CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

In this chapter the previous work done on existing stress measurement on concrete members using various techniques are discussed. Brief descriptions of the methods, theory described in the published works are also presented.

2.2 LITERATURE REVIEW

2.2.1 Laboratory Investigations

Chandu Shenoy and Gregory Frantz (1991) tested two 27 year old precast concrete box beams[36in wide×27in. deep(914mm×686mm)] which were removed from a deteriorated 54ft(16.5m) span multi-beam Walnut street bridge, built in 1960 in East Hartford, Connecticut. This bridge was made of 13 prestressed concrete box beams. These beams were tested to determine the prestress losses that had occurred. The prestress force in each beam was determined by carefully observing the reopening the flexural crack in the beam. After the first crack had developed, the beam was unloaded until the
crack closed. Load was slowly reapplied, and the reopening of the crack on the bottom face was carefully monitored. At the instant of crack reopening, the stress at the bottom fiber was zero. With the beam weight and the applied loads were known, the prestress force was calculated. Using this method good estimate of prestressing force was determined.

Habib Tabatabai and Timothy Dickson (1991) discussed the structural evaluation of a 34-year-old precast post-tensioned concrete girder. A 43ft 4 in.(13.2m) long AASHTO Type II prestressed concrete girder was removed from the I-94 bridge over US 81 in Fargo, North Dakota. This bridge was built in 1958 and had sustained approximately 34 years of service life prior to dismantling. The girder was subjected to a comprehensive series of tests to evaluate structural strength, serviceability and material properties. Two point loads were applied to the girder to create a constant moment region near midspan. A crack gage was used to determine the decompression load. The crack gage was placed across the main flexural crack after its appearance. An increasing load was applied to the girder until the cracking load was reached. Crack occurrence was monitored visually and by several sensor based methods. The first crack load was determined by an accelerometer mounted on the bottom flange. After the girder was cracked, the load was reduced to zero to close the flexural crack and install a crack width gauge at the crack location. The load was then increased until the flexural crack reopened. The load at which this reopening occurred (decompression load) was used for direct calculation of the effective post-tensioning force. The reopening of the crack was monitored with crack gage. The load was reduced below the decompression load to close the crack and again increase to verify the load required to open the crack. The effective prestress was calculated based on the decompression load determined form load testing and using actual tendon eccentricity. The measured prestress was compared with the prestress
predicted based on AASHTO specifications and found to be matching closely. It was concluded that the calculation of prestress losses using the decompression is a more direct method and is therefore more accurate.

Charles Abdunar (1993) described a method which directly measures the stress in either concrete or masonry bridges. In this method a small slot is cut in the plane normal to the desired stress direction, and a very thin flat jack is then placed in this slot and used to restore the initial displacement field. The amount of hydraulic pressure required to do so provide a value for the absolute compressive stress normal to the slot. The advantage of the method is that it is a direct measurement technique and the elastic properties of the material are not required.

Owens (1993) described the adaptation of the centre hole technique to the in-situ stress determination in reinforcement, stressing tendons and concrete. In the centre hole technique, the stress relief is caused by the drilling of a relatively small hole. The hole diameter and depth are usually equal. The hole diameter can be from 0.8mm to 20mm depending upon the structure and the depth to which the in-situ stresses are required. The most standard hole size is 1.6mm. As the hole is drilled into a stress field, the strain change in the vicinity of the hole is measured using electrical resistance foil strain gages which are aligned radial to the hole. The strain change due to drilling complete hole depth is one quarter of the in-situ strain present in the structure and drilling mid range depth increment is approximately one tenth of the total relieved strain. The accuracy of the in-situ stress determination is a function of the modulus of the structure and the gage/hole geometry. These techniques are mainly used for reinforcing bars and prestressing tendons. The centre hole technique can be used in the concrete but due to the characteristic of concrete the procedures are changed accordingly. The hole size and gage
length must be increased to be at least twice the size of the aggregate. Vibrating wire strain gages of 50mm active length are attached radially outside and at centre of an intended 75mm diameter hole with four gage alignments of $0^\circ/180^\circ$, $45^\circ/225^\circ$, $90^\circ/270^\circ$ and $135^\circ/315^\circ$. It also explains the use of photo elastic gages in the in-situ stress determination in concrete elements. Experimental verification of these methods was done on laboratory loaded elements and by applying live load on concrete beams at site. In a concrete structure it is possible to determine the dead loads in the concrete, reinforcements and stressing tendons.

Owens et al., (1994) explained the new coring method using a progression of smaller holes typically 36-52mm diameter with a radial configuration of vibrating wire strain gages attached to the concrete using suitable quick setting adhesive. The gage configuration varies depending on the number of holes and their relative position. The smaller diameter hole, however, reduces the sensitivity of the gages and accuracy decreases. The use of several holes with gages situated between them counteracts this effect as the strain relief between holes is increased. The small diameter holes used have little effect on the overall integrity of the structure, and the minimum depth of holes provides less likelihood of damage to any reinforcement. Experimental work was carried out on a 600mm high by 250mm square concrete block instrumented with gages for use with a 36mm diameter hole. The coring procedure was carried out using conventional drilling method with a 36mm diameter. During the coring process strain reading was taken at 5mm intervals of depth up to 25mm and a final set of reading at 36mm. A finite element analysis was done for comparison with experimental results. Results form the experimental work carried out under laboratory conditions compared favorably with the theoretical values obtained form three dimensional finite element models.
Ryall (1994) described an instrumented hard inclusion technique for measuring existing stresses. This method involves drilling a small pilot hole of about 40mm diameter in the concrete and bonding into it an instrumented mild steel inclusion. The inclusion is over cored and the resulting strain changes in the inclusion used as basis for determining the local in-situ stresses. The form of inclusion employed was made of steel composed of a number of interlocking cylindrical sections 10mm long and 40mm diameter which have rosette strain gages cemented to their ends. This enables the strain distribution throughout the depth of an element to be assessed. The surface of the inclusion has been knurled to facilitate bonding. The pilot hole into which the inclusion was bonded and drilled with a bit 42mm in diameter, and the over coring bit is 150mm in diameter. Laboratory investigations have been made on concrete cubes by applying uniaxial compressive stress of 5 N/mm$^2$. From the tests calibration factors were arrived. A finite element analysis was also carried out using ANSYS software package to validate the experimental results. Because of the two state of stress in the element due to first of all to the pilot hole, and then to the over coring situation, the principle of superposition was adopted to determine the final distribution of direct stress. It was concluded that the hard inclusion technique for determining in-situ stresses in concrete bridge structures is viable.

Mehrkar (1996) discussed an instrumented concrete coring technique known as stress relief coring. 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 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 vibrating wire gauges to measure the release of stresses around the hole. Details of the test including gauge arrangement, theoretical and calibration coefficients and method of converting the measured strains to in situ stresses were explained. In addition, details were provided of a jacking system, which was also developed, 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. At least three measurements are required at representative positions. The author suggested that the areas with stress concentration or high stress gradient should be avoided.

Parivallal et. al., (2001) and Kesavan et. al., (2005) described an experimental method known as the concrete core trepanning technique for the determination of residual prestress in prestressed concrete structures. Studies were carried out to identify the gage length for 50mm diameter core. Under no load condition the manufacturing stress was less for 30mm gage with 50mm diameter core. Hence, 30mm length of gage with 50mm diameter core was used for concrete core trepanning technique. Laboratory studies were carried out to formulate proper procedure for measurement of existing stress in prestressed concrete structures. In order to carry out further reliability studies on the core trepanning technique, a seven year old pretensioned concrete beam was studied. These studies show that this method can be used to evaluate the existing prestressing force in prestressed concrete structures.

McGinnis et. al., (2005) presented a non-destructive technique for the determination of in situ stresses in concrete structures called core-drilling method. The core-drilling method was formulated in terms of displacement rather than strain. They used a optical displacement measurement technique called three-dimensional (3D) digital image correlation and photogrammetry.
In three-dimensional (3D) digital image correlation technique a random pattern of dots was photographed on the specimen and by correlating the patterns within versions of the photographs taken before and after core drilling, deformation information was derived. From the studies performed on specimens made of steel, the normal stresses calculated were within 17% of applied values for photogrammetry, and 7% for three-dimensional digital image correlation. It is concluded that the photogrammetry and 3D digital image correlation were robust enough to capture the expected displacements involved and can be extended to concrete structure subjected to the core-drilling method. McGinnis and Pessiki (2006) explained that the core-drilling method for evaluating in-situ stress in a concrete structure. Displacement measurements were performed using 3D digital image correlation and industrial photogrammetry. The perturbations caused by steel reinforcement within the concrete were studied. The reinforcement is significantly stiffer than the surrounding concrete, altering the expected displacement field. It is concluded that the numerical investigation performed indicates an under-prediction of stress by as much as 18 percent in a heavily reinforced structure, although the effect is significantly smaller for more common amounts of reinforcement.

Lambda Technologies (2005) described a ring-core method which is a mechanical technique used to quantify the principal residual stresses within a specified depth of material. This technique was based upon linear elastic theory and consists of dissecting a circular plug containing a strain gage. During the sectioning operation the residual strain in the part was relieved. The change in strain as a function of cut depth was monitored by an on-line computer. The principal residual stresses were determined using the derivative of the strain vs. depth data. The ring-core technique can be used on metals, ceramics, and polymers, where linear elastic theory can be assumed.
Sandberg Consulting Engineers (2005) developed two techniques to measure the in-situ stress in reinforced and prestressed concrete members. Both techniques involve instrumenting the concrete surface prior to the release of local stresses either by coring or saw cutting. Measurement of the consequent strain changes in conjunction with knowledge of the elastic modulus of the concrete yields a measure of the in-situ stress. In one method, a combination of vibrating wire strain gauges and Demec studs provides three independent measures of the strain changes in each of four directions. From the measure strain, principal stresses and their directions were arrived. In the second method a saw cut into the concrete in a preplanned direction. Released stress was derived from the measurements carried out by vibrating wire gauges and Demec studs.

Che-Way Chang et. al., (2009) described the digital discrete reflection photoelasticity and hole drilling method to measure the whole relieved stress field of the pre-stressed concrete component with a drilled hole. Tests were conducted on the concrete test specimen of rectangular cross-section rod of 15 cm x 15 cm x 30 cm. Photoelastic coating was applied to the flat surface by bonding flat precast sheets directly to the stressed test specimen. Then, a small hole was drilled normal to the surface of the specimen in the center of the photoelastic coating region. The residual stresses induced by the drilling of a hole in the specimen were measured by the reflection photoelastic method, where the stress relieving hole was bored with a 3 mm diameter drilling machine. A digital discrete image processing photoelastic coating hole drilling system that performs automatic data analysis was developed to determine the magnitude of the residual stress in a concrete component subjected to a uniaxial compressive stress state. The experimental values of stress agree reasonably with the theoretical solution. From this technique the
magnitude of the initial compressive pre-stress can be evaluated from the measured stress by digital image processing photoelastic coating and hole drilling method.

Pagliaro and Zuccarello (2007) discussed the development and the application of the through-hole drilling method for the residual stress analysis in orthotropic materials. Through a systematic theoretical study of the stress field present on orthotropic plates with a circular hole, the relationships between the relaxed strains measured by a rectangular strain gauge rosette and the cartesian components of the unknown residual stresses were obtained. The theoretical formulas of each influence coefficient allow the user an easy application of the method to the analysis of uniform-residual stresses on a generic homogeneous orthotropic material. Furthermore, to extend the method to the analysis of the residual stresses on orthotropic laminates, caused by initial in-plane loadings, an alternative formulation that permits to extend the method to the analysis of the through-thickness non-uniform residual stresses (not equilibrated) in a generic orthotropic laminate due to in-plane initial loads, has been implemented. FEM simulations have been carried out to verify the proposed formulations. In order to verify the accuracy of the method, experimental tests on three different GFRP orthotropic laminates, have been carried out and corroborated the theoretical and numerical results.

2.2.2 Field Investigations

Brookes et al., (1990) presented the results of trials carried out on a post-tensioned concrete six cell box structure to determine the in-situ stress level. The methods used to determine the in-situ state of stress in concrete structures based upon measurements of released strains obtained during removal of standard cores. In addition, a unique jacking system has been
evolved which can be used to determine the in-plane elastic properties of the concrete and provides a direct measure of the existing stress. The jacking tests use the application of load to the periphery removed hole to assess the strain response of the material and hence plane elastic constants for the concrete. In addition, re-establishing strain released on the surface and the use of superposition for the direct loading directions provides a direct measure of the existing stresses. Laboratory and site tests of 150 and 75mm diameter have been used in conjunction with 140mm long Vibrating Wire (VW) gauges and 50, 100 and 200mm long demec gages. An assessment of a 144m long prestressed concrete bridge compared the stresses predicted using the in-situ stress-relief technique with those obtained from numerical study.

Mehrkar (1994) discussed the in-situ stress assessment of two bridges namely Cadnam Green Bridge and Andover Town Bridge. The Cadnam River Bridge built in the mid 1950’s with a clear span of 10.05 m consists the deck of pre-cambered post-tensioned concrete beam 450 mm wide and 305 mm deep. The remaining level of prestress was assessed by sampling the soffit at midspan using four 75 mm diameter stress-relief cores with complementary jacking tests and four saw cuts. The average midspan soffit compressive stress in the longitudinal direction (equating to dead load tension and prestress compression) was estimated to be 4.6N/mm². This corresponds to 47% loss of prestress which appeared a likely result after some 40 years. In the transverse direction, complete loss of prestress was confirmed from the in-situ stressed measured. Andover Town Bridge was built in the mid 1950’s with a skew clear span of 7.87m and skew angle of 14.75°. The deck consists of 33 longitudinal precast post-tensioned concrete beams with mortar packing in between. Both longitudinal and transverse prestressing consists of LeeMcCall (Mecalloy) bars of diameter 25.4mm and 19 mm respectively. Due to the limited head room under the bridge (only 0.7m) in-situ stresses were
determined on the top of the deck at midspan. The stress was measured by using four 75mm diameter stress-relief cores with complementary jacking tests and four slot cuts. The average midspan soffit compressive stress in the longitudinal direction (equating to dead load tension and prestress compression) was estimated to be 8.2N/mm$^2$ corresponding to 47% loss of prestress, again a realistic value for a structure of this age. A compressive stress of 0.6 N/mm$^2$ was assessed in the transverse direction corresponding to 59% loss of prestress. This was considered reasonable in view of leakage and sign of corrosion through the longitudinal joints.

Maria Helena Leite and Robert Corthésy (2001) presented the use of the modified doorstopper technique for measuring both absolute and relative stresses in concrete structures. The "Doorstopper" method is based on the strain relief at the flattened bottom of the strain cell. A strain rosette at the bottom of the strain cell, resembling the shape of a doorstopper, is cemented to the end of the borehole. The measurements of baseline strains were recorded. Then, the borehole was extended to leave the strain cell attached on top of the rock stub released from the surrounding stresses. Thus, the changes in strains can be related to the in situ stresses for a given configuration at the end of the borehole with the material properties. The equipment, procedure, and the stress calculation model were presented and followed by the results of some stress measurement campaigns in concrete structures. Results from both laboratory tests and a 7-month field monitoring period show the stability and sensitivity of the method.

Santiago Sanchez-Beita and Luc Schueremans (2009) employed hole drilling for the onsite deduction of the stresses in structural elements of the two cultural heritage monuments: the Saint Jakobs Church (Leuven, Belgium) and the Cathedral Of Tarazona (Zaragoza, Spain). The experiments uses eight
strain gages to have sufficient redundancy in the system and able to make an objective analysis of the quality of the results. It is concluded that the derivations of the stress states from the strain measured by the strain gages is in agreement with the general methodology of the hole drilling technique.

2.3 SUMMARY

This chapter presents review of relevant studies reported in the literature. It includes the details of different evaluation methods like decompression moment method, flat jack technique, centre hole technique, instrumented hard inclusion technique, concrete coring technique, concrete core trepanning technique, etc. Most of these methods available to assess the existing stress in concrete structures are for uniaxial stress state only. These methods have some limitations, which include lower level of strain release, difficulty to apply for field measurements, complexity in the application, etc. Also, the assessment of stresses in concrete structures under biaxial stress state is complex and there is hardly any reported work in the field of measurement of existing stresses on concrete structures under biaxial stress field.