CONCRETE STRESS-RELIEF CORING: THEORY AND PRACTICE

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Measurement of concrete stresses has become a major tool in assessing the residual level of prestress in post-tensioned concrete bridges. This technique provides a global picture of the state of stress in the bridge. The concept of a stress-relief coring technique was initiated by Gifford and Partners in the early 1980's. Calibration tests were carried out at the University of Surrey. The technique has an accuracy of about ±0.5N/mm^2 in the laboratory and ±1N/mm^2 for site testing. An in situ jacking system was developed so that by reloading the drilled holes, the in situ stress and elastic modulus can be calculated. Some practical considerations for the use of the technique are discussed.

INTRODUCTION

Post-tensioned concrete bridges can suffer from loss of prestress due to a number of reasons. These include concrete creep and shrinkage, corrosion of the tendons due to ingress of de-icing salts and, occasionally, construction or design faults such as duct flotation due to the lack of adequate duct restraints. Inadequate grouting also lends itself to a potential source for tendon corrosion. The net effect of these losses manifests itself as a global reduction of compressive stress in the concrete.

There are two basic methods for the measurement of the remaining level of prestress; measurement of remaining stress in prestressing tendons using a blind hole stress-relief technique and measurement of concrete stresses by a similar stress-relief technique. Each approach has its own advantages and disadvantages. The former gives the tendon stresses directly but back-calculation is required to derive the remaining level of prestress when the latter approach is used. If a proportion of the tendons at a cross-section are severed, the tendon stress measurements may miss the severed tendons and could be misleading. When the concrete stress-relief technique is used a global picture of stresses is obtained but stresses due to other effects are also released during the test and must be accounted for. These include locked-in differential temperature and shrinkage stresses, dead load stresses and structural effects such as differential settlement. In tendons, however, the manufacturing stresses are released during the blind hole stress-relief test.

In the early 1980's Gifford and Partners initiated a programme of work on an instrumented concrete coring technique now known as stress-relief coring. Trial tests were performed on structures in service and calibrations carried out in the laboratory on uniaxially and biaxially loaded slabs. These tests resulted in two nominal stress-relief core size of 75 and 150mm diameters. The calibration tests were performed at the University of Surrey and resulted in two Doctorate theses, Mehrkar(1) and Buchner(2). The author has since been involved in the assessment of post-tensioned concrete bridges using the concrete stress-relief coring technique, Brookes et al (3), Mehrkar (4).

The 75mm diameter core has proved to be the most suitable size due to limited spacing between the reinforcement. The 150mm diameter core, however, is the most suitable size with respect to the ratio of the maximum aggregate-size to the dimension of the released area. A ratio of about 1 to 6 is considered necessary to give a representative stress release. Unpublished work carried out on the original lining of the Channel Tunnel, where both core sizes were used, proved that similar results are obtained from both core sizes. In the following, for the first time, the results of the calibration tests for the 75mm diameter core size are published. Details of the test including gauge arrangement, theoretical and calibration coefficients and method of converting the measured strains to in situ stresses are explained. In addition, details are provided of a jacking system, which was also developed by the author, to estimate stresses from the loads required to re-establish the original strain field. The jacking system can also be used to estimate the in-plane elastic modulus of the concrete.

CALIBRATION TESTS

Slabs

In total, fifteen 100mm thick slabs were cast and tested. Three were loaded biaxially and the rest were loaded uniaxially. The biaxially loaded slabs were used in the calibration of the 150mm core arrangement. Only four slabs were used to calibrate the 75mm diameter core arrangement. These included three 1x1m slabs and one 0.8x0.8m slab.

Gauge Pattern

The gauge arrangement for a 75mm core is shown in Figure 1. The gauge pattern comprises a central array of four 50mm Demec gauges to measure stress releases on the core, an array of four 100mm Demec gauges across the hole to measure the distortion of the hole and an array of eight 64mm (2.5 inch) vibrating wire gauges to measure the release of stresses around the hole. The pattern can accommodate to some extent, lack of concentric drilling and changes in material properties over a bigger area.

Jacking Equipment

In order to load against the walls of 75mm diameter hole, a cylindrical assembly of solid steel was designed with special casing for a small jack. A detailed drawing of the assembly is shown in Figure 2. The function of the key parts are as follows:

Studs A are used to restrain the movement of the two platens in one direction.

Studs B are mounted on the stationary platen to guide the small jack for concentric loading with respect to the assembly.

Step C is there to provide a concentric reaction from the small jack onto the stationary platen.

The assembly has a radius of 36.5mm and mild steel sheets of 1mm thickness are used to provide a uniform contact between the assembly and the boundary of the hole. An Enerpac jack (RMC-50), capable of applying up to 50kN, sits inside the assembly. Calibration of the jack against load cells indicated a load of 5kN for every 80bar pressure.

Slab Tests

Loading. Each slab was uniaxially loaded in increments up to $5N/mm^2$ and strain gauges were read at each load increment, stage-1. Arrays of 100mm Demec gauges were also placed along the centreline of each slab to determine the elastic modulus. Each slab was then cored under this load. Concrete strains in each of the arrays were monitored for up to 24 hours, stage-2. The load was then removed. The slab with the hole was then loaded, stage-3. Strain releases measured during stage-2 were due to the applied load of $5N/mm^2$ and any effect such as locked-in differential shrinkage. The difference of the strain gauge readings between stage-3 and stage-1 gives the strain releases for the applied stress of $5N/mm^2$. This is referred to as the simulated release and is the most reliable result to be used in the calibration.

Diamond Drilling. Slabs were drilled under load using a diamond drill bit of 75mm diameter. Water used as a coolant can affect the vibrating wire gauge readings. Depending on the ambient humidity and dryness of the concrete, this water could also cause expansion of the concrete and particularly the core.

Gauge Monitoring. Monitoring of the strain gauge readings after coring indicated that strains were varying with time. The readings at 24 hours after coring were similar to the simulated release values. Further investigation indicated that the concrete mix used had caused high differential shrinkage stresses in the slabs. Therefore, significantly longer time was required for the strains to reach a steady state with this self-equilibrating stress field acting on the slabs. Subsequent site tests on over 200 core stress-relief tests have proved that 1 to 2 hours monitoring of the strain gauge readings is adequate to achieve this steady state.

Jacking test. The last stage of the test on each slab included a number of jacking tests using the assembly shown in Figure 2. The assembly was placed along the line of the vibrating wire gauges. Loads were applied in increments of 5kN up to 25kN and vibrating wire gauge readings recorded. Least-squares analyses were then carried out to determine concrete strains along and perpendicular to the jack.

Principal Strains

The principal strains are calculated from the released strains. As only three strain gauge directions are adequate for the calculation of the two principal strains and their directions, a least-squares approach derived by Lightfoot(5) is used to improve the accuracy. In addition any spurious measurement can be detected and if necessary eliminated. The Lightfoot equations are as follows:

$$\varepsilon_1 = p + q \quad (1)$$
$$\varepsilon_2 = p - q \quad (2)$$
$$\phi = \tfrac{1}{2}\,\mathrm{Arctan}[(\varepsilon_d - \varepsilon_b)/(\varepsilon_a - \varepsilon_c)] \text{ and } \tfrac{1}{2}\,\mathrm{Arccos}[(\varepsilon_a - \varepsilon_c)/2q] \quad (3)$$
$$p = \tfrac{1}{4}(\varepsilon_a + \varepsilon_b + \varepsilon_c + \varepsilon_d) \quad (4)$$
$$q = \tfrac{1}{2}\sqrt{[(\varepsilon_a - \varepsilon_c)^2 + (\varepsilon_b - \varepsilon_d)^2]} \quad (5)$$

Stresses

Stresses are calculated by using the plane stress equations of the elastic theory to convert the principal strains into the principal stresses. The equations are as follows:

$$\sigma_1 = E(\varepsilon_1 + \mu\varepsilon_2)/(1-\mu^2) \quad (6)$$
$$\sigma_2 = E(\varepsilon_2 + \mu\varepsilon_1)/(1-\mu^2) \quad (7)$$

Core Stresses. Stresses in a core are fully released. Therefore stresses can be directly obtained using equations 1 to 7. Monitoring the variation of strains with time was adequate for their calibration.

Hole Distortion Stresses. Strains in the Demec gauges across the hole represent the distortion of the hole. If equations 1 to 7 are applied to these strains, a set of apparent principal stresses are obtained which have to be converted into the actual stresses.

Rosette Stresses. The vibrating wire strain gauges are referred to as the rosette. These gauges are equipped with temperature coils and their readings must be temperature corrected as they are sensitive to temperature variation caused by the heat generated during drilling and passage of the coolant water over some of the gauges. Stresses around the hole are only partially released. Therefore, the use of equations 1 to 7 results in a set of apparent principal stresses which have to be converted into the actual stresses.

Jacking Stresses. These are based on the loads required to re-establish the vibrating wire gauge readings to their original values before coring. However, as it is not possible to do this physically with the jacking assembly designed, the principle of superposition is used to find the forces in the particular directions. To simplify it even further, only the jacking loads required to re-establish the principal strains are obtained. Therefore, combining the strains along and perpendicular to the jacking load and the principal strains, a set of two equations and two unknowns is obtained to be solved for a pair of loads to restore the original strain field.

STRESS CONVERSION COEFFICIENTS

Stress conversion coefficients are used to convert the apparent stresses from the Demec gauges across the hole and the rosette of vibrating wire gauges to actual stresses. These are calculated both theoretically and experimentally. The general form of the conversion equations are as follows:

$$\sigma_1 = A_1 \underline{\sigma}_1 + A_2 \underline{\sigma}_2 \quad (8)$$

$$\sigma_2 = A_2 \underline{\sigma}_1 + A_1 \underline{\sigma}_2 \quad (9)$$

Theoretical coefficients

Muskhelishvili(6) has derived the equations for displacements of an infinite plate under a uniaxial state of stress around a circular hole. If equations of displacement in an infinite plate are subtracted from his equations, the resulting equations give the displacement due to making a hole in an infinite plate. As all the strain measurements are in the radial directions, knowledge of the displacements in radial directions is adequate to calculate theoretical conversion equations. The equation for radial displacement in an infinite plate under a uniaxial stress of unity due to the introduction of a circular hole is as follows:

$$V_r = [2R^2(1+\mu) + 2R^2(4-R^2(1+\mu))\mathrm{Cos}(2\alpha)]r/(4E) \quad (10)$$

Hole Distortion Coefficients. Dividing equation 10 by r results in the average strains that are measured in each direction by the Demec gauges across the hole. As only a stress of unity is applied, substituting 0 and 90 for α would result in the ε_1 and ε_2 values. Hence, it is possible to calculate the theoretical apparent stresses by applying equations 1 to 7. By substituting the resulting apparent stresses and the actual stresses of one and zero in equations 8 and 9, it is possible to calculate A_1 and A_2 as follows:

$$A_1 = (1-\mu)/A + (1+\mu)/B \quad (11)$$
$$A_2 = (1-\mu)/A - (1+\mu)/B \quad (12)$$
where:
$$A = 2R^2(1+\mu) \quad (13)$$
$$B = 2R^2[4-R^2(1+\mu)] \quad (14)$$

Rosette Coefficients. Derivation of stress conversion coefficients for the rosette is very similar to the hole coefficients, except that the average strain is calculated by the difference between the displacement of the end points of vibrating wire gauges, divided by the distance between these two points. The derivation is described in detail in reference (1). The conversion coefficients are as follows:

$$A_1 = -[(C_f+D_f)K_f-(C_n+D_n)K_n]/Det \quad (15)$$
$$A_2 = -[(C_f-D_f)K_f-(C_n-D_n)K_n]/Det \quad (16)$$
where:
$$Det = 4K_f^2(C_fD_f)+4K_n^2(C_nD_n)- 4K_fK_n(C_nD_f+C_fD_n) \quad (17)$$
$$K_i = r_i/(r_f-r_n) \quad (18)$$
$$R_i = R_o/r_i \quad (19)$$
$$C_i = 2R_i^2[4-R_i^2(1+\mu)]/[4(1+\mu)] \quad (20)$$
$$D_i = 2R_i^2(1+\mu)/[4(1-\mu)] \quad (21)$$
Subscript i = n or f, near or far end of vibrating wire gauge

Experimental Coefficients

Calculation of the experimental coefficients is similar to the theoretical approach. The strains measured by the simulated approach are first used to obtain the principal strains using the equations 1 to 5. Then by using the elastic modulus obtained from the incremental loading of the slabs and a Poisson's ratio of 0.18, apparent principal stresses are calculated by using equations 6 and 7. Now by solving the two-by-two simultaneous equations 8 and 9, conversion coefficient A1 and A2 are obtained. In Table 1, the experimental and theoretical conversion coefficients are compared. The theoretical coefficients are calculated for R_o=39mm, r=50mm (for 100mm Demec gauges giving R=0.78), r_n=66.35mm, r_f=129.85mm and μ=0.18.

TABLE 1 – Comparison of Experimental and Theoretical Conversion Factors.

Slab	Hole Coefficients		Rosette Coefficients	
	A1	A2	A1	A2
0.8x0.8	-	-	3.070	0.870
1.0x1.0 iv	0.853	0.342	2.815	1.274
1.0x1.0 v	0.935	0.371	3.129	1.503
1.0x1.0 vi	0.715	0.218	3.716	1.573
Average	0.834	0.310	3.183	1.305
Theory	0.867	0.276	2.988	0.949

When theoretical and experimental conversion coefficients were used on the results of the simulated release strains, the difference between the applied and estimated stresses had an error of the order of ±0.3N/mm^2 for both hole and rosette arrangements. However, the maximum difference between the applied and estimated stresses was ±0.8N/mm^2. Therefore, ±0.5N/mm^2 is considered a reasonable accuracy for the laboratory measurements. It should be mentioned that the most consistent test result has been the difference of the two principal stress values. Monitoring of the gauge readings after coring on each of the slabs indicated that even though magnitude of the stresses were changing with time, the difference between the two principal stresses were always within $\pm 0.5 N/mm^2$ of the applied stress.

Jacking test equations

The jacking test calibration resulted in two sets of equations. The first set converts the forces required to re-establish initial strains in the principal strain directions to the principal stresses. The second set provides an estimate of the in situ in-plane elastic modulus of the concrete. The equations are as follows:

$$\sigma_1 = (32.84F_1 + 12.14F_2)/t \qquad (22)$$

$$\sigma_2 = (12.14F_1 + 32.84F_2)/t \qquad (23)$$

and

$$E = 101000/(tS) \qquad (24)$$

The above equations are suitable for slabs where the jacking load is applied over the whole depth of the hole. In practice blind holes of up to 175mm in depth are drilled to limit the effect of the blind hole on the jacking test even though 75mm depth is adequate for almost full stress release. The jacking test is carried out with the assembly flush to the concrete surface and also at a depth of 20mm. This would allow the distribution of the load on the tail end of the jack to be predicted. As numerous tests have indicated that the longitudinal surface strain due to the jack at a depth of 40mm is almost zero, the following equation has been used to calculate parameter S to be used with t=100mm in equations 24 and for the calculation of F_1 and F_2.

$$S = 1.2S_s + 0.4S_{20} \qquad (25)$$

CONCLUDING REMARKS

Concrete should be cored on the side of the section with the highest prestress component to improve the accuracy in the back-calculation of the prestressing forces, ie soffit at midspan and on top of the deck over the supports of a continuous bridge. At least three measurements are required at representative positions. Areas with stress concentration or high stress gradient should be avoided. For example, a reasonable distance should be kept from the corners of box girders, transverse diaphragms and anchorage areas.

Instrumentation should be carried after the surface of concrete is cleaned and a covermeter survey performed to avoid the steel bars. Hard Plastic Padding has been used to stick gauges with relative success. Coring equipment should produce a concentric hole of 77 to 79mm diameter with a square edge and smooth surface. Coring should start slowly to bite into the concrete and avoid damaging the gauges.

As locked-in stresses due to differential shrinkage and temperature, and temperature restraints are also released, tests should be carried out when these effects are at a minimum. Very cold or warm weather would affect the results significantly. It should be remembered that the most reliable piece of information is the difference between the magnitude of the principal stresses.

With the 75mm core, avoiding reinforcement is not difficult. But cutting small diameter bars does not affect the results due to the relative size of the steel and the core. However, coring close to large diameter bars affects the jacking test but has less influence on the release strains.

SYMBOLS USED

$\varepsilon_{a,\ b,\ c\ and\ d}$ = strains measured at 45 degree intervals, expansive strains +ve on core, –ve across hole and +ve on rosette.

$\varepsilon_{1\ and\ 2}$ = maximum and minimum principal stains, respectively.

ϕ = Direction of the maximum principal strain from ε_a, +ve ε_a to ε_b.

$\sigma_{1\ and\ 2}$ = maximum and minimum principal stresses.

E = elastic modulus (kN/mm^2 in equation 24).

μ = Poisson's ratio.

$\underline{\sigma}_{1\ and\ 2}$ = maximum and minimum apparent principal stresses.

$A_{1\ and\ 2}$ = conversion coefficients.

V_r = displacement in the radial direction.

α = angle from the unit stress direction in the infinite plate.

r = radial distance from centre of the hole.

R_o = radius of the hole.

R = ratio of the hole radius to radial distance.

$F_{1\ and\ 2}$ = jacking forces in the two principal stress directions to re-establish original strains (kN) (+ve compressive).

t = thickness of the slab (mm).

S = longitudinal strain due to jacking test (microstrain for 10kN).

S_s = Similar to S above but in a blind hole (+ve contraction).

S_{20} = Similar to S above but for jacking 20mm depth in a blind hole.

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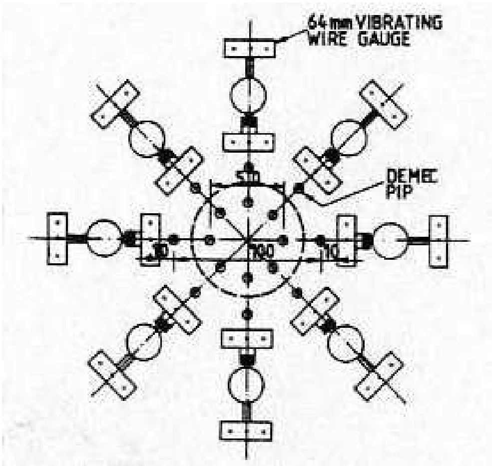

Figure 1 Gauge arrangement for the 75mm diameter cores

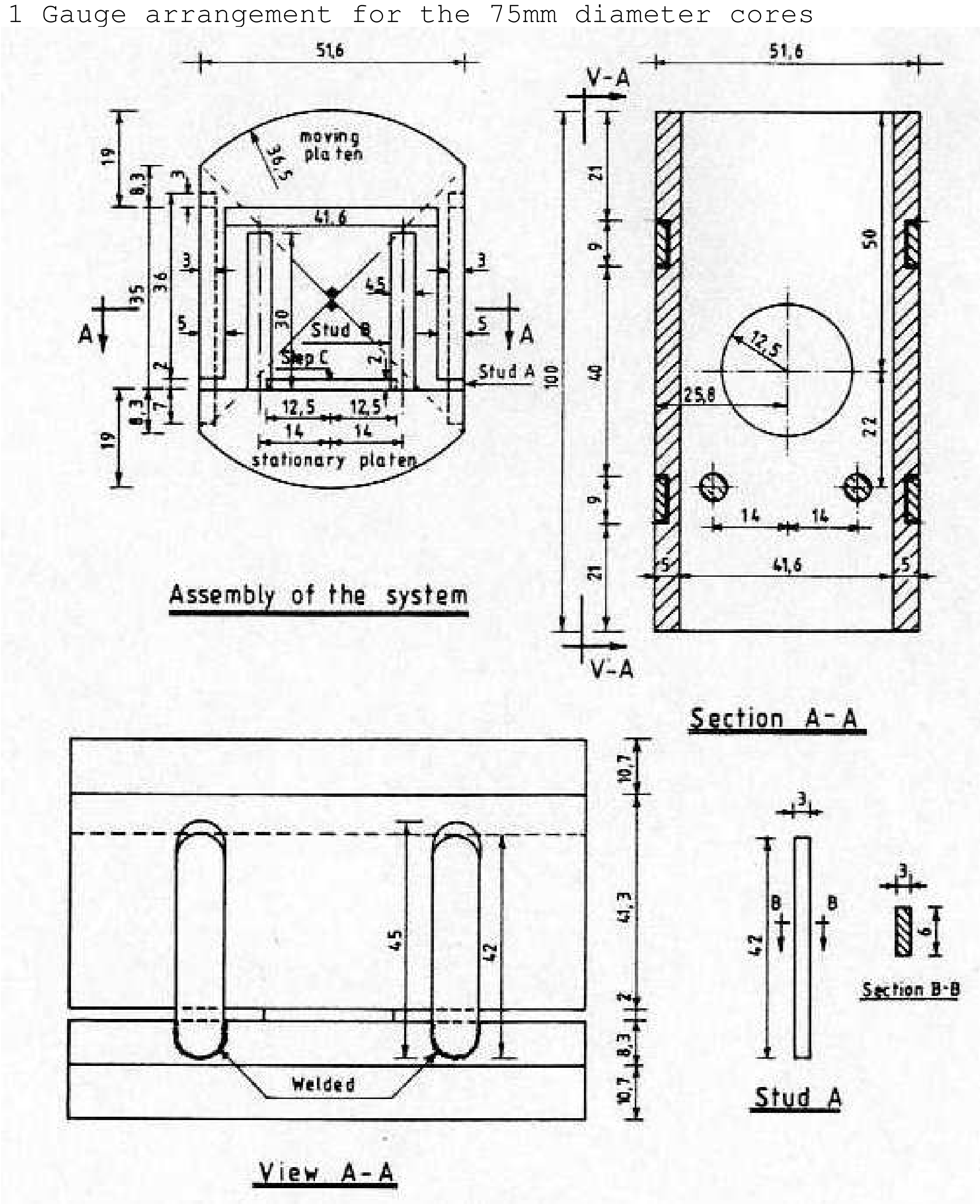

Figure 2 Jacking assembly for 75mm Diameter holes