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Autor: Carfagno, Michael G. / Noorai, Faired S. / Brauss, Michael E.

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X-Ray Diffraction Measurement of Stresses in Post-Tensioning Tendons

Mesure des contraintes par diffraction des rayons X dans les câbles de précontrainte

Spannungsmessung in vorgespanntem Beton durch Röntgenbewegung

Michael G. CARFAGNO
Structural Engineer
Port Authority of NY & NJ
New York, NY, USA

Faired S. NOORAI
Supervising Struct. Eng.
Port Authority of NY & NJ
New York, NY, USA

Michael E. BRAUSS
R & D Manager
Proto Manufacturing Ltd
Oldcastle, ON, Canada

James A. PINEAULT
Physicist
Proto Manufacturing Ltd
Oldcastle, ON, Canada

SUMMARY

As part of an ongoing inspection and maintenance program for the prestressed, post-tensioned concrete runway extension decks at La Guardia Airport, a state-of-the-art method known as X-ray diffraction was utilized to non-destructively measure stresses in existing post-tensioning tendons. A review of the theory of X-ray diffraction stress measurement is given and a case study of the first known application of X-ray diffraction stress measurement to in-situ post-tensioning tendons as undertaken by the Port Authority at La Guardia Airport is presented.

RÉSUMÉ

Il est ici question d'une méthode relevant de l'état actuel de la technique, connue sous le nom de diffraction des rayons X et destinée à la mesure par essais non destructifs des contraintes dans les câbles de précontrainte; cette méthode fait partie intégrante du programme d'inspection et d'entretien continus des pistes d'aviation exécutées en béton précontraint sur l'aéroport de La Guardia. Les auteurs fournissent un rappel de la théorie de la mesure des contraintes par diffraction des rayons X, ainsi qu'une étude de la première application pratique connue de cette méthode, mise en oeuvre par la "Port Authority" de cet aéroport sur les câbles de précontrainte.

ZUSAMMENFASSUNG

Als Teil des Inspektions- und Wiederherstellungsprogramms für die vor- und nachgespannten Betonflugpisten-Verlängerungsflächen des La Guardia Flugplatzes durch die "Port Authority" wurde eine neuentwickelte Methode der Röntgenbeugung zur Feststellung der Spannungen und Eigenspannung der Verstrebungskabel angewendet. Ein Überblick der Theorie des Messens mit Röntgenbeugung wird gezeigt und eine Fallstudie der ersten praktischen Anwendung der Röntgenbeugung, an Ort und Stelle des La Guardia Flugplatzes wird dargestellt.

1. BASICS OF THE X-RAY DIFFRACTION STRESS MEASUREMENT TECHNIQUE

The x-ray method does not measure stress directly but does measure strain from which stress values are calculated. The x-ray method takes advantage of the crystalline structure of the material itself by using the interatomic lattice spacing as a strain gage. As a result, thousands of "built in strain gages" within the crystals that comprise the material are available for strain measurement by the x-ray diffraction method. More precisely the surface strain present can be determined by the measurement of the elastic atomic lattice spacing or "d-spacing" as it is commonly called. This lattice spacing, the distance between the planes of atoms, is a function of the material and the stresses present in the material. The x-ray diffraction angle θ for a given x-ray wavelength λ can be used to determine the material "d" spacing by solving Bragg's law:

$n\lambda = 2d\sin\theta$ ....Eq. 1

For x-ray diffraction to occur, e.g. constructive wave interference, the path difference traveled by the diffracted beam through the material as compared to a non-diffracted beam, must be equal to $n\lambda$ [1]. The presence of residual stresses in the material produces a shift in the x-ray diffraction peak angular position [2], which is directly measured by the detector. Once the lattice d-spacings are measured for the stressed (d_i) material condition, the atomic lattice strain can be calculated using the known unstressed (d_o) spacing by the following relationship [3]:

strain (ε) = $(d_i-d_o)/d_o$ ....Eq. 2

For isotropic materials, strains can be converted to stress values using the equation shown below.

stress (σ) = $[(d_\psi-d_o)/d_o]\,[E/(1+\nu)][1/\sin^2\psi]$ ....Eq. 3

where $E/(1+\nu)$ is the x-ray elastic constant, ψ is the angle subtended by the bisector of the incident and diffracted beam and the surface normal, d_ψ is the lattice spacing at a given ψ tilt, and d_o is the unstressed lattice spacing.

Residual stresses are measured using either of the following two techniques: The first is single exposure technique (SET), whereby a stress measurement is performed using only one tilt angle. This technique gives the user a fast and efficient method to perform a stress measurement and is particularly suited for the need to take many measurements very quickly. The second is the multiple exposure technique (MET), whereby multiple tilts are used in the analysis. This method is more revealing for materials where the relationship between d and $\sin^2\psi$ is not linear, as assumed in equation (3), but takes much longer than the SET [4].

The stress measurements described in this paper were performed using MET with CrKα radiation and the (211) hkl plane.

2.0 APPLICATION TO THE LA GUARDIA AIRPORT RUNWAY EXTENSIONS

2.1 Description of the structure

La Guardia Airport, located in Queens, New York, is bounded by Flushing Bay to the East and Bowery Bay to the West. As a result of the construction of an over-water structure in 1966, Runway 4-22 was extended approximately 610 meters (2,000 feet) northeast into Flushing Bay and Runway 13-31 was extended approximately 305 meters (1,000 feet) west into Bowery Bay to accommodate the first series of Boeing 727 and Convair 880 aircraft.

The structure consists of circular cast-in-place reinforced concrete piles constructed inside a steel shell that support cast-in-place pile caps. Precast, prestressed concrete I-beams span longitudinally (parallel to runways) from pile cap to pile cap. The 40.5 centimeter (16-inch) thick deck slab is supported by the concrete I-beams and is composed of precast, prestressed concrete inverted double tee planks with a cast-in-place concrete topping, which was post-tensioned in both the transverse (perpendicular to runways) and longitudinal directions. Once the deck slab was in place, the I-beams were subsequently post-tensioned to achieve a composite "T" beam in conjunction with the slab. Each runway extension consists of a set of panels approximately 111 meters (365 feet) by 101 meters (330 feet), separated by expansion joints.

The deck slab transverse post-tensioning consists of parabolically draped bundles of 6.35 millimeter (1/4 inch) diameter high strength (f_{pu} = 1,655 MPa = 240 ksi) wires conforming to the BBRV post-tensioning system (Figure 1). The number of 6.35 millimeter (1/4 inch) diameter wires in each tendon varies from 20 to 32 with the spacing of tendons at either 0.75 meter (2'-6") or 1.5 meter (5'-0") intervals, with both parameters, depending on its location, e.g. runway, taxiway or field area. The tendons were initially stressed to $0.7f_{pu}$=1,067 MPa (168 ksi). Depending on the location along the tendon, the theoretical effective stress (after all losses) was initially estimated to range from 986 MPa (143.0 ksi) to 703 MPa (102.0 ksi). After stressing the tendons were grouted.

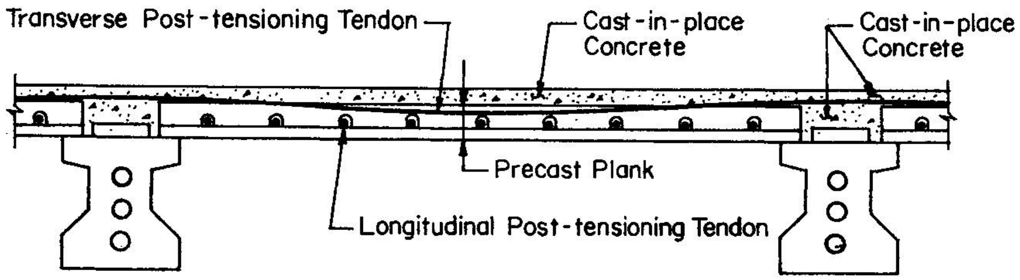

Figure 1: Typical transverse deck cross section

2.2 Reason for testing

Measuring the actual stress in the transverse, parabolically draped tendons (wires) was undertaken to rule out the possibility of loss of post-tensioning force as a reason for the presence of continuous longitudinal (parallel to runways and I-beams) hairline cracks in the top of the concrete deck in negative moment regions adjacent to the concrete I-beams. X-ray diffraction was the only non-destructive method available that could measure the actual stress without requiring the unloading of a tendon or isolating individual wires, instrumenting them and cutting them free.

2.3 Access and surface preparation

Port Authority personnel core drilled 20.3 centimeter (8 inch) diameter access holes in the runway deck concrete to intersect the transverse (parabolic) tendons (Figure 2) such that it formed a "chord" approximately 4 to 5 centimeters (1.5 to 2 inches) (radial) into the core. Concrete removal was accomplished using a small pneumatic jack hammer just to expose the tendon conduit. The depth of the individual holes ranged from 10 to 25 centimeters (4" to 10") (Figure 2) due to the vertical parabolic drape (Figure 1) of the post-tensioning tendon. Then the conduit (galvanized flexible metal pipe, 0.25 mm =0.01" thick) was peeled back to expose the grouted bundle of 6.35 millimeter (1/4 inch) diameter post-tensioning wires. The grout surrounding the wires was carefully removed by hand with a small chisel. Water and debris were removed from the access hole via compressed air. Surface preparation was not applied to the wire surfaces to be measured.

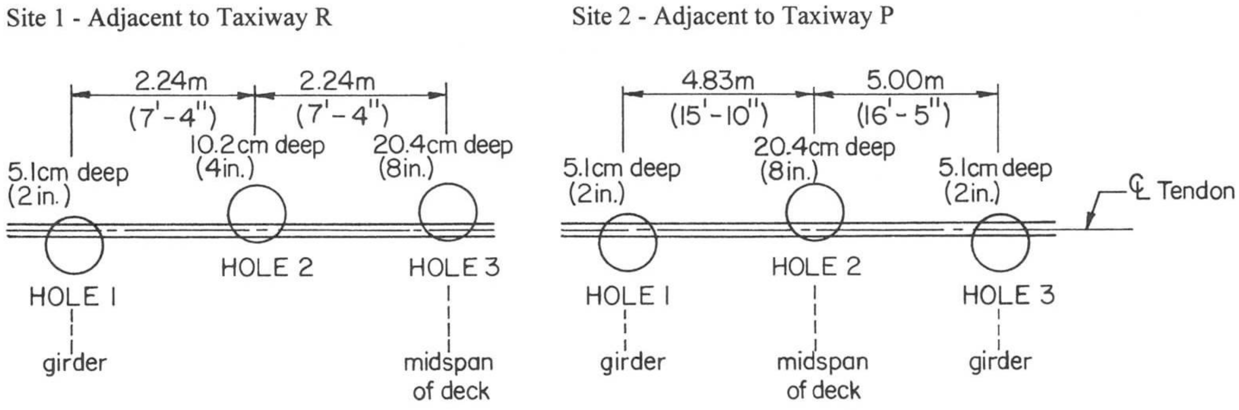

Figure 2: Access hole locations and depths

2.4 Field setup and equipment

An x-ray diffractometer designed specifically for field stress measurements was used to perform measurements. The modular instrument fits inside a van and was powered by a portable generator.

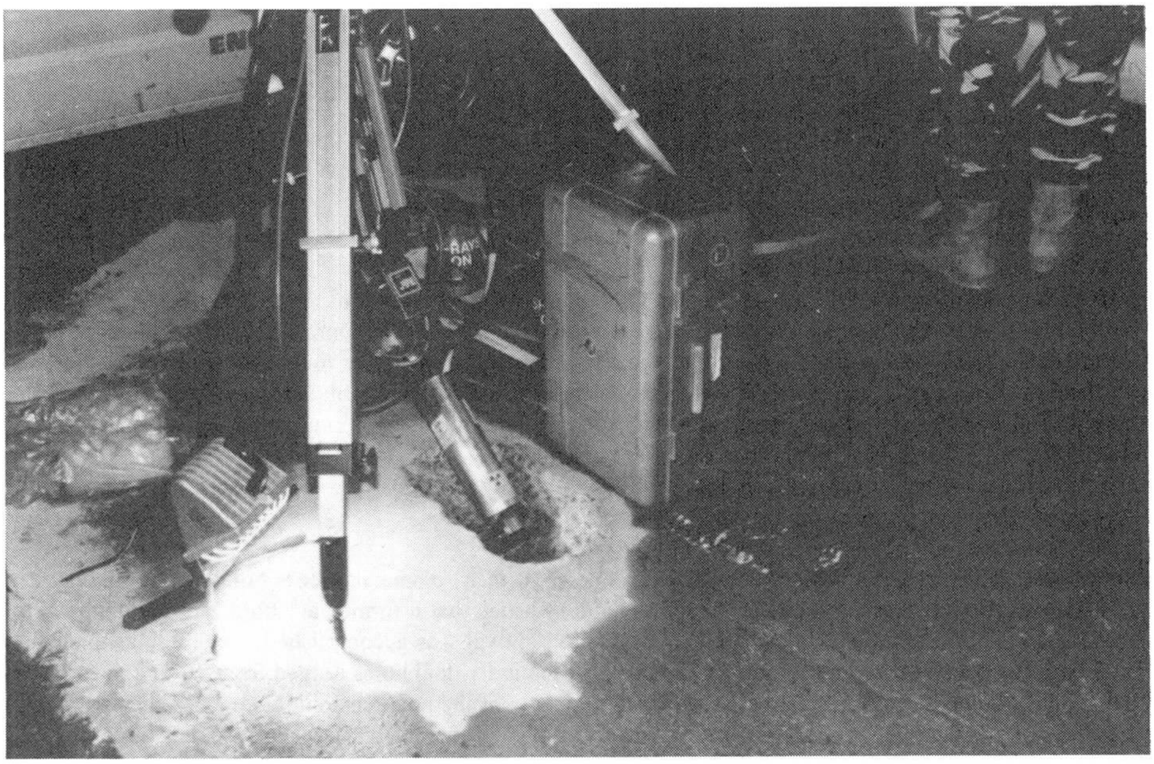

Figure 3: X-Ray stress measurements being performed adjacent to Taxiway R at La Guardia Airport, New York City. The modular instrument fits inside a van and was powered by a portable generator.

2.5 Stress measurement results

Strain measurements were performed at a total of six locations (two different parabolically draped tendons) on post-tensioned wires embedded in the concrete deck. All measurements were performed at two sites: Site 1 adjacent to Taxiway R and Site 2 was adjacent to Taxiway P. Table 1 gives the resulting calculated stresses at each site and location.

Taxiway	Hole	Wire	Spot	X-Ray Axial Stress (+ = tension) (ksi)	(MPa)	Corrected Axial Stress** (+ = tension) (ksi)	(MPa)	Remarks
P	1	1	1	+12	+83	+17	+184	Wire was struck by jackhammer during concrete removal.
P	1	1	2	+36	+248	+51	+349	
P	1	2	1	+97	+669	+112	+770	
P	1	3	1	+74	+510	+89	+611	
P	3	1	1	+67	+462	+82	+563	
P	3	2*	1	+82	+565	+97	+666	
P	3	3	1	+91	+627	+106	+728	
P	3	4	1	+91	+627	+106	+728	
P	2	1	1	+60	+414	+75	+515	
P	2	2	1	+75	+517	+90	+618	
R	1	1	1	+81	+558	+96	+659	
R	2	1	1	+107	+738	+122	+839	
R	2	1	2	+100	+690	+115	+791	
R	2	2	1	+105	+724	+120	+825	
R	3	1	1	+112	+772	+127	+873	

Table 1: X-Ray stress measurement data
* A section of wire 2 was removed from site 2 after in-situ stress measurements were completed to determine the residual stress and to perform other characterization experiments in the lab.
**Corrected axial stress is measured stress with average estimated residual stress deducted.
The experimental error for each stress measurement ranged from 13.8 to 20.7 MPa (2 to 3 ksi).

2.6 Residual stresses

One 10.2 centimeter (4 inch) section of wire 2 from hole 3, site 2 was carefully removed using bolt cutters. Residual stress measurements were then performed on this section of wire in the lab since the applied stress on the wire due to post-tensioning was removed. All measurements were performed near the center of the specimen so as to avoid areas of localized plastic deformation created during sample removal. The average residual stress measured was -101.4 MPa (-14.7 ksi) (compression). In the case of hole 3 wire 2, the total in-situ stress was measured to be +563.3 MPa (+81.69 ksi) (tension). The average residual stress was found to be -101.4 MPa (-14.7 ksi), hence the applied stress due to the load on this wire can be determined as follows:

Total Stress = Residual Stress + Applied Stress (due to post-tensioning)
Applied Stress = Total Stress - Residual Stress
= +563.3 MPa - (-101.4 MPa)
= +664.7 MPa (+96.4 ksi)

2.7 Calibration procedure

To ensure that the correct elastic constant was used in the calculation of stress using the measured strain data and to determine conclusively the applicability of the wire surface to XRD, a stress/strain relationship was developed. The stress on a 10.2 centimeter (4-inch) section of wire taken from hole 3, site 2 was measured under an incremental uniaxial tensile loading regime. The load was monitored using a load cell and by a strain gage during x-ray data collection.

The generally accepted values of Young's Modulus (E) and Poisson's Ratio (ν) for steel are 200,000 MPa (29,000 ksi) and 0.29 respectively. The close agreement of the experimentally determined Young's Modulus of 196,294 MPa (28,469 ksi) ± 2096 MPa (304 ksi) with the generally accepted value gives the strain gage data credibility and demonstrated the linearity of this relationship. The data collected at zero strain and zero load was ignored since there was some slack in the fixture, which caused low readings to be anomalous.

A plot of x-ray stress vs. stress calculated using strain gage strain readings was created. This data was used to determine the experimental value for $E/(1+\nu)$. The x-ray stress was calculated using the generally accepted values of E and ν. When the stress under the loading regime was plotted against the stress calculated using the strain gage data, we would expect a slope equal to 1 in the case where the generally accepted value for $E/(1+\nu)$ was the correct one for the particular alloy being tested. This is rarely the case, thus an experimental x-ray value for $E/(1+\nu)$ must be determined.

$$
\begin{aligned}
K_{x\text{-ray}} &= K_{mechanical} / 0.868033 \\
&= 155{,}006 \text{ MPa} / 0.868033 \\
&= 178{,}572 \text{ MPa } (25{,}899 \text{ ksi})
\end{aligned}
$$

and the ratio 1/0.868033= 1.15203

With this new x-ray elastic constant, the slope of the x-ray stress vs. strain gage stress plot will be equal to 1. Hence, all stress measurement values obtained at LaGuardia were adjusted by this factor.

2.8 Conclusions

At site 1 adjacent to Taxiway R, total stress measurements ranged from +560.6 MPa to +774.3 MPa (+81.3 ksi to +112.3 ksi) (tensile). At site 2 adjacent to Taxiway P total stress measurements ranged from 460.6 MPa to 669.7 MPa (+66.8 ksi to +97.13 ksi) (tensile). One reason for the range in readings is that the stress in the tendon varies with the location along the parabolically draped tendon due to friction losses that occurred while stressing the tendon. It should be noted that the x-ray diffraction method measures the stress only at the surface of the sample. Assuming an average compressive residual stress of 101.4 MPa (14.7 ksi) for all wires, to arrive at a number for the actual applied tensile stress in the wire due to post-tensioning, the 101.4 MPa (14.7 ksi) must be added to the observed measurements. After making this adjustment, the measured tensile stresses were found to be in rough agreement (within 20%) with the calculated estimate of stress in the tendon after losses. One explanation for the compressive residual stress is that the wires were drawn through a die that induced residual stresses. Because the measurements could only be made on the outer layer of wires in the bundle it is not known if the outer wire stress is representative of the average wire stress in the bundle which is the basis for the theoretical computation.

The x-ray diffraction method of measuring stresses proved to be a relatively simple and efficient technique to non-destructively measure stresses in post-tensioning steel wires in an existing concrete member. It would be of value if the technique could be tested in a laboratory setting and readings taken on interior and exterior wires under post-tensioning forces as well as, correlation being made directly with instrumented wire tensile stresses.

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