of structures with unbonded post-tensioned reinforcement.

1.5 Limitations

This protocol is not intended to eliminate the need for the investigating engineer to have experience in the design and assessment of unbonded post-tensioned structures. Post-tensioned structures are unlike ordinary reinforced concrete structures. Thus owners should investigate the credentials and relevant experience of professionals when seeking their advice.

This document does not provide all of the background information required to undertake a complete condition review. The experience of the consultant performing the work should be used to compliment this document in determining the best strategy to employ on a given project.

Judgment must be exercised when extrapolating test results obtained from a limited sampling to the overall structural performance.

The durability and performance of the post-tensioning system can vary widely between different structures and within particular structures. Each building must be considered individually.

This document is not intended to be a specification dictating minimum levels of testing or minimum standards for maintenance. Any opinions or recommendations therefore should be seen as general information upon which the real estate industry, in conjunction with their consultants, can develop programs for the evaluation and maintenance of properties containing unbonded post-tensioned reinforcement.

This document is limited to single strand unbonded post-tensioning systems. When considering the overall structural performance, potential deterioration or deficiencies of the mild reinforcement and concrete must also be considered. Reports from ACI Committee 201 and Committee 364 provide guidance on the inspection and assessment of concrete and other non-tendon related issues. Additional references are included in the attached appendices.

This document deals strictly with buildings constructed with unbonded post-tensioned tendons. Different procedures are involved in assessing grouted (bonded) single and multi-strand post-tensioning systems and pretensioned (precast) building components. Bonded post-tensioning and pretensioned (prestressed) elements are outside the scope of this document.

1.6 Experience Requirements for Intended Users

This document assumes that all engineering users of this guideline are familiar with unbonded post-tensioning through firsthand knowledge gained in the design and construction of structures containing unbonded post-tensioned reinforcement. This report focuses on extending the user's basic knowledge of design of post-tensioned structures to the challenges associated with assessment of existing structures.

1.7 Key Points

- High strength steel strands used in unbonded post-tensioned construction are particularly susceptible to corrosion.

- Specialized expertise is required to assess unbonded post-tensioning systems.

2. ESTABLISHING CLIENT REQUIREMENTS AND RISK TOLERANCE

2.1 Reasons for Investigation

Client input should be solicited prior to establishing the scope of investigation as the extent of information to be obtained can be influenced by a number of factors. An investigation of the post-tensioning system may be prompted by one or more of the following requirements:

- Pre-purchase due diligence
- Pre-financing due diligence
- Directives from municipal building officials
- Response to visible distress
- Routine condition inspection
- Maintenance expenditure forecasting
- Building operation cost audit
- Capital reserve fund study
- Remaining service life prediction
- Litigation
- Change in intended use of the structure

Note that in many of the above situations, the consultant's client may not own the building.

2.2 Achieving a Balance Between Risk Tolerance and Investigation Scope

The challenge in evaluating post-tensioned buildings is to gain sufficient information about existing conditions to make informed decisions within budgetary constraints of the client. The scope of investigation must therefore be tailored to meet the clients risk tolerance and business objectives at reasonable cost.

Due diligence investigations are often driven by the need to identify whether there are any significant concerns regarding a particular facility with a minimum investment in initial investigation costs. Supplementary investigation may be warranted if the client desires a greater level of confidence in predicting future performance or further refinement of costs related to remedial work.

For a building owner or property manager, the investigation priority may be to gain a thorough understanding of existing conditions and their implication with regard to future maintenance expenditures. If the client has limited tolerance for unanticipated expenses, the initial testing program can be designed to assess conditions throughout the structure rather than selective testing in representative areas. This would reduce the potential that an area experiencing greater deterioration would be missed. Conversely, if the client has a short term hold strategy for the building, or wishes to minimize short term expenses with the recognition that undetected deterioration may be discovered in the future, a limited investigation may be suitable.

With older facilities, some consideration may be given to redevelopment options rather than repair or maintenance, particularly if there is uncertainty in predicting the effectiveness or longevity of repairs. This may influence the scope of testing required to reach a decision.

Financial and insurance institutions or government agencies could have a lower risk tolerance in comparison to other clients. This will influence the level of investigation required to reduce uncertainties.

2.3 Key Points

- Clients and consultants should identify and agree upon the purpose of the investigation and end objectives.

- Consultants must recognize business influences and risk tolerance of the client when defining investigation scope.

- Building owners and managers need to resolve the conflicting objectives of minimizing investigation costs versus reducing uncertainties in predicting future performance.

3. INVESTIGATION PLANNING

3.1 Document Review

A condition assessment should include a review of all available documentation for the particular building. Attempts should be made to procure any record construction drawings that may be available. Sources of information could include the original designers and contractors, municipal archives, previous owners and managers. The structural drawings and post-tensioning system shop drawings are of particular use.

Experience shows that the original structural design depicted in the engineering drawings prepared by the Structural Engineer of Record may not represent the actual construction on site. Suppliers of post-tensioning systems often retained their own design engineers, and substantial portions of the original design were revised to suit the systems and components supplied by the subcontractor. Details, such as the number and size of tendons actually incorporated into the work, may differ from those shown on the original structural drawings.

Copies of construction photographs are helpful in determining the construction methods utilized by the general contractor and can be helpful in determining the time of year that the building was constructed. In addition photographs may provide information on the anchorage details, the construction sequencing, hoarding and other measures that may suggest a lower or higher potential for moisture access during construction.

Construction related information can also be obtained from the superintendent's diaries and from correspondence files. Strand stressing records and inspection reports are additional sources of information.

3.2 General Design Review

Prior to deciding on the scope of testing, a general review of the structural design should be completed. This is not intended to be a calculation intensive or thorough review of the structural design.

If drawings are available, they should be reviewed to determine the general arrangement of the post-tensioning system. The type of post-tensioning installation should be confirmed; one way or two way; banded and distributed; basket weave installations; and, portions of the structure that are post-tensioned, i.e., beams only. The location of live end stressing anchorages should be determined along with the size, spacing, and type of tendon installed.

Specified numbers of tendons should be used to determine average pre-compression in the cross section (P/A). This would be compared with what the engineer would expect for the given application to see if it is a typical design. An approximate punching shear calculation for two-way slabs should be performed. The span to depth ratio for elements should be reviewed to see if they are reasonable. The arrangement of the spans and their regularity should also be confirmed.

Conventional reinforcement shown on the drawings should be included in preliminary strength calculations. Care should be taken when assessing the ultimate strength contribution of conventional reinforcement, as this reinforcement may have been specified to satisfy serviceability requirements at maximum moment areas, and it may not extend far enough to be adequately developed at critical sections at ultimate loading.

The use of add-on tendons, that is, tendons added in perimeter bays or longer intermediate spans to supplement capacity in portions of the structure and which do not extend the entire distance between slab edges, should also be confirmed. As such, individual bays may have more tendons than other bays. This difference in tendon layout may suggest preferred locations of inspection recesses.

3.3 Original Design Code

The structural design drawings may indicate the codes and loads used for the original design. Early projects may have been designed to American standards or Canadian codes that were more conservative than current codes in some respects. Conversely, current codes generally have greater minimum reinforcing bar requirements than some of the early codes. Identifying which code was used for the original design can give the investigator useful clues about the amount of overdesign or underdesign that may be present. Applicable design codes may also be inferred from the dates indicated on the design drawings in the absence of additional information.

3.4 Post-Tensioning Supplier

Identifying the supplier of the post-tensioning system is helpful as this information will assist in determining the type of post-tensioning components and details installed on the project. Post-tensioning suppliers obtained their strand from various sources that may be foreign or domestic. Occasionally strands from more than one source were used during fabrication of tendons for a project. There can be variations in strand quality.

3.5 Waterproofing Details and History

The detailing of the waterproofing systems around the post-tensioning system should be reviewed with some caution. Details shown on the drawings may not be representative of the final installation. A more accurate understanding of the waterproofing techniques utilized on site may be obtained by field review where the slab edges are visible and the condition of the waterproofing and quality of the installation can be assessed.

Waterproofing systems were not common in parking garages until the mid to late 1980's. Many structures were left unprotected for several years before installation of waterproofing.

3.6 Tendon Type

The type of tendon incorporated into the work depended upon the supplier of the post-tensioning system as well as the age of the structure. Early installations (between 1955 and 1965) used paper wrapped strands or smooth parallel button headed wires. Minimal corrosion protection was provided by paper sheathing. These installations were common in Eastern Canada, with limited use in Western Canada.

As technology developed, seven-wire prestressing strand with wedge type anchors replaced button headed wire and plastic tubes replaced paper sheathing. The strands were greased and pushed into plastic tubes (sheaths). These are known as "stuffed" or "pushed-through" tendons. A second type of plastic sheathing fabrication was also used. It consisted of a flat plastic strip that was rolled over the strand and joined with a longitudinal heat-sealed seam. This system was known as "cigarette wrapped".

Stuffed and cigarette wrapped systems were often used between 1970 and 1983. It is not uncommon to find splices in the plastic sheath when the available tubing lengths or the length of tubing that was practical from a fabrication perspective was less than the strand length. The annular space between the strand and the plastic sheath was not completely filled with grease and has often been the location where water has collected adjacent to the strand surface.

After 1983, standard specifications introduced by the Post-Tensioning Institute (PTI) permitted use of only extruded sheaths. Extruded sheaths were first available in the late 1970's and were produced by a number of suppliers. Tendons manufactured using the extruded process consist of a seven-wire strand that passes through a grease bath before being encased in plastic sheathing. The plastic is extruded directly on to the greased strand in one continuous operation. As the plastic cools, it shrinks in size and places the grease coating under pressure. Quality control standards for extruded tendons specified more consistent plastic sheathing thickness and increased hardness that reduced the potential for damage to sheathing during handing and installation of the tendons. Specifications also require that the annular space between the strand and the sheath be completely filled with grease so that water could not flow within the sheath. Additional information regarding the current industry standards for unbonded post-tensioning tendon fabrication, is contained in reference PTI (2000a).

The storage and handling of the strand prior to assembly into tendons, storage and transportation of tendons after assembly, and handling of tendons during the construction process also presented opportunities for moisture to gain access to the strands. If the strands were permitted to come in contact with water during fabrication, transport, storage or construction, the durability of the post-tensioned reinforcement could be greatly reduced. Additional information regarding the current industry standards for the handling and installation of unbonded post-tensioning tendons is contained in reference PTI (2000b).

3.7 Prestressing Steel Type

The type and grade of prestressing steel used in strands should be determined. Current practice in Canada is to use seven-wire strand conforming to ASTM A416 Grade 270 Low-Relaxation Strand. CSA Standard G279 is the reference CSA standard, but most strands in Canada are manufactured to the ASTM specification. Some older structures may utilize Grade 270 Stress-Relieved Strand instead of Low-Relaxation Strand. While both have an ultimate tensile strength, (f_{pu}), of 270 ksi (1860 MPa), the Stress-Relieved Strand experiences considerably more relaxation than Low-Relaxation Strand. This will affect the magnitude of long term losses and the effective stress in the strand (f_{pe}) after all losses. A second practical difference is that Low-Relaxation Strand has a yield strength (f_{py}) of $0.9f_{pu}$ while stress-relieved strand has a f_{py} of $0.85f_{pu}$. Even older structures may have Grade 250 Stress-Relieved Strand. This strand has a f_{pu} of 250 ksi (1724 MPa). Systems with ¼ inch diameter button headed wire often used Grade 240 Stress-Relieved Wire with a f_{pu} of 240 ksi (1655 MPa).

All strand types identified above are included in ASTM A416, however they cannot be distinguished by visual inspection. If conclusive evidence regarding strand type is not contained in the project documentation and tension tests are not performed on strand samples from the structure, a conservative assumption may have to be made regarding the type and grade of prestressing steel.

3.8 Preliminary Visual Inspection

Prior to commencing any physical investigative work, a visual inspection of the property is required to confirm that the building construction is in general conformance with the drawings and specifications. At this time, a cursory check should also be performed to confirm the building occupancy is as was anticipated by the original structural designer. For example, a building may have been designed as an office or mercantile occupancy but now is being used as a storage facility. The potential difference in live loading is significant and may impact the structural capacity requirements.

A general visual assessment of the condition of the structure is necessary. Signs of visible distress such as cracking, spalling, deflection, failed waterproofing, leakage, grease staining, or corrosion should be documented. In addition, the service conditions to which the structural elements are exposed should be noted along with the condition of the protective systems (if any).

Once the general structural conditions have been assessed, physical constraints affecting access to perform testing should be identified. The presence of interior finishes or exterior cladding at the desired inspection locations or the inaccessibility of critical components will impact the effectiveness of the inspection program.

An important consideration for organizing the investigation program is to assess the impact this work will have on the users of the building during the investigation. Interior fixtures or tenant property may hinder access to desired locations thereby restricting the inspection program. Additionally, noise and dust created during the investigation may create conditions that are not acceptable to users of the affected space. The affected areas may need to be removed from service or the work may be performed at times when no users are in the building.

Building systems can also be affected by the investigation. Dust from the concrete chipping/jackhammering program may enter HVAC systems and be dispersed throughout the building. Additionally, embedded electrical components or alarm systems not shown on drawings may become damaged, not only endangering the safety of the workers conducting the survey, but also rendering some building services inoperable.

3.9 Sample Sizes and Proportioning of Sample

The selection of the number of tendons to be evaluated will be dependant upon a number of variables. Factors to be considered in determining sample size include:

- exposure conditions in service (waterproofed, indoors and heated, etc.)
- location of tendon anchorages (above grade, below grade, behind building envelope)
- exposure conditions during fabrication and construction
- evidence of structural distress
- evidence of water ingress or leakage through the structure
- evidence of strand deterioration (eruptions, rust stains, exposed sheathing)

The sample should therefore be proportioned to reflect various exposure conditions within different parts of the structure. For example, tendons in parking decks, exterior plazas, roofs, and areas exposed to rain during construction may warrant a higher sample density (approaching 10 to 15% of the tendons within the slab). This would reduce the potential that areas with extensive moisture access or significant strand breakage would be missed during the evaluation. Conversely, evaluation of tendons within areas judged to have a lower risk of past moisture access such as high-rise floor slabs with slab edges protected by the building envelope may be of a lesser sampling density (perhaps only 5%) of the total number of tendons within the areas under review. It is suggested that a minimum of 20 strands be exposed and tested for each exposure condition within a particular building

The following minimum initial sample size targets are suggested for exposure and testing of strands at inspection recesses:

- Single level structure under 1000 sq m :	20 strands
- Single or multiple levels, total area under 3000 sq m :	60-80 strands
- High-rise (over 10 floors):	100 strands
- Multiple tower or larger buildings (over 50000 sq m)	200 strands

If there are any critical members whose failure would be catastrophic (e.g. transfer girders) some strands should be inspected in each member.

Pandey and Nessim (1996) present a statistical method for determining if, given the findings, the sample size needs to be increased to give a desired confidence level. Their analysis indicates that if there is inherent excess capacity in the original design such that a high tendon loss ratio can be tolerated, the sample size may be reduced. Conversely, if there is minimal tolerance for tendon loss, or if significant tension deficient strands are identified in the initial testing, additional testing may be required to achieve a satisfactory confidence level.

3.10 Recess Location Selection

Inspection recesses should be located where the greatest amount of information can be obtained on tendon conditions. Historically, inspection recesses have been constructed in the underside of the structure at tendon low-points where concrete cover is typically the least. Recesses are also selected at locations where exposure conditions suggest a potential for concern exists; for example, adjacent to actively leaking cracks, construction joints and expansion joints, or at the first tendon low-point adjacent to a slab edge containing unprotected stressing anchorages.

3.11 Key Points

- Review available documents such as drawings, specifications and construction records.

- Conduct a preliminary design review prior to deciding on the scope of testing. Findings would include the overall robustness of the design, where the most critical areas are, and what items and problems one should look for in the field.

- Try to identify the post-tensioning supplier, the waterproofing details, the tendon type, and strand grade.

- Perform a preliminary visual inspection to confirm occupancy loads, obvious deviations from original design and identify areas with signs of visible distress that would warrant special investigation.

- Identify accessibility and other physical constraints and requirements that impact on the testing program.

- Proportion sampling throughout the structure that reflects differing moisture access exposure conditions throughout the building

- Select inspection recess locations where it is most likely to discover potential concerns.

4. INVESTIGATION FIELDWORK

4.1 Investigation Contractor Experience and Working Procedures

Hire a contractor with demonstrated experience in unbonded post-tensioned construction. Their knowledge of tendon layout, anchor details and stressing procedures will be invaluable during the investigation. When removing concrete adjacent to anchors, or chipping to expose strands at inspection recesses, considerable care should be taken to avoid damage to the strands and avoid concrete spalling at the highly compressed anchor regions. Investigations within occupied premises require stringent dust control and thorough clean-up by the contractor.

4.2 Confirmation of Super-Imposed Loadings and As-Built Construction

Current superimposed dead loads such as partitions, toppings, and landscaping should be confirmed. This may require exploratory removal of finishes to confirm wall assemblies, thickness of toppings and landscaping, etc. Also determine if building alterations and renovations represent changes from the original design drawings.

The presence and condition of waterproofing in areas subjected to in-service moisture should be assessed where not readily visible. This may require removal of roofing ballast, concrete/asphalt toppings, landscaping or architectural finishes in representative areas. Where practical, below grade slab edges should be excavated and inspected to identify live end anchors and moisture protection.

Confirmation of anchor details at expansion joints or construction pour joints may require removal of coverplates and exploratory concrete removal. It is recommended that grout in anchor pockets be removed at a number of locations to assess grout quality, grout contaminants, concrete cover, anchor type and signs of moisture contact.

The extent, size, and distribution of conventional reinforcement should be confirmed as consistent with the design drawings. This can be accomplished on site through the use of a pachometer supplemented with observations at inspection recesses or other exploratory concrete removal locations.

4.3 Recording of Field Data

The use of standard data collection forms simplifies data recording and reduces the likelihood of errors or missing information. Appendix A includes examples of forms used for inspection recesses and extracted strand inspections. Test locations and results of testing should be recorded on key-plan drawings to identify any moisture access patterns and relate signs of external distress to the condition of the post-tensioning system. Identification of inspection locations will also be helpful when retesting strand tension in future monitoring programs or expanded investigations. Consistent nomenclature should be used to describe post-tensioning system components, visual observations and test results.

4.4 Strand Inspection Recesses

Removal of concrete cover (by chipping/jackhammering taking care not to damage the strand) and inspection/testing of the exposed strand lengths is the most frequently used investigation method. The inspection recesses are usually made in the soffit at the low points in the tendon profile. The inspection recess should be of sufficient length to allow for inspection and penetration testing of all 6 perimeter wires of the 7 wire strand (approximately 250-300mm).

Visual inspection of strands should be completed immediately after concrete removal to avoid the potential for moisture within the sheathing to drain or evaporate at the recess.

Samples of grease present within the sheathing should be removed and subjected to the crackle test on site. This involves placing a sample of grease on a hot plate. If there is any moisture present within the grease, a bubbling and crackling of the sample is observed.

Whenever possible, inspection recesses should be chipped on the underside of the structure in facilities exposed to moisture to avoid the possibility of moisture accessing the strands through the recess.

Information recorded at recesses should include the following:

- inspection recess number and floor level
- individual strand identification
- strand orientation
- sheathing type and thickness
- sheathing condition (cracked/broken/split/brittle)
- odors present after removal of sheathing (earthy, ammonia, suphurous)
- visual appearance, consistency and coverage of grease
- strand size and direction of wire twist (right-hand or left-hand lay)
- presence of water and other contaminants within the sheathing
- moisture detected within the grease (crackle test)
- evidence of corrosion or damage to the strand
- results of testing for strand tension deficiencies
- clear concrete cover(s) to strand (and reinforcing bars if present)

Where appropriate, samples of grease and bulk water should be retained for further analysis.

The most common method used to assess strand tension is the "Penetration" or "Screwdriver" test. It is also possible to estimate the force in the tendon from a cut-wire test, or deflectometer. Further information on these test methods is included in Appendix B.

After completion of testing, exposed strand lengths should be coated with a layer of new grease, fireproof insulation placed in the recess and steel coverplates installed to prevent strand eruption in the event a strand was to break in the future. Coverplates allow for retesting of the strand tension at a later date.

A limitation of recess inspections is that they expose only a small portion of the strand length. Conditions at other points along the tendon may be different than those at the recess. The inspection recess should be installed where deterioration is most likely to be found. Extraction and full-length inspection of a small number of strands is sometimes done to reduce the uncertainty associated with inspection at recesses.

4.5 Strand Extraction and Inspection

Removal and full-length inspection of a small number of strands can yield additional information regarding the extent of moisture present in the system and the degree of strand corrosion. Moisture accessing strands at anchorages or at other locations along the strand length may not be detected at inspection recesses, particularly when extruded sheathing has been used. It is not possible to chip inspection recesses within the highly compressed anchor zone concrete. Removal and inspection of strands is the only means to identify if corrosion is occurring at the anchors.

Where strand tension deficiencies have been detected by penetration testing or other means, removal of a number of suspect strands is recommended to confirm the cause of the tension deficiencies. Reasons for tension deficiencies include:

- strand breakage due to corrosion
- strand broken or cut by workers drilling or coring through member
- excessive anchor set or slippage at anchors
- movement of anchors (voids in compression zone)
- strand was partially tensioned initially as a result of an improperly calibrated stressing jack or missed entirely during stressing operations

4.6 Metallurgical Analysis and Testing of Strands

Additional testing is often performed on removed strand lengths to identify the deterioration mechanism and gain additional information to help predict the time to failure of corroded strands. Electromagnetic Induction (EMI) and Wet Fluorescent Magnetic Particle inspection (WFMPI) techniques can be performed on strand lengths to detect section loss and stress corrosion cracking of the wires. Sectioning and scanning electron microscopic examination of individual wires at failure surfaces can be used to measure cross-section loss and topology of fracture surfaces for signs of brittle failure mechanisms.

Sections of strand can be tension tested to failure to assess ultimate strength and elongation characteristics of un-corroded and corroded samples. This can help to confirm or identify the grade and type of strand, and give a quantitative measure of the changes in mechanical properties in corroded zones.

Strand tension tests should be performed in accordance with ASTM A370. Data from the stress strain curve should be evaluated in accordance with ASTM A416 to determine the grade to which the strand properties correspond. The oldest structures may have used steels that do not correspond to any of the grades in ASTM A416. In this event, one should consult the literature of the day. CSA A135-1962 was the first Canadian design code for prestressed concrete. It can be found in the Canadian Prestressed Concrete Institute Handbook, First Ed. (1964). Leonhardt (1964) also provides valuable information on older prestressing materials and systems.

4.7 Measurement of Humidity Within Strand Sheathing

A proprietary test method has been developed to measure the humidity within the strand sheathing and thereby assess the potential for corrosion of the strands. Injection ports are typically installed at the cable anchors. Dry air is pumped into the sheathing at one port and the exhaust air is measured for relative humidity at the venting port. Increases in humidity in the exhaust air indirectly indicate that there is entrapped water or moist air present within the sheathing that may contribute to further corrosion of the strand. The advantage of this approach in comparison to inspection of strands at recesses is that it yields information regarding moisture along the entire strand length rather that just at the inspection point. This method is potentially applicable to tendons with pushed-through sheaths and heat sealed sheaths. Tendons with extruded sheaths have a tighter fitting sheath that is completely grease filled and will not allow air to flow along the tendon. For more information on this evaluation method see reference NRC (1998b).

4.8 Analysis Of Contaminants Within Strand Sheathing

Post-tensioned strands have been found to deteriorate in the presence of even pure water, however, a number of other contaminants can accelerate the corrosion process. Bulk water obtained from within the sheathing can be analyzed for the presence of chlorides or fertilizer that may have accessed the sheathing in below grade parking decks or slabs under landscaped areas. Grease samples can be analyzed for the presence of nitrates, valences of sulphur, fungi or microbiological activity that may be producing hydrogen sulfide. Fourier transform infrared spectroscopy (FTIR) can be used to identify organic species present that may exacerbate strand corrosion rates.

Testing may be employed to assess the ability of the existing grease to offer corrosion protection in the presence of moisture. PTI (2000a) gives criteria for acceptable performance when tested using the ASTM B-117 test method.

The Post-Tensioning Institute has established maximum tolerable levels for contaminants within tendon grease, see reference PTI (2000a).

4.9 Key Points

- Hire a contractor with demonstrated experience to assist with the investigation.

- Confirm the as-built details, and any super-imposed loads.

- Document field observations so that they are useful to others in the future. Tracking the rate of deterioration over time requires that at comparison can be made of test results from one inspection to the next.

- Assess strand tension by the screwdriver penetration test. Consider supplementing this with selected cut-wire or deflectometer tests.

- In cases where additional information is required to reduce the uncertainty in the assessment, extract a number of strands for full-length inspection, and other tests.

- Measurement of humidity within the sheath of push-through, and heat sealed tendons can be used to obtain an indication of moisture present along the tendon.

- Analysis of contaminants within the tendon sheath can yield additional information to help predict strand corrosion rates.

- The extent of fieldwork and testing depends upon the client's requirements and the initial test results. If the initial findings lead to uncertain or ambiguous conclusions, the scope may need to be expanded to increase the level of confidence.

5. INTERPRETATION OF TEST RESULTS

5.1 Limitations of Selective Sampling

Investigation results reflect observed conditions only at the inspection location. Conditions away from the inspection location have been found to vary significantly from results obtained at the inspection location and considerable judgment is required when extrapolating testing information to the overall post-tensioning system condition.

Investigations typically involve testing a limited number of tendons. Conditions observed must not be considered to definitively reflect the condition of the post-tensioning system in other building areas or on other floors not tested.

Statistical methods are helpful in defining the level of testing required to obtain the desired confidence levels, however, care must be taken when selecting the probability model [Pandey and Nessim (1996)]. Moisture access to strands should not be modeled as a uniform risk because conditions can change throughout the structure as a function of exposure to moisture during construction, varying exposure to moisture in service and protection at anchors. Partitioning of the test sample is required to reflect this variability, with areas grouped according to comparable risk of past moisture access.

Initial test results obtained will also influence the extent of testing required in individual areas. For example a floor area exhibiting numerous strand tension deficiencies in the initial test sample may require expanded testing to confirm that an adequate number of cables are intact and contributing to structural capacity. This requires an iterative process to be employed. Guidance contained in Pandey and Nessim (1996)

Observed conditions reflect the condition at the time of inspection. With the passage of time, actual conditions within the tendon sheathing can change. For example, additional moisture may access the strands through failures in waterproofing membranes, or additional strand breakage may occur as a result of continuing corrosion.

5.2 Causes of Strand Tension Deficiencies

If cable extraction has indicated that detected strand tension deficiencies are related to mechanical damage (coring, drilling, etc), improper stressing procedures during original construction or excessive slippage and wedge set at anchors, and no evidence of moisture is detected in the sample, future durability concerns may not be justified. If the extent of tension deficient strands can be established and structural analysis suggests that the reduced tension in strands can be tolerated, no short term remedial action may be warranted.

Conversely, if tension deficiencies appear to be related to corrosion-induced strand failures, future performance of the post-tensioning system may be in question. Expanded testing or monitoring of strand tension may therefore be warranted.

5.3 Determination of Structural Adequacy

The primary objective of a structural review is to determine if the structural members, in their current condition, are adequate for the current loads. A secondary objective is to determine the tolerable tendon loss ratio and to estimate when this might be reached or when a subsequent inspection should be performed. Most structures have more tendons than required by current design codes. They can therefore tolerate the loss of some tendons. The determination of structural adequacy involves the comparison of the demands on the structure with its capacity.

Establish Demand on the Structure

Establishing the demands on the structural system involves the assessment of loads and consequent load effects such as shears, moments, and axial loads. Considerations include:

- assessment of dead loads on the basis of field data

- measurement of slab thickness and concrete densities

- evaluation of partitions, finishes, and mechanical/electrical system loads

- confirmation of specified live loads for the current use and occupancy

- application of appropriate live load tributary area reduction factors. Commentary K [NBC (1996)] can be utilized to establish appropriate load factors

- structural analysis to obtain theoretical elastic factored moments and shears

- moment redistribution effects to reflect a more favorable distribution of moments and shears at critical sections

Establish Structural Capacity

Before computing the capacity of the structural system, one needs to establish the material properties. Considerations include:

- Use the specified compressive strength of the concrete (f'_c) unless concrete cores indicate that a different value can be used.

- Use the specified yield strength of the steel (f_y) unless samples of non-prestressed reinforcement indicate that a different value can be used. Refer to S6-00 [CSA (2000)] Appendix A14.1 for guidance on how to determine appropriate values for f'_c and f_y from test samples taken from a structure.

- Use the specified properties for the prestressing strand with caution because the substitution with other sizes and grades of strand was and is common. Data from shop drawings is more reliable than data from the engineering drawings. Strand size and spacing should be confirmed on-site. While most Canadian designs use North American strand sizes of 0.5" and 0.6" with areas of 99 mm^2 and 140 mm^2 respectively, contractors occasionally substituted European strands with areas of 100 mm^2 and 150mm^2.

- Consider tension tests of samples obtained from intact portions of strands removed from the structure to determine the ultimate tensile strength of the strand (f_{pu}), which is typically either 1750 MPa, or 1860 MPa.

- Examine the shape of the stress-strain curve to determine if the strand is stress relieved or relaxation grade. The shape of the curves near the yield point is used to differentiate between the two strand types. (Similar considerations apply to wire systems.)

- For preliminary assessment purposes, it is common practice to assume that the net effective tension in the strand (f_{pe}) is equivalent to $0.6f_{pu}$ unless otherwise noted in the original drawings and specifications or unless calculated. Note that this assumption may overestimate the effective stress in the strand for tendons with low jack forces and large losses.

- Use the nominal structural dimensions and effective depths from the original design drawings unless as-build dimensions deviate from the "expected" values. Note that the load and resistance factors in A23.3 [CSA (1994)] recognize that actual values are expected to be different from nominal values. MacGregor (1976) discusses the geometrical errors in cross section and errors in placement of reinforcement assumed when establishing safety factors. For example, the actual effective depth of negative moment reinforcement in slabs is expected to be an average of 19 mm less than the nominal effective depth.

Flexure

The flexural capacity of the system should be determined and compared against the flexural demand. Both ultimate and serviceability limit states should be considered. At the ultimate limit state, secondary moments due to prestressing should be included as well as moment redistribution. In computing the capacity, one should recognize that broken or unstressed strands give a local reduction in balance loads, but a reduction in average P/A across one or two bays. That is, the member experiences an average P/A (except near the anchorages) but local balance loads. One should assess if there will be warning signs such as large cracks and deflections before failure. Consider minimum reinforcement ratios and M_{cr}/M_r in making this determination. Daher (1997) and Rogowsky and Daher (1997) provide information on the behavior of structures when reinforcement levels are below current code minimums.

Because the serviceability limit state is more subjective and does not relate to public safety, engineers and owners may use more judgment with regard to what is acceptable cracking and deflection. Assessment of current serviceability is usually done by simple observation – is the building able to be used by occupants for it's intended purpose? Structures often have crack widths and deflections greater than current suggested design code limits but the users still find the structure to be useable. When assessing future serviceably with further loss of tendons one should recognize the very approximate nature of calculations for cracking and deflections when the applied bending moments approach or exceed the cracking moment.

Shear

The shear capacity of the system should be assessed for the ultimate limit state. One-way and two-way shear should be checked as appropriate for the structure in question. Engineers should be aware that older two-way slabs may not have integrity steel or bonded top mat reinforcing bars. Older codes did not recognize the benefit of P/A on punching shear capacity. Except for columns near anchorages, the average P/A for the bay should be considered rather than the local P/A that one might incorrectly expect with tendons banded over the columns. If simplified calculations show that one-way shear is critical, one should consider the benefits of computing V_{ci}, and V_{cw}. One should be cautious about using current code calculations if the members and reinforcement do not comply with current code requirements such as $\rho_{v\,min}$. In such cases one should resort to the modified compression field theory or other refined methods. Particular care should be taken when assessing moment transfer and shear conditions at corner columns because these are generally more critical than at interior columns.

Determine Tolerable Tendon Loss Ratio

The simplest determination of structural adequacy is to compute and compare the current live load capacity with the current live load requirement. Live load capacity can be derived by subtracting the current dead load demand from the current total load capacity.

Test results may identify different tendon loss ratios (the proportion of tendons that are not considered to be effective) within various areas of the structure, and the service live load capacity of individual structural bays may vary as a result of differing reinforcement. It may be helpful to plot the service live load capacity versus the tendon loss ratio for each differing structural bay as shown in Figure 1. This graph allows for a quick comparison of the safe live load for a given tendon loss ratio, or conversely, the tolerable tendon loss ratio for the desired live load. Analysis of structural members with differing reinforcement or geometry will produce unique capacity curves for each member. The curve may be kinked where the failure mode governing the capacity changes from flexure to shear. In the case of two-way slabs, curves are required for each of the two directions when the spans and reinforcement are different in each direction.

Estimate When Tendon Loss Will Warrant Repairs

Predicting the time to repair requires an estimate of the tendon loss ratio over time as shown in Figure 2. The projections of future tendon losses are highly speculative and often depend on the performance of waterproof membranes and other variables. Some engineers estimate the rate from previous inspections on the building. Others estimate the rate from data on similar structures with appropriate adjustments based on experience and judgment. Because every building is different, the estimates should be adjusted to reflect the specifics of the building in question.

5.4 Risk of Strand Eruptions

Failures of strands can occur quite suddenly with a significant amount of energy released. Instances have been recorded where strands have projected from anchors or erupted in loops projecting from the top or underside of the structural slabs. The frequency of strand eruptions relative to the number of strand failures identified to date has been quite limited, however, the potential for personal injury or property damage still exists.

Installation of steel restraint plates over live end anchors is recommended at slab edges adjacent to pedestrian areas to mitigate the potential for strand eruptions. Typical installations would include slab edges or beam ends at perimeter sidewalks or split-level parking decks, mezzanines, etc.

Experience to date suggests that strands with at least ¾ inch (19mm) concrete cover at high and low points in the strand drape are unlikely to create a loop type eruption in the event of breakage. Typical concrete cover at these locations should be confirmed when assessing this potential. If loop type eruptions have been recorded at a particular facility, installation of steel plate or other restraining measures at locations of reduced concrete cover to strands should be considered (i.e. at high points and low points in the strand drape).

5.5 Prediction of Future Performance

The major factors influencing the potential for corrosion-induced strand breakage are the amount and extent of moisture access, contaminants within the sheathing and the susceptibility of the strands to develop stress corrosion cracking.

The time to strand breakage can vary widely between buildings. Some structures have experienced widespread strand breakage within 7 years of construction, while strand breakage in others structures is only beginning to occur after 25 years in service. Assessment of strand metallurgy and corrosion mechanisms is a relatively new area of study with little understanding of how specific factors relate to time to failure of strands.

There is a growing database of information from ongoing monitoring programs which helps to define trends for particular types of structures and exposure conditions, however predictions regarding individual structures should be based on test results obtained over time for that particular facility. Strand breakage does not occur uniformly over time. Typical results suggest corrosion advances within the system to a threshold level, at which time the frequency of strand breakage increases.

The potential for future moisture access to the post-tensioning system must also be considered when predicting performance. Some of the items to consider include:

- effectiveness of parking deck membranes and roofing systems
- change in occupancy (mechanical rooms, parking conversion)
- washing or flooding (equipment failure, sprinkler discharge, plumbing backup)
- building envelope issues – exfiltration/condensation within wall assembly, moisture penetration through building envelope, inadequate insulation leading to condensation at anchors
- condensation within strand sheathing in exterior unheated structures
- protection of anchor locations from moisture access

5.6 Key Points

- Judgment must be exercised when interpreting test results obtained at inspection recesses as they may not reflect overall conditions.

- Causes of detected strand tension deficiencies should be confirmed.

- Familiarity with design of post-tensioned structures is required to assess impact of strand breakage on structural capacity.

- Calculation of tolerable tendon loss ratios and strand failure rates is required to predict time to repair.

- The risk of strand eruptions should be considered and mitigated.

- Prediction of future performance should be based on information obtained for the particular structure and the potential for future moisture access to the post-tensioning system.

6. REPORTING

Investigation observations and analysis should be summarized in a report that will provide sufficient information to formulate a maintenance or monitoring strategy as well as giving future investigators the necessary information that allows them to do meaningful follow-up work. Some clients may require more extensive background information or explanations, while others may be satisfied with reduced reporting.

Reporting of investigation results in a format that is consistent within the consulting community is important to assist users of these reports in understanding the condition of the buildings being examined and the related repair and protection recommendations.
To date, the scope of investigation and reporting standards are inconsistent among consultants.

As a result of reporting inconsistencies within the industry, the following problems can arise:

- conflicting opinions by different consultants on the same structure making it difficult to make business decisions

- investigations fail to identify serious safety issues

- investigations provide ambiguous conclusions or overly-conservative recommendations because of limited testing information

- reports written with such variability in terminology and approach that it makes it difficult for the non-experts to understand what the reports mean

- inconsistent use of terminology within the industry

It is recommended that the following items be addressed in a typical evaluation report.

6.1 Background Information

Investigation mandate and special client requirements

General description of the facility and age

Description of the post-tensioning system type and extent

Summary of previous investigations and related maintenance

6.2 Summary of Test Results

Description of current investigation scope, including drawings identifying locations of testing and samples obtained

Test results for each exposure condition within the facility should be presented separately (detected moisture and strand tension deficiencies)

Probable source and extent of any moisture detected within the P/T system

Statement of limitations regarding testing methods and sample size

Opinion of original design capacity based on information shown on design drawings and test results (excess capacity or shortcomings)

Impact of detected strand tension deficiencies on structural adequacy

Tolerable tendon loss ratio for the current specified live load

6.3 Repair and Maintenance Recommendations

Supplementary investigation recommendations if required to reduce uncertainty in the assessment

Identification of areas of concern

Immediate shoring or repair requirements and associated costs

Potential for future strand breakage (timing and extent)

Preventative maintenance and corrosion mitigation options

Future maintenance expenditure forecast

Monitoring requirements
-periodic (recommended period and scope)
-continuous acoustic monitoring (scope)

6.4 Key Points

- Client requirements should be reflected in reporting.
- Format of reporting and nomenclature used should be consistent throughout the consulting industry.
- Background information and details concerning previous test/repair programs should be included in reporting.
- Test results should be clearly presented for differing areas throughout the facility.
- Repair and maintenance recommendations should identify areas of immediate concern, implications for future performance and monitoring requirements.

7. MONITORING

When testing has identified past or present moisture penetration into the unbonded post-tensioning system, continued monitoring of strand tension is recommended to identify any future strand breakage and implement repairs in a timely fashion. The inspection interval should be selected such that it is unlikely the structure will deteriorate to the point of concern prior to the next inspection. Annual testing of strand tension is recommended initially, with frequency of monitoring dependent upon results of testing. If no change in strand tension is identified within the first 3 years the period between update testing could be extended.

Caution should be exercised when assessing whether an existing structure can be monitored for future strand breakage. In some cases structural elements with a limited number of tendons may not be able to tolerate loss of a single strand without compromising the structural adequacy in the immediate area. This would preclude the possibility of delayed repairs until such time as strand breakage is detected.

In situations where not all strands within an element can be accessed to confirm cable tension, and advancing strand breakage is identified, analysis of monitoring results may prudently assume inaccessible cables do not contribute to the strength of the member.

7.1 Monitoring Strand Tension at Existing Inspection Recesses

Initial test results provide an indication of strand breakage that may have occurred to date, however, strand breakage rates can vary widely between different structures and within individual structures. Care must be taken when extrapolating test results obtained at inspection recesses because the test sample may represent less than 2% of the total number of strands within the structure. If advancing strand breakage is detected in an area, additional strands should be tested to confirm that an adequate number of intact strands are present within a particular structural bay. Comments regarding partitioning of the test sample and selection of appropriate sample sizes to obtain satisfactory levels of confidence are presented in Section 3.9, with additional information in references by Pandey and Nessim (1996) and Harder (1997).

7.2 Visual Review of Structure

Periodic visual inspection of the structure should be included as a normal maintenance procedure, with any signs of floor deflection, cracking or obvious distress noted for further review. Caution should be exercised when relating the external appearance of the structure to the condition of the post-tensioning system, as numerous structures have experienced significant strand breakage and significant loss of capacity with no signs of external distress.

7.3 Acoustic Monitoring For Strand Breakage

A proprietary monitoring system has been developed which detects the sudden release of energy that is associated with wire failures within strands. A series of sensors distributed throughout the structure transmit vibrations associated with wire breakage to a computer which analyzes the acoustic profile of the event, and through triangulation identifies the location.

An advantage of acoustic monitoring in comparison to testing strand tension at recesses is that it identifies strand breakage throughout the structure rather than only identifying strand breakage within the test sample. The increased level of information obtained can lead to less conservative repair recommendations. Acoustic monitoring also reduces the likelihood that advancing strand breakage goes undetected, and allows for a timely implementation of any required repairs.

Acoustic monitoring cannot detect strands that may have failed prior to installation of the monitoring system. Therefore, it's use should be combined with tests of strand tension at inspection recesses when the monitoring system is installed. Further description of this approach is contained in references Elliot and McCarthy (1998) and NRC (1998a).

7.4 Key Points

- Continued monitoring is required where testing has identified a potential for future deterioration of the post-tensioning system.

- Monitoring strand breakage may not be appropriate in structures where minimal strand breakage can be tolerated.

- Periodic visual inspection of the structure is recommended to identify any obvious deterioration.

- An acoustic monitoring system has been developed which can identify ongoing strand breakage throughout the structure. This system can reduce the uncertainty in predicting strand breakage and timing of repairs.

8. MAINTENANCE

Maintenance can be classified as either restorative or preventative. Restorative maintenance includes any work required to address current shortcomings. Preventative maintenance is an attempt to prevent or mitigate further deterioration, thereby extending the service life, or delaying the need for repairs.

8.1 Restorative Maintenance.

When tension deficient strands are identified, strand replacement may be done on a selective basis or repairs could involve replacement of all strands once the tolerable tendon loss ratio has been reached. During strand replacement, sheaths should be cleaned of any moisture and deleterious substances. Installation procedures should ensure that the annular space between the existing sheathing and the replacement strands be completely filled with grease conforming to PTI requirements. This can be accomplished by filling a portion of the sheathing length with grease prior to inserting the new strand and then injecting additional grease as the replacement strand is threaded into the structure. It may be possible to utilize a higher grade of steel for the replacement strands than used in the original construction and by using Low Relaxation grade strand. A higher effective stress in the strand is possible because most concrete shrinkage and creep have already taken place. This increases the contribution to structural capacity provided by each replacement strand and may allow for a reduced extent of strand replacement, or if all cables are replaced, the total load carrying capacity of the structure may be increased.

Sub-framing is a method, which involves the installation of additional external support to structural members affected by strand breakage. It may involve the installation of load bearing walls, additional columns and beams, or external post-tensioning. Usually, sub-framing consists of the installation of steel beams, plates, or shear collars to the underside of the existing structure.

Supplemental support considerations include:

- headroom limitations
- fire rating
- aesthetics
- interference with use
- capacity (what load is sub-framing to support)
- deflection (is deflection to be recovered by active systems such as preloading steel members, wedges, or, "stressed" shores)
- sub-framing support (alternate load path down to foundations)

Other methods of providing additional strength include bonded concrete toppings with additional mild steel reinforcement. In some cases extra reinforcement can be provided without the extra weight of a topping by grouting the reinforcement into grooves cut into the top surface of slabs. Stainless steel, glass fibre, or carbon fiber rods can be used to provide corrosion resistance with minimum concrete cover.

Delamination repairs are often done in conjunction with other maintenance to restore the effectiveness of the bonded reinforcement and effective thickness of the concrete. Timely repair of concrete delaminations caused by corrosion of the conventional reinforcement contained within the structure is important to reduce the potential for moisture accessing the post-tensioning system.

8.2 Preventative Maintenance

Sealers and membranes can be used to reduce moisture access into the structure and thereby reduce the potential for moisture to access the post-tensioning system. Factors to be considered when selecting a waterproofing system include:

- traffic vs. non-traffic bearing
- skid resistance
- abrasion resistance
- odor and toxicity
- installation constraints such as temperature, humidity/moisture, and surface preparation
- crack spanning ability
- ultraviolet resistance
- service life
- maintainability
- weight

As an alternative to waterproofing of the structure, upgrading the watertightness of the post-tensioning system can be attempted. Sealing of the stressing anchorages can involve removal of loose or deteriorated grout and replacement with new non-shrink grout. The grout pockets can be protected with a membrane. Tendons can be dried with a gas purge technique. They can be kept dry by permanently connecting them to a dry air supply. Alternatively, additional grease (or urethane) can be injected into the tendons to impede the penetration of moisture. The reduced cost of the above measures in comparison to a full waterproofing program must be weighed against the likelihood of future moisture access to strands

Cathodic protection is a technique that is sometimes used to control corrosion of pipelines and steel structures and conventionally reinforced concrete structures. The application of cathodic protection systems to concrete structures containing unbonded post-tensioned reinforcement is problematic. Impressed current systems require knowledgeable design, operation, and maintenance.

Too much impressed current can lead to hydrogen formation and embrittlement of the post-tensioned strands. Too little impressed current renders the system ineffective at controlling corrosion. Conditions can vary along the tendon length such that it may be impossible to provide consistent uniform protection to the strands. Use of cathodic protection systems in structures with unbonded post-tensioned strand is not recommended at this time.

Improving drainage is useful if it reduces the likelihood of moisture reaching the concrete and tendons. Plugged drains should be cleaned and repaired. Installation of additional drains or placement of sloped toppings helps to eliminate potential ponding of moisture. Improve roof slopes by adding tapered insulation under roof membranes. Berms and swales can be added to direct water away from anchorage zones to drains.

8.3 Key Points

- Numerous options are available to repair structures with advancing unbonded post-tensioned strand breakage.

- Methods have been developed to purge moisture present within the tendon sheathing and thereby mitigate the potential for future strand breakage.

- Installation of waterproofing and improvement of drainage may be helpful in reducing future moisture access to the post-tensioning system.

9. CLOSURE

Assessment of buildings containing unbonded post-tensioned reinforcement must recognize the unique nature of this type of construction.

Planning of investigation programs and interpretation of test results requires a significant amount of judgment and experience with the design and assessment of these types of structures.

The durability and performance of the post-tensioning system can vary widely between different structures and within particular structures. Each building must be considered individually. Similarly, the unique requirements of the client must be recognized in order for the investigation strategy to meet their needs.

Corrosion of unbonded post-tensioning is a relatively new issue. Not all information is known. The engineering profession will continue to learn from future performance of structures. It is expected that there will still be significant developments in the area of testing and repair.

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FIGURES:

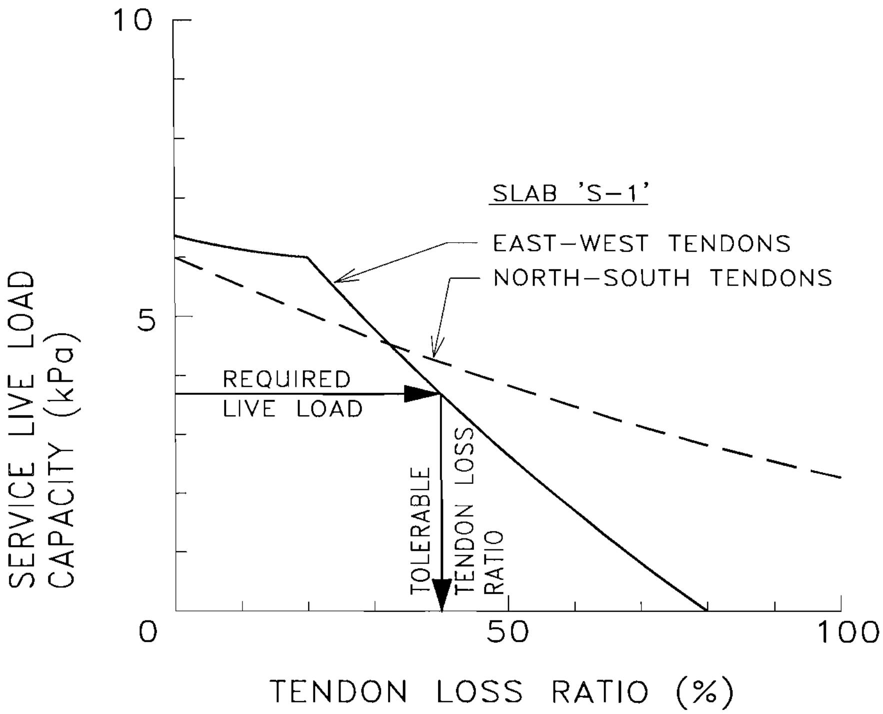


FIGURE 1. EXAMPLE CAPACITY CURVES

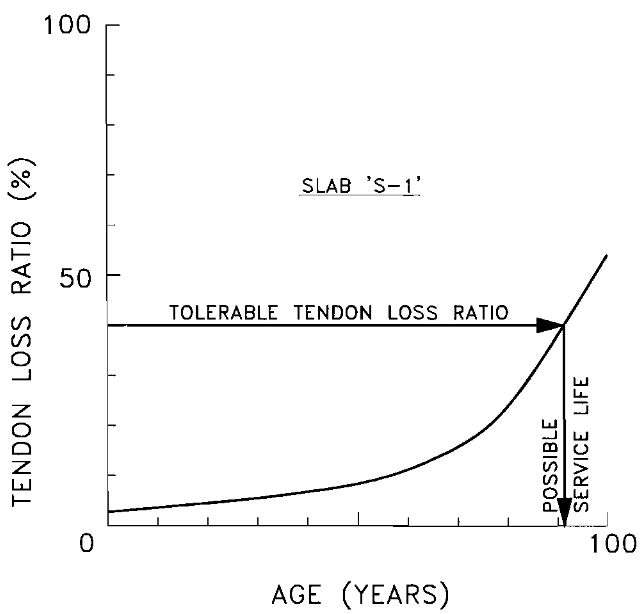


FIGURE 2. EXAMPLE TENDON LOSS CURVES

APPENDIX A – SAMPLE INSPECTION FORMS

P/T RECESS INVESTIGATION LOG

Page ___of ___

Project ____________________

Job No. ____________________

Inspected By: ______________

Date: ______________________

Recess Designation	Strand Direction	Free	Grease Condition	Strand Condition	Penetration		Comments

Grease Condition

G	Apparently good condition
E	Emulsified
R	Runny/oily
D	Dry Strand
M	Cement mortar between wires

Strand Condition

G	Apparently good condition
R	Rust Staining, no pitting
IP	Intermittent pitting, some shiny strand
HP	Heavy pitting, no shiny strand
B	Broken / not stressed

* Indicate number of wires where penetration achieved

P/T STRAND INVESTIGATION LOG

PROJECT ____________________

JOB NO. ____________________

INSPECTED BY ____________________

DATE ____________________

PAGE

STRAND IDENTIFICATION ____________________

RUNNING DIMENSIONS (mm) 0'-0" ←— Length = —→

STRAND CONDITION
G - - - - - - - - - -
R - - - - - - - - - -
IP - - - - - - - - - -
HP - - - - - - - - - -

STRAND DISCONTINUITY

GREASE CONDITION
G - - - - - - - - - -
E - - - - - - - - - -
O - - - - - - - - - -
D - - - - - - - - - -
M - - - - - - - - - -

ANCHOR PRESENT ____________

ANCHOR CONDITION ____________

▼ LOW POINT ALONG CABLE PROFILE

____________ ANCHOR PRESENT

____________ ANCHOR CONDITION

GREASE CONDITION
G Apparently good condition
E Emulsified
O Runny/oily
D Dry strand
M Cement mortar in sheath

STRAND CONDITION
G Apparently good condition
R Rust staining, no pitting
IP Intermittent pitting, some shiny strand
HP Heavy pitting, no shiny strand

STRAND DISCONTINUITY
C Cut *
CT Torch cut *
T Cup/Cone Tension failure (ductile) *
F Fractured (brittle) *

* Indicate number of wires affected

P/T STRAND INVESTIGATION LOG

PAGE 3

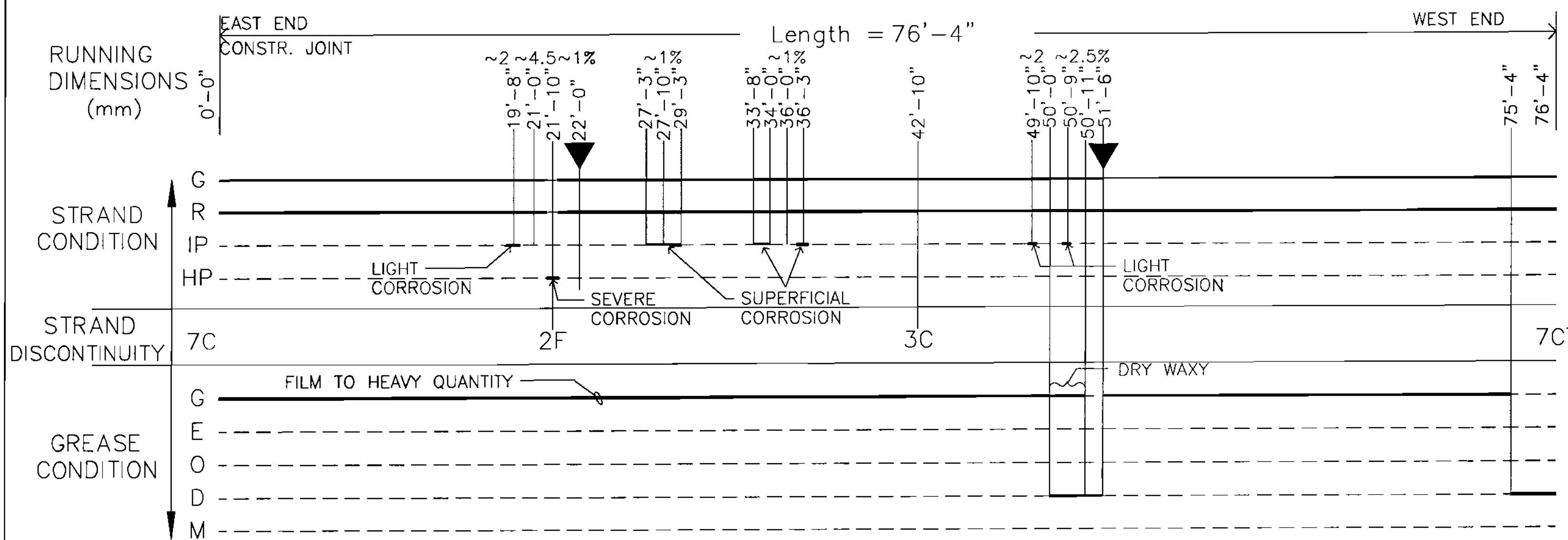
PROJECT ____________________

JOB NO. ____________________

INSPECTED BY ____________________

DATE ____________________

STRAND IDENTIFICATION 92S447.1



ANCHOR PRESENT NO

ANCHOR CONDITION -

▼ LOW POINT ALONG CABLE PROFILE

NO ANCHOR PRESENT

- ANCHOR CONDITION

GREASE CONDITION
- G Apparently good condition
- E Emulsified
- O Runny/oily
- D Dry strand
- M Cement mortar in sheath

STRAND CONDITION
- G Apparently good condition
- R Rust staining, no pitting
- IP Intermittent pitting, some shiny strand
- HP Heavy pitting, no shiny strand

STRAND DISCONTINUITY
- C Cut *
- CT Torch cut *
- T Cup/Cone Tension failure (ductile)*
- F Fractured (brittle) *

* Indicate number of wires affected

APPENDIX B – METHODS FOR ASSESSING TENSION IN STRANDS

Cut-Wire Test for Estimation of Effective Tension in Strands

The cut-wire test estimates the tension in the strand by measuring the elastic shortening of the strand when it is cut. The basic procedure is as follows:

- Select a strand that can be cut without jeopardizing the structure, or that can be conveniently replaced. Alternatively, with some simple calculations, one can often identify areas where there are clearly more strands than required for strength. Cutting a strand in such an area can be done without requiring strand replacement. Often, the strand is not selected until after screwdriver penetration tests have been performed at all of the available inspection recesses. The investigator may choose a strand that exhibits full tension, partial tension deficiencies or one that appears to have no tension. The choice will depend upon the investigator's objective.

- Open two recesses as far apart along the strand as practical. The objective is to release the force over the entire length of the strand. Friction may prevent release of force in the strand at locations that are far from the cuts. Space the recesses to mitigate friction effects.

- Establish a safety zone at each of the anchors and along the strand length where people are excluded to avoid injury in the event that the strand erupts out of the slab top or bottom, or is expelled through the end anchor.

- At the first recess, cut the strand with a grinding disc, or Dremmel tool. The strand portions on either side of the cut will separate.

- At the second recess, cut the strand with the same device. The sounds made when these wires are cut will give an indication as to whether or not friction prevented full release of the strand force by the first cut. When the wires at the first cut release with a bang, the wires at the second cut will usually release with a whimper. This suggests that the strand has been freed of force throughout its entire length.

- Measure the average gap at each of the two cuts. There will be minor differences between the gaps of each of the seven wires. There will be some untwisting of the strands making it difficult to determine which wires ends match. Fortunately, neither the differences, nor the twisting matter if one uses the average gap.

- Remeasure the average gap at each of the two cuts after a period of at least 15 minutes. Friction can cause a slight delay in the strand movement. If the measurements have changed substantially, repeat the measurement at appropriate time intervals until the measurements stabilize.

- On a section of unstressed strand, make a partial cut and measure the width of the "saw cut" produced by the cutting device. The cut should be most of the way through the strand but leave at least part of one wire intact.

- The effective elastic recovery is taken as the sum of the final average gaps plus two times the width of the "saw cut".

- Divide the effective elastic recovery by the length of the strand between anchors. This gives the effective strain in the strand.

- To obtain the effective stress in the strand, multiply the effective strain by the modulus of elasticity for the strand. This is usually assumed to be approximately 197 MPa. Alternatively one could extract the portion of strand between the recesses and have it tested to determine the modulus of elasticity. Freymuth (1991) reports that the modulus of elasticity is almost always within 4% of 197 MPa.

- To obtain the effective force in the strand, multiply the effective stress by the cross-sectional area of the strand. The cross-sectional area is the sum of the cross-sectional areas of the seven wires in the strand. These are readily computed from measured wire diameters.

- An error analysis can be performed to establish the uncertainty in the prestress force. For a strand that is 30 m long, the effective elastic recovery will be approximately 180 mm. Measurement of the strand length anchor-to-anchor and the gaps to plus or minus 1 mm, along with measurements of the "saw cut" width and wire diameters with calipers to plus or minus 0.01mm will generally suffice. In short strands more accurate measurements and devices may be necessary.

- The cut wire test is easy and inexpensive and should be performed whenever strands are extracted for examination.

Screwdriver Penetration Test for Assessing Tension in Strands

Penetration tests are a subjective method of assessing the tension in the strand. They are based upon the effort required to drive a tool between the outer wires of the strand. If the strand is fully tensioned, it is virtually impossible to drive a tool between the wires. If the individual outer wires of the strand are loose, or only have small tension forces in them, it is easy to drive a tool between the wires.

The penetration test is not standardized. The test described here is the one most commonly used in western Canada. The test uses a "Craftsman 4 x ¼ standard screwdriver" and a regular carpenter's hammer (28-32 oz). The screwdriver tip has a standard blade thickness of 0.04 inch, a blade width of 0.25 inch, and a shaft length of 4 inches. The test generally proceeds as follows:

- At an inspection recess, remove the concrete to expose one lay length of strand with hand clearance.

- Open the sheath and expose one lay length of strand.

- Place the screwdriver tip in the groove between two of the outer wires. The screwdriver should be held perpendicular to the strand and struck smartly with the hammer. The force in the hammer swing should be similar to that which one would use to drive a nail. If the screwdriver tip penetrates between the wires, it indicates that one, or both of the wires touching the screwdriver are not fully stressed.

- Move the screwdriver to the next groove and repeat the test until six consecutive grooves have been tested. Because there are six outer wires and six grooves it is possible to determine if one, two, or more of the wires are not fully stressed.

- It is desirable that the concrete is not removed from behind the strand because the strand requires a back-up medium to absorb the hammer blow without moving around.

- With use, the screwdriver tip wears out. Or, more correctly, the point gets sharper and more chisel-like. When this happens it becomes easier to drive the wires apart and achieve penetration. This can give one the false indication that the wires are not carrying full tension. At this point the screwdriver tip should be ground to it's original shape or the screwdriver should be replaced. A screwdriver typically can be used to test about 50 strands before being discarded.

- With many consecutive tests done in succession, the operator gets tired and the force of the hammer blow may reduce. When this happens it appears to be harder to get penetration. This can give one the false indication that the wires are carrying full tension. At this point the operator should rest or be replaced. If the recesses are opened and there is ready operator access (e.g. don't have to climb up and down tall ladders), the operator can test about 100-200 strands in an 8 hour work day.

- The primary variables in this test are the effort applied with the hammer and the operator's subject judgment on how much resistance to penetration was experienced. The latter is particularly important when strands were not fully stressed in the first place. The operator may not get repeatable results, and different operators may get conflicting results. A modification of this test is under development at the University of Alberta [Linghede and Rogowsky (1998)] to overcome these difficulties. It involves mounting the screwdriver tip on a Schmidt hammer (standard rebound hammer used to estimate concrete strength). The rebound hammer is a spring-loaded device that delivers a standard impact (i.e. same energy every time) and measures a "rebound number" which gives an objective measure of resistance to the blow. In trials against the manual screwdriver test, it was found that the rebound hammer based screwdriver test was able to identify more partially tensioned wires. Subtle differences in resistance that go undetected in the manual test are readily detected by differences in the rebound number. Tests correlating the rebound number with strand force are promising, but the device is not likely to provide the accuracy that one could obtain from a cut-wire test.

Deflectometer Test for Assessment of Strand Tension

Some investigators use a screwdriver, or pry bar to pry the strand laterally. They subjectively judge the tension in the strand by the force required to move the strand laterally. This is a crude form of deflectometer test. The force required to deflect the strand a given amount is indeed a function of the tension force in the strand. It is also a function of the length of the portion of strand that deflects (i.e. the lateral span). This length is hard to estimate, because of the irregularity of the support provided to the strand at the ends of the recess.

Mechanical deflectometers have been developed to overcome the subjectivity and uncertainty of the pry test. These devices have been used to measure the tension in guy wires and other tension elements and are available from manufacturers such as Proceq and others.

Halsall and Associates have developed a version that is suitable for unbonded post-tensioned strands. The mechanical deflectometer requires a large recess and unobstructed access to about 600 mm of strand that is free to deflect. The device also requires side clearance so that it can grip the strand, which may present a challenge when assessing bundled strands. The device is reported to have an accuracy of better than 5%. See reference Gupta, P., Trépanier, S., and Welch, E. (2001) for further information on this test method.