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Determination of concrete properties in situ

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Abstract

This paper describes how finite element analyses were used to develop a method of in-situ determination of concrete material properties. A 3-D model of a concrete block with single hole under diametrical hydraulic jack force is idealised as a finite element model with 2308 nodes and 582 solid elements and is used as the prototype in this study. The strains, stresses and deformations of the block for nine possible combinations of Young's modulus E and Poisson's ratio ν were used to determine the variation of strain at radial gauge locations. The relationship between strain and material property for the block with fixed geometry is investigated numerically, from which a formula is derived for E and ν in terms of the measured in-situ strains. The practical application of the technique on a real structure is also presented.

1 Introduction

The need to assess the possibility of structural degradation and the load carrying capacity of ageing structures has increased the requirement for knowledge of the magnitudes of in-situ stresses. In situ stress determination techniques for concrete structures have been developed[1-4]. These techniques although originally applied in the stress analysis of metallic components of aircraft extension of the principle have proved to be efficient and applicable to structural members of concrete bridges[4]. When applied to concrete, however, it is often necessary to remove a large diameter(150mm x 300mm) sample for subsequent laboratory determination of Young's modulus and Poisson's ratio.

These mechanical properties are then used to convert measured surface strains into in-situ stresses. This paper describes the developement of a technique whereby these mechanical properties are also determined in-situ. This development has relied heavily on models of the test arrangement both for examination of the sensitivity of the general arrangement of the test, and the evaluation of varying mechanical properties. The standard arrangement of gauges for in-situ stress determination is utilised with an internal jack being inserted in the remaining hole. This jack is then used to incrementally load the surface of the hole while measurements of surface strain are made. A relationship between surface strains around the hole and the material's mechanical properties is thus all that is required to complete the determination. For this purpose, a 3-D model of a concrete block with single hole subject to diametrical hydraulic jack force is used as the prototype. The strains, stresses and deformations of the block for nine possible combinations of Young's modulus E and Poisson's ratio ν were evaluated and used to determine the variation of strain at radial gauge locations. The relationship between average strain and material property for the block with fixed geometry and loading angle is investigated numerically, from which a formula is derived for E and ν in terms of the measured surface strains.

2 Finite element modelling of the concrete block

To obtain practical results and make sure that the analytical model is representitive, a concrete block with dimensions $250 \times 250 \times 500mm$ which has been employed in privous research [4] , is studied again in the following analysis.

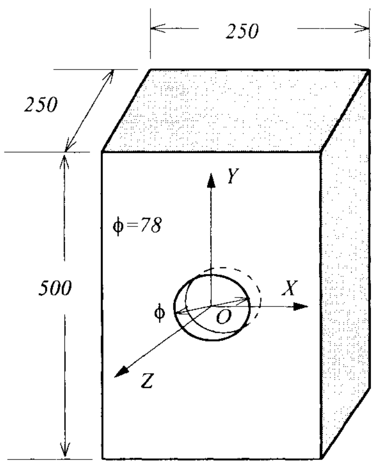

Figure 1: Concrete block with surface hole of 50*mm* depth

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As shown in Figure 1, the hole of 78*mm* diameter and 50*mm* in depth is drilled at the centre of the surface *Z*=0. A load of 20*kN* is applied inside of the hole in *Y*-direction to simulate the hydraulic jack pressure.

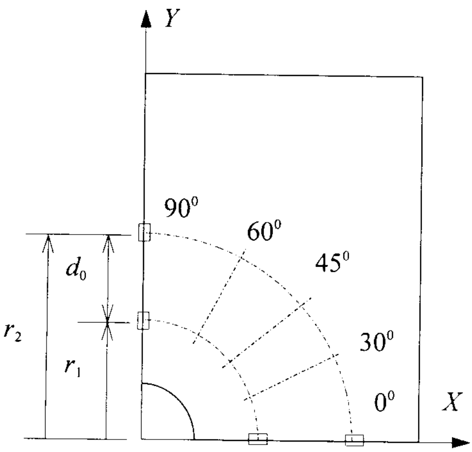

Figure 2: Possible locations of strain gauges

Figure 2, where $d_0 = r_2 - r_1 = 50.8mm$, shows the possible layout of the five gauges. The suggested angles can be coincident with the locations in the in-situ measurement and can provide enough information for the determination of

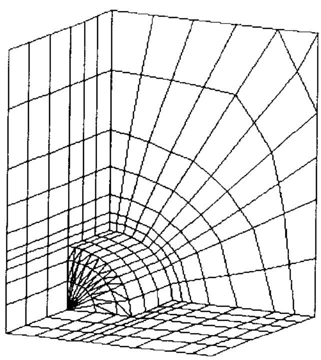

Figure 3: Finite element mesh using symmetry

material property. To take the advantage of the symmetry of the problem, only quarter of the block is idealised. Two kinds of solid element, i.e. PN6 and HX8M [4] are employed for the modelling. The quarter block is separated into 2308 nodes and 582 solid elements with *Y*=0 and *X*=0 surfaces fixed in *Y* and

X directions, respectively.Figure 3 shows the element mesh of the quarter block, in which the coordinates of the positions of the possible gauges are exactly the same as that of the external nodes of elements. The applied force for the quarter block from the hydraulic jack is treated as uniform surface force with 10 kN resultant.

By using LUSAS FE software package [5], numerical analyse were carried out for nine combinations of three different values of Young's modulus $E_1 = 30000, E_2 = 34000$ and $E_3 = 36000 N / mm^2$, and three different values of Poisson's ratio $\nu_1 = 0.18$, $\nu_2 = 0.2$ and $\nu_3 = 0.22$.

Table 1: Evaluated average strains by LUSAS

(units: $E - N / mm^2$, $strain - microstrain$ ($\mu\varepsilon$))

E	ν	θ=0°	θ=30°	θ=45°	θ=60°	θ=90°
E_1	0.18	8.6658	14.992	8.1674	-39.115	-205.72
	0.20	7.5509	13.975	7.5288	-42.617	-205.72
	0.22	6.0940	13.013	6.6961	-42.626	-208.07
E_2	0.18	7.8234	13.692	6.5351	-36.212	-181.53
	0.20	6.5956	13.015	6.3188	-36.832	-181.51
	0.22	5.3771	12.300	6.1528	-38.494	-182.60
E_3	0.18	7.4544	13.102	6.1724	-33.109	-170.40
	0.20	6.2924	12.292	6.1141	-33.371	-171.43
	0.22	5.1390	11.641	4.3532	-34.165	-173.47

Because the measured strain used is the average between the two ends of the gauge, say, take $\theta = 0$ for example, the measured strain ε_m is

$$\varepsilon_m = \frac{u(r_2) - u(r_1)}{d_0} \tag{1}$$

where $u(r_1)$ and $u(r_2)$ are the displacements of left and right ends of the gauge, respectively. So that the comparable strain evaluated by FEM should be the average strain between the ends of the gauge. Let l and r be the left and right ends of the gauge located in θ direction from OX axis. From LUSAS, the displacements at nodes l and r are $(u,v)_l$ and $(u,v)_r$, where u and v are displacements in X and Y directions, respectively. Then the average strain in θ direction can be written as

$$\varepsilon_{avr}(\theta) = \frac{1}{d_0}\{(u \quad v)_r - (u \quad v)_l\}\begin{Bmatrix}\cos\theta \\ \sin\theta\end{Bmatrix} \tag{2}$$

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By using this equation, the average strains ε_{avr} in $\theta = 0^\circ, 30^\circ, 45^\circ, 60^\circ$ and 90° directions for the nine combinations of material are calculated and shown in Table 1.

3 Determination of Young's modulus and Poisson's ratio

According to Table 1, an approximate formula, which relates ε_{avr} to E, ν and θ, can be derived by assuming

$$\varepsilon_{avr}(\theta) \approx \frac{1}{E}\alpha(\theta) + \frac{\nu}{E}\beta(\theta) \tag{3}$$

where α and β are two coefficients associated with θ and determined by a *least square* technique for the 9 material combinations. The variations of α and β with angle θ are depicted in Figure 4.

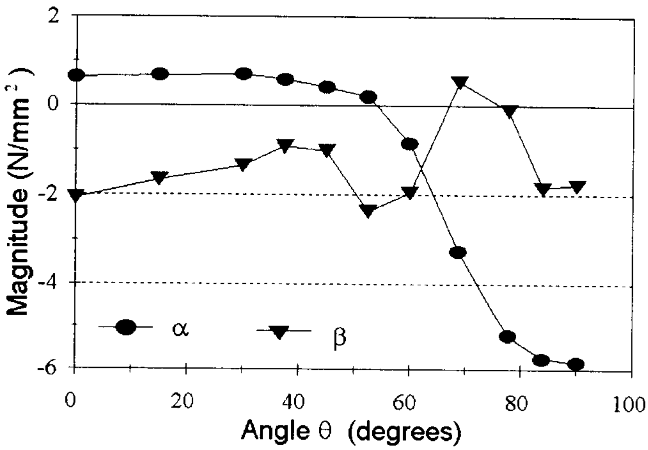

Figure 4: Variations of coefficients α and β with angle θ

The values of E and ν can be calculated from equation (3) by taking two different values of θ, i.e.

$$\begin{cases} E = \dfrac{\alpha(\theta_1)\beta(\theta_2) - \alpha(\theta_2)\beta(\theta_1)}{\varepsilon_{avr}(\theta_1)\beta(\theta_2) - \varepsilon_{avr}(\theta_2)\beta(\theta_1)} \\ \\ \nu = \dfrac{\alpha(\theta_1)\varepsilon_{avr}(\theta_2) - \alpha(\theta_2)\varepsilon_{avr}(\theta_1)}{\varepsilon_{avr}(\theta_1)\beta(\theta_2) - \varepsilon_{avr}(\theta_2)\beta(\theta_1)} \end{cases} \tag{4}$$

It is assumed that the strain obtained by FEM, so the strain by equation (3), is the best approximation to the measured strains of concrete members. This means that equation (4) is applicable to in-situ problems if $\varepsilon_{avr}(\theta_1)$ and $\varepsilon_{avr}(\theta_2)$ are replace with measured strains $\varepsilon_m(\theta_1)$ *and* $\varepsilon_m(\theta_2)$ and the real load with an amplitude *f* is incorporated. The material property is then represented by

$$\begin{cases} E = \dfrac{\alpha(\theta_1)\beta(\theta_2)-\alpha(\theta_2)\beta(\theta_1)}{\varepsilon_m(\theta_1)\beta(\theta_2)-\varepsilon_m(\theta_2)\beta(\theta_1)}\cdot f \\ \\ \nu = \dfrac{\alpha(\theta_1)\,\varepsilon_m(\theta_2)-\alpha(\theta_2)\,\varepsilon_m(\theta_1)}{\varepsilon_m(\theta_1)\,\beta(\theta_2)-\varepsilon_m(\theta_2)\,\beta(\theta_1)} \end{cases} \tag{5}$$

The accuracy of equation (5) depends on that of equation (3). It can be found from Table 2 that the interpolated strain $\varepsilon_{avr}(\theta)$ by equation (3) has good agreement with the average strain obtained from LUSAS, and that the errors are less than 1.6%.

Table 2: Percentage errors of average strain obtained from equation (3)
(units: $E - N/mm^2$, $strain - microstrain$ $(\mu\varepsilon)$)

E	ν	$\varepsilon_{avr}(0^{\circ})$	error (%)	$\varepsilon_{avr}(90^{\circ})$	error (%)
	0.18	8.8072	-1.63	-205.27	0.22
E_1	0.20	7.5270	0.31	-206.36	-0.31
	0.22	6.1144	-0.33	-207.44	0.30
	0.18	7.7711	0.66	-181.12	0.22
E_2	0.20	6.6415	-0.69	-182.08	-0.31
	0.22	5.3951	-0.33	-183.04	-0.24
	0.18	7.3393	1.54	-171.06	-0.38
E_3	0.20	6.2725	0.36	-171.96	-0.31
	0.22	5.0953	0.85	-172.87	0.34

4 Application

The present method has been used in determination of mechanical properties in a concrete bridge. The strain change was caused by making use of a simple hydraulic jack with curved platens inside a cylindrical hole in the concrete bridge and measured using strain gauges as shown in Figure 2. The sizes of the jack and the hole are the same as those used for both laboratory and FE modelling. The jack pressure is 6.8948 N/mm^2 and the area of the piston is 490.87 mm^2 giving a real load amplitude factor in equation (5) of f=0.16908.

Take $\theta_1 = 0^0$ and $\theta_2 = 90^0$ as the two reference directions. It is known from the FE analysis results that $\alpha(0°) = 0.64143 \; N/mm^2$, $\beta(0°) = -2.0806 \; N/mm^2$, $\alpha(90°) = -5.8333 \; N/mm^2$, and $\beta(90°) = -1.7756 \; N/mm^2$. Substituting above coefficients and f in the first equation of equation (5) gives

$$E = \frac{1.26413 \times 10^3}{\varepsilon_m(0°) - 1.1717729\varepsilon_m(90°)} \; kN/mm^2 \tag{6}$$

where $\varepsilon_m(0°)$ and $\varepsilon_m(90°)$ are, respectively the measured microstrains in X- and Y-directions (see Figure 2). Since $\varepsilon_m(0°)$ is much less than $\varepsilon_m(90°)$ in magnitude, it can be neglected and so that equation (6) can be simplified as

$$E = -\frac{1.078 \times 10^3}{\varepsilon_m(90°)} \; kN/mm^2 \tag{7}$$

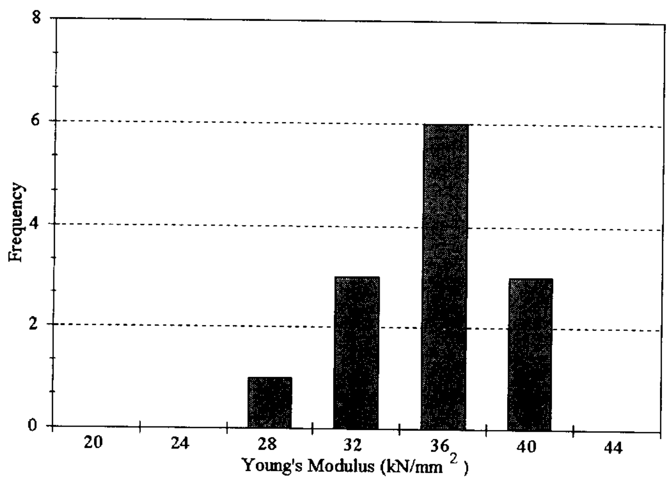

Figure 5: Modulus frequency distribution

The strain changes $\varepsilon_m(90°)$ were measured at 13 different positions of the bridge and the corresponding Young's modulus were evaluated by using equation (7). The highest value of the Young's modulus is $38.39 \; kN/mm^2$ whilst the lowest value is $26.75 \; kN/mm^2$. Figure 5 is the modulus frequency photogram which indicates a mode of Young's modulus within 33.0-37.0 kN/mm^2.

5 Conclusions

A finite element analysis based method for the determination of the mechanical properties of concrete has been investigated. The results show good correlation between the numerical and experimental values, which suggests that although the approach was a simplified idealisation the results will be practically applicable. The expressions obtained by numerical analysis for Young's modulus and Poisson's ratio have also been shown to hold good for values outside the range of those analysed and can in fact be used for all values of mechanical properties of concrete likely to be encountered providing the same experimental arrangement is maintained.

The method described has allowed the extension of the in-situ stress determination technique to locations where the more usual 150mm diameter hole would be prohibited, with concurrent material modulus and Poisson's ratio determination being obtained from the much smaller diameter holes in-situ. The only disadvantage with this technique has been a slight reduction in accuracy which is more than compensated for by the increased coverage of the structure allowed by the much smaller holes. An accuracy of ±2% can be expected based on the sensitivity of the vibrating wire strain gauges used in practice, although local material variability is likely to be far more significant. Further work is now under way to extend the technique to more complex stress distributions together with corroboration of Young's modulus from the testing of Brazilian disc specimens[6].

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