RESEARCH ARTICLE OPEN ACCESS

Crack Identification in Reinforced Concrete Beams Using Ansys Software

T. Subramani[1], R. Manivannan[2], M. Kavitha[3]
[1]Professor & Dean, Department of Civil Engineering, VMKV Engineering College, Vinayaka Missions University, Salem, India.
[2]PG Student of Structural Engineering, Department of Civil Engineering, VMKV Engineering College, Vinayaka Missions University, Salem
[3]Managing Director, Priyanka Associates, Civil Engineering Consultant and Valuers, Salem

ABSTRACT
Analytical determination of displacements and stresses in reinforced concrete material was difficult task and engineers had to rely on empirical formulas because concrete consists of heterogeneous material and creep and shrinkage influenced deformations in it. Due to these complexities engineers in past had been facing difficulties in coping such problems, but with the advancement of digital computerization and modern numerical methods for analysis such as finite element method, these problems can be addressed in a very efficient way. There were two ways to carry out modelling in ANSYS software, one was smeared approach and the other one was discrete. In the past, Smeared approach was used to identify the cracks in RC beam using ANSYS but in this work it was extended using discrete approach of modelling and shear cracks were identified in RC beam and load deflection curve was simulated which showed good agreement with the experimental results. Beams, made of brittle materials like concrete or cement, show increasing crack development during their service life due to mechanical and environmental loadings. This local damage can be translated into a reduction of the local bending stiffness. Stiffness modifications, while assuming constant mass distribution, can be observed by monitoring the vibration behaviour of the beam. In this paper the modal parameters of an undamaged beam are monitored and compared with the vibration behaviour of the beam subjected to controlled damaging. Selected stiffness parameters in the finite element model are adjusted in such a way that the computed modal quantities match the measured quantities. FEMtools has been used to establish a damage distribution in beams associated with increasing stress patterns. State of the art scanning laser modal equipment has been used for this purpose. It has been found that modal updating is indeed a possible tool to reconstruct the damage patterns.
KEYWORDS: Crack Identification, Reinforced Concrete Beams, Ansys Software

I. INTRODUCTION

Concrete structural components require the understanding into the responses of these components to a variety of loadings. There are a number of methods for modelling the concrete structures through both analytical and numerical approaches. Finite element (FE) analysis is a numerical one widely applied to the concrete structures based on the use of the nonlinear behaviour of materials. FEA provides a tool that can simulate and predict the responses of reinforced and prestressed concrete members.

A number of commercial FE analysis codes are available, along with the advanced modules for complex analyses. The use of FEA has increased because of progressing knowledge and capability of computer package and hardware. Any attempts for engineering analyses can be done conveniently and fast using such versatile FE analysis packages. Nonlinear material models have been integrated in many of general purpose finite element codes, i.e., ABAQUS, ANSYS, STRAND7, or MSC.NASTRAN.

Those nonlinear models play a vital role in nonlinear response analyses since each material component tends to possess the complicated stress-strain behaviour. Among those packages, ANSYS provides a three-dimensional element (SOLID65) with the nonlinear model of brittle materials similar to the concrete materials. The element features a smeared crack analogy for cracking in tension zones and a plasticity algorithm to take into account the concrete crushing in compression zones.

It is eight-nodded solid isoparametric element with the integration points for the cracking and crushing checks. The linear elastic behaviour governs the analyses until exceeding either the specified tensile or compressive strengths. Once the principal stresses at the integration points reach the tensile or compressive strength, the cracking or crushing of concrete elements can be formed. Then, the cracked or crushed regions will form in perpendicular with the locally redistributed residual stresses to the direction

of principal stress. These require the nonlinear iterative solution with high performance computer.
Concrete structural elements behave differently under different variety of loading. The identification and calculation of these responses is very laborious and requires lot of expense and time. But now a days there are several techniques available to solve this problem, amongst those indigenous techniques the widely used one is finite element method.

Finite element method is a numerical analysis method that divides the structural element into smaller parts and then simulates static loading conditions to evaluate the response of concrete and pre stressed concrete members. The use of this technique is increasing because of enormous advancement of engineering and computer knowledge. This method responds well to non linear analysis as each component possesses different stress strain behaviour.

This behaviour is efficiently addressed by software ANSYS which provides number of elements for modelling of materials and apply loads to evaluate the response. The objective of this study was to make a comparison between experimentally tested RC beam and the one modelled using ANSYS by incorporating discrete approach as suggested by Dahmani , etal(2010). The model beam of Ayman and Banerjee (2007) was taken as the reference beam for our analysis and shear cracks are compared with it as obtained from ANSYS.

II. MATERIALS AND METHODS

2.1Failure Criteria for Concrete:

The model developed using ANSYS is capable of predicting failure for concrete materials. Both cracking and crushing failure modes are accounted for. The two input strength parameters i.e. ultimate uniaxial tensile and compressive strengths are needed to define a failure surface for the concrete. Consequently, a criterion for failure of the concrete due to a multiaxial stress state was calculated by William and Warnke's (1975) constitutive model for multiaxial stresses. Bangash (1989) proposed that in a concrete element, cracking occurs when the principal tensile stress in any direction lies outside the failure surface.

After cracking, the elastic modulus of the concrete element is set to zero in the direction parallel to the principal tensile stress direction. Crushing occurs when all principal stresses are compressive and lie outside the failure surface, subsequently, the elastic modulus is set to zero in all directions and the element effectively disappears.

2.2 Finite Element Modeling:

Experimental RC beam specimen was analyzed by using ANSYS which is an engineering simulation commercially used software offering a comprehensive suite that spans the entire range of physics, providing access to virtually any field of engineering simulation that a design process requires. The software use it's tools to put a virtual product through a rigorous testing procedure such as testing a beam under different loading scenarios before it becomes a physical object. ANSYS can carry out advanced engineering analyses quickly, safely and practically by variety of contact algorithms, time based loading features and nonlinear material models. In this study it used to carry out discrete modelling of RC beam to analyze it under static loading conditions.

2.3 Reinforced Concrete:

For modelling of concrete the ANSYS used an element named as Solid65 which is non linear model of brittle material similar to concrete. It was an eight node solid iso parametric element with three degrees of freedom at each node.

2.4Steel Reinforcement:

for the modeling of steel ANSYS provided an element named as Link180 There were two ways to use it one was smeared and the other is discrete, discrete was considered to be more convergent as it subtracts the area of steel from total concrete which was the actual scenario where as in smeared the steel was embedded in the concrete and behaved as one unit which was not the actual case.

2.5Experimental Data:

Ayman and Banerjee (2007) carried out their experiment showing the average ultimate failure load of as-built specimen as 86 kN. The width and height of the beams tested were 0.160 mm and 0.280m respectively, the length of the beam was 3.76m with supports located 0.08m from each end of the beam as shown in Fig.

The mild steel flexural reinforcements used were 2#13 bars, 2#10 hanger bars and shear reinforcement included #10 U-stirrups. Cover for the rebar was set to 40mm in all directions.

III. CAUSES OF CRACKING

Concrete structures do not frequently fail due to lack of strength, rather due to inadequate durability or due to improper maintenance techniques. The most common cause of premature deterioration is attributed to the development of cracks (Mehta, 1992; Hobbs, 1999). Cracking can occur in concrete pavements and structures for several reasons that can primarily be grouped into either mechanical loading or environmental effects. It should also be noted that for most practical structures, reinforcement is used to bridge and hold cracks together when they develop, thereby assuring load transfer while adding ductility to a relatively brittle material.

Therefore not all cracking causes concern. Reinforced concrete elements are frequently designed on the assumption that cracking should take place under standard loading conditions (Nilsson and Winter, 1985; Nawy, 2000). For example continuously reinforced concrete pavements (CRCP) are designed with longitudinal steel in an amount adequate to hold shrinkage cracks tight, while joints exist only at locations of construction transitions and on-grade structures. In this pavement type wherein shrinkage cracks develop over time and stabilize over the first 3 to 4years, cracking in the transverse direction in specific patterns is not detrimental to the structure as long as the cracks remain tight and retain good load transfer.

Therefore, cause of cracking should be carefully identified to determine which cracks are common and acceptable and which cracks merit repair or further investigation. Several guides currently exist to assist in determining the cause of cracking including the American Concrete Institute (ACI) committee reports "Guide for Making and Condition Survey of Concrete in Service" (ACI 201-92) and "Causes, Evaluation and Repair of Cracks in Concrete Structures" (ACI 224-R93). Mechanical loads induce strains that can exceed the strain capacity (or strength capacity) of concrete, thereby causing cracking. Concrete may be particularly susceptible to cracking that occurs at early-ages when concrete has a low tensile capacity (Kasai, 1972).

If the loads are applied repeatedly or over a long period of time, fatigue and creep can affect the strain (or strength) development that can lead to failure (Bazant and Celodin, 1991) or reduce stresses (Shah et al., 1998). Although numerous factors influence whether concrete would be expected to crack due toenvironmental effects, it can be simply stated that cracking will occur if the stress that develops in response to internal expansion or the restraint of a volumetric contraction that results in stress development exceeds the strength (or fracture resistance) of the material. Internal expansion is primarily caused by chemical attack or freezing of the pore water while volumetric contraction is typically attributed to moisture changes, chemical reactions, and thermal changes.

3.1 MECHANICAL LOADING

Static Loading

Concrete is a composite material that is made by binding aggregates together with a cementitious paste. While the independent response of a cement paste and aggregate to an applied load is linear as shown in Figure, it can be seen that response of the composite concrete is highly nonlinear. This non-linearity can be attributed to the development of small cracks (microcracks) throughout the concrete matrix as load is applied (Hsu et al., 1963). Others have suggested that this may be attributed to existence of a weak bond or interfacial transition zone between the aggregate and the paste matrix (Mehta, 1996). While these cracks occur over a wide range of load levels they can be attributed to the development of high local stresses that occur at the interface of the aggregates and paste (Shah and Slate, 1965).

The response of unreinforced concrete to mechanical loading must first be described to fully understand how reinforced elements react. Immediately upon loading, concrete typically is thought to develop some micro-cracking (Shah and Slate, 1965; Attiogbe and Darwin, 1987; Li et al., 1991), though it is frequently assumed to be negligible since little change is detected in the load-displacement response.

The load-displacement response remains fairly linear until the load level reaches approximately 40% to 50% of the maximum strength. At this time the stress-strain response becomes less linear as an increase in micro-cracking occurs resulting in the decrease of the elastic modulus of the material. As the load level approaches 90% to 95% of the peak, the slope of the load-displacement curve is once again reduced as the cracks begin to coalesce and localize in one region of the specimen.

This localized area will eventually become the location of a visible crack. Depending on how the specimen is loaded (i.e., load control, displacement control) the crack may result in sudden failure (load control) or continue to develop and grow after the peak load is reached (displacement control) resulting in large visible cracking. After the peak load is achieved the specimen begins to demonstrate strain-softening behaviour resulting in a gradual decrease in load carrying capacity with increasing strain as shown in Figure (Jansen and Shah, 1995).

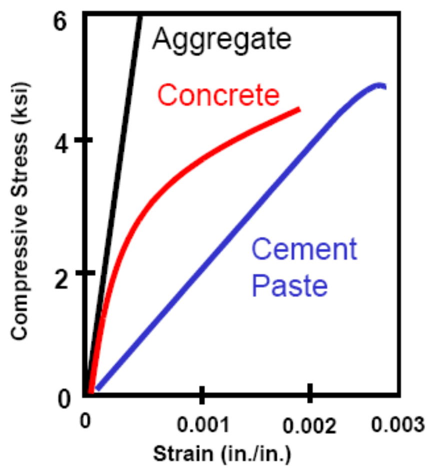

FIGURE 3.1 Stress strain response of behaviour of concrete (1 ksi = 6.89 MPa).

3.2 VOLUMETRIC STABILITY

Settlement

Settlement cracking occurs in freshly mixed concrete as the concrete settles over time and encounters some restraint. The heavier particles ‘sink’ due to gravity until the concrete sets. Plastic settlement cracking has been frequently observed to occur at changes in cross section (i.e., over reinforcing bars or at change in section height). The practical significance of settlement cracking is in the construction of reinforced slabs, and bridge decks.

The magnitude of tensile stress generated as a result of plastic settlement, along with the capillary stress and the autogenous effect, may be sufficient to initiate plastic cracking. The role of settlement in plastic cracking has been studied for several decades. Powers (1968) measured the settlement of cement paste by manually monitoring the displacement of a steel pin resting on the surface of fresh concrete.

The amount of settlement observed was related to specimen height, water-to-cement ratio (w/c) and concrete consistency (Powers, 1968). A uniform settlement (i.e., homogenous volume contraction) in a fresh concrete mixture does not lead to plastic cracking. Differential settlement however can lead to cracking. Differential settlement can be caused by either external boundaries or embedded rigid inclusions. Weyers et al. (1982) simulated the settlement behaviour occurring due to embedded rigid inclusions using a model where rebar was positioned in a photo elastic material (gelatin) at variable cover depths and spacing.

It was concluded that clear cover depth, rebar size and rebar spacing are the major factors affecting the magnitude of differential settlement with lager bars and smaller cover depths typically resulting in larger cracks. Kayir and Weiss (2002) used a non-contact laser device to quantify the amount of settlement occurring in between the time of concrete placement and setting for mortar containing chemical admixtures.

It was shown that the mixing and placement time significantly influence the amount of settlement that may occur. For example, when compared with the settlement measured immediately after mixing, the settlement in a material placed 40 minutes after mixing showed nearly a 50% reduction in settlement. Qi et al. (2003; 2005a) demonstrated that fiber reinforcement dramatically reduces settlement capacity of fresh concrete. Qi et al. (2005b) demonstrated a moving laser system to measure differential shrinkage over reinforcing steel or at changes in cross-sectional height.

IV. CRACK DETECTION

Cracks may be either macro cracks, detectable by visual inspection, or micro cracks, which can be detected only with microscopes or non-destructive testing. Another distinction is between discrete cracks, for which each has to be located and counted individually, and distributed fine cracks, for which calculations of an area may be more important.

4.1 Discrete Crack Detection

To find an alternative to the detection of individual cracks by visual inspection, a significant amount of effort has gone into development of automated analysis software for pattern recognition of cracks in digital images (Koutsopoulos and El Sanhouri, 1991). In earlier work, the digital images were obtained by scanning analog photographs.

As the resolution, i.e. number of pixels, of digital cameras has improved the practice is now to take direct digital images of the area under investigation. This reduces the work involved and avoids the image degradation introduced by the scanning process. In the image analysis process, the software examines each black pixel and its neighbours to decide if it belongs to a given crack. When a crack is detected, it is then characterized by a set of parameters including location, length, width and direction (Mahler and Kharoufa, 1990).

There are two major considerations in the sensitivity of this process: one is the probability of detection and the other is the probability of false positives. An algorithm with a low probability of detection will miss a significant number of cracks. An algorithm with a high number of false positives may detect a high percentage of actual cracks, but may also mistake other features for cracks. After a crack has been detected and characterized, it may then be assigned to a particular class. Several classification systems have been proposed for particular applications (Koutsopoulos and El Sanhouri, 1991; Ritchie et al., 1991). It is important to distinguish between systems that are simply descriptive, and those that are diagnostic, i.e. those that assign causes to each crack. The problem with diagnostic classifications is that more than one cause of damage may produce the same crack appearance.

4.2 Micro crack Measurement Techniques

Conventional methods for measuring micro cracks include optical microscopy, scanning electron microscopy and radiography. These have been reviewed by Slate and Hover (1984). They are all destructive, requiring the drilling of cores from the concrete followed by sectioning of the specimens, and the results are two-dimensional.

More recently three-dimensional methods using computed tomography based on conventional X-ray or synchrotron radiation have been introduced. These can image entire specimens. The true crack area can be measured, rather than its two-dimensional projection. However, the overall size of the specimen is limited to less than 100 mm (4 in.) in thickness for useful resolution. Moreover, these cannot be applied in the field.

4.3 Ultrasonic's

Other methods for measuring micro cracks are based on ultrasonics (Kesner et al., 1998; Jacobs and Whitcomb, 1997). These methods do not count individual cracks, but rather measure a bulk ultrasonic property of the concrete, usually attenuation. This can then be calibrated against radiographs to give micro crack density (Kesner et al., 1998). Ultrasonic methods offer the possibility of making measurements in the field on real structures. Their drawback is that features other than micro cracks in the concrete can contribute to attenuation.

4.4 Acoustic Emission

Acoustic emission describes a field of testing that has been popular recently in crack detection because of its non-invasive nature (Ouyang and Shah, 1991; Ohtsu, 1994; Ohtsu, 1996). Recent research has indicated that it is possible to quantify cracking using acoustic emission.

The sensors detect acoustic activity when the specimen undergoes cracking, and they are amplified. Applying threshold levels to the activities helps in detecting events produced by cracking as well as background noise (Puri and Weiss, in press). While some applications of acoustic emission have been performed in the field, majority of the applications have been performed in the laboratory.

4.5 Cracking due to Chemical Reaction:

Deleterious chemical reactions may cause cracking of concrete. These reactions may be due to materials used to make the concrete or materials that come into contact with the concrete after it has hardened. Concrete may crack with time as the result of slowly developing expansive reactions between aggregate containing active silica and alkalis derived from cement hydration, admixtures or external sources (e.g. curing water, ground water, alkaline solutions stored or used in the finished structure).

The alkali silica reaction results in the formation of a swelling gel, which tends to draw water from other portions of the concrete. These causes local expansion and accompanying tensile stresses and may eventually result in the complete deterioration of the structure Certain carbonate rocks participate in reactions with alkalis, which in some instances produce detrimental expansion & cracking. These are usually associated with argillaceous dolomite limestone.(Fig.4.1)

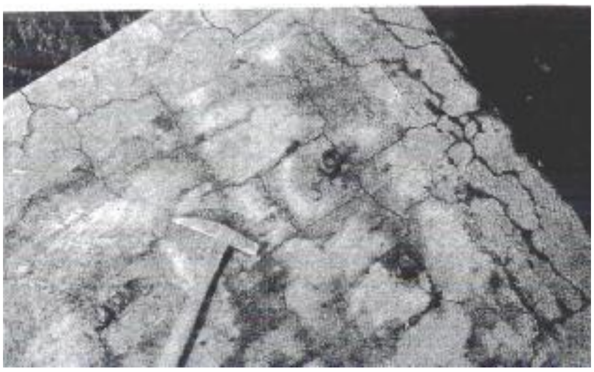

Fig. 4.1, Deterioration From Alkali-Silica Reaction

Preventive Measures:

- Dense concrete with low permeability.
- Adequate cover to steel.
- In case of large bars and thick covers, it may be necessary to add small transverse reinforcement while maintaining the min. cover requirements to limit splitting and to reduce the surface crack width.
- For severe exposure conditions – coated reinforcement, sealers and overlays on concrete surface, corrosion inhibiting admixtures and catholic protection.
- Concrete should be allowed to breathe, that is, any concrete surface treatment must allow water to evaporate from the concrete.

V. FINITE ELEMENT MODELING.

5.1 Reinforced Concrete.

An eight-node solid element (SOLID65) was used to model the concrete. The solid element has eight nodes with three degrees of freedom at each node – translations in the nodal x , y , and z directions. The element is capable of plastic deformation, cracking in three orthogonal directions, and crushing.

5.2 Steel Reinforcement.

To model concrete reinforcing, one of two methods is usually followed. In the first method, the reinforcing is simulated as spar elements with geometric properties similar to the original reinforcing. These elements can directly be generated from the nodes in the model. This method of discretization is useful in simple concrete models.

The second idealization of steel reinforcing is the smeared concrete element method (used in this paper). In this case, the concrete and the reinforcing are discretized into elements with the same geometrical boundaries and the effects of reinforcing are averaged within the pertaining element (Fig. 2b). Cracks can also be idealized into either the discrete type or the smeared type.

Since the SOLID65-3D concrete element simulates tension and compression in reinforcing bars, the volumetric ratio of reinforcing steel to concrete along with the direction of the steel had to be provided for each volume, in order for the program to account for the reinforcing steel.

5.3 FE Model Input Data.

For concrete, ANSYS requires input data for material properties as follows: elastic modulus Eb , ultimate uniaxial compressive strength f c, ultimate uniaxial tensile strength (modulus of rupture) f r , Poisson's ratio _, shear transfer coefficient _, and compressive uniaxial stress-strain relationship for concrete. The shear transfer coefficient, _, represents conditions of the crack face. The value of _t ranges from 0 to 1.0, with 0 representing a smooth crack (complete loss of shear transfer) and 1.0 representing a rough crack (no loss of shear transfer) (ANSYS 8.0).

The value of _ used in many studies of reinforced concrete structures, however, varied between 0.2 and 0.5. A number of preliminary analyses were attempted in this study with various values for the shear transfer coefficient within this range, but convergence problems were encountered at low loads with _ less than 0.2. Therefore, the shear transfer coefficient used in this study was equal to 0.3.

5.4 Failure Criteria for Concrete.

The model is capable of predicting failure for concrete materials. Both cracking and crushing failure modes are accounted for. The two input strength parameters – i.e., ultimate uniaxial tensile and compressive strengths – are needed to define a failure surface for the concrete. Consequently, a criterion for failure of the concrete due to a multiaxial stress state can be calculated. In a concrete element, cracking occurs when the principal tensile stress in any direction lies outside the failure surface.

After cracking, the elastic modulus of the concrete element is set to zero in the direction parallel to the principal tensile stress direction. Crushing occurs when all principal stresses are compressive and lie outside the failure surface; subsequently, the elastic modulus is set to zero in all directions, and the element effectively disappears.

FE Discretization.

As an initial step, a finite element analysis requires meshing of the model. In other words, the model is divided into a number of small elements, and after loading, stress and strain are calculated at integration points of these small elements. A beam is composed of two regions; a concrete element without reinforcement and a concrete element with a smeared reinforcement.

Nonlinear Solution.

In nonlinear analysis, the total load applied to a finite element model is divided into a series of load increments called load steps. At the completion of each incremental solution, the stiffness matrix of the model is adjusted to reflect nonlinear changes in structural stiffness before proceeding to the next load increment. The ANSYS program uses Newton–Raphson equilibrium iterations for updating the model stiffness. In this study, for the reinforced concrete solid elements, convergence criteria were based on force and displacement, and the convergence tolerance limits were initially selected by the ANSYS program.

It was found that convergence of solutions for the models was difficult to achieve due to the nonlinear behaviour of reinforced concrete. Therefore, the convergence tolerance limits were increased to a maximum of 5 times the default tolerance limits (0.5% for force checking and 5% for displacement checking) in order to obtain convergence of the solutions.

Load Stepping and Failure Definition for FE Models.

For the nonlinear analysis, automatic time stepping in the ANSYS program predicts and controls load step sizes. Based on the previous solution history and the physics of the models, if the convergence behaviour is smooth, automatic time stepping will increase the load increment up to a selected maximum load step size. If the convergence behaviour is abrupt, automatic time stepping will bisect the load increment until it is equal to a selected minimum load step size. The maximum and minimum load step sizes are required for the automatic time stepping.

Results.

The goal of this study is to show:

- the different phases of the FE model behaviour from initial cracking,
- yielding of steel until failure of the concrete beam;
- the applicability of ANSYS software for analyzing and predicting of crack patterns in the reinforced concrete beam;
- The advantage of performing numerical simulation instead of experimental tests in saving time and costs.

Behavior at First Cracking.

The analysis of the linear region can be based on the design for flexure for a reinforced concrete beam. Comparisons were made in this region to ensure deflections and stresses were consistent with the FE model and the beam before cracking occurred. Once cracking occurs, deflections and stresses become more difficult to predict. The stresses in the concrete and steel immediately preceding initial cracking were analyzed.

The load at step 42602 was analyzed and it coincided with a load of 42,602 N applied to the beam. Calculations to obtain the concrete stress, steel stress and deflection of the beam at a load of 42,602 N are given in Appendix. A comparison of values obtained from the FE model and Appendix can be seen in Table 5.2. The maximums exist in the constant-moment region of the beam during load application.

5.5 Behavior beyond First Cracking.

In the non-linear region of the response, subsequent cracking occurs as more loads are applied to the beam. Cracking increases in the constant moment region, and the beam starts cracking out towards the supports at a load of 50,000 N.

Significant flexural cracking occurs in the beam at 60,000 N. Also, diagonal tension cracks are beginning to form in the model at load of 70,000 and 90,000 N. This cracking can be seen in Figs.

REPAIRING CRACKS

While books have been authored to provide an easy to use general guide to describe how concrete can be repaired (Emmons, 1992), the following section discusses crack repair in bridges, pavements and footings.

Bridge Structures

Loose material is removed from cracks by blowing the portion with compressed air or by hosing the area off with water. Just prior to the placement of the repair material, the area is dried. According to the ACI, structural cracks are V-grooved to a depth of 1 in. and then blown clean. Then the groove is filled with a neat epoxy. Latex-modified concrete can be brushed into the groove instead of the epoxy when latex concrete is monolithically placed.

Concrete cracks as tight as 0.2 mm (0.008 in.) may also be repaired by gravity-fill crack sealers. These sealers are either low viscosity epoxy, or high molecular weight methacrylate, or urethane.

To perform this method the concrete must be at least 28 days old. The surface of the concrete must be dry and clean. To remove all dust, dirt, and debris, compressed air can be used. The surface temperature should not be less that 13°C (55°F).

To ensure that the cracks are the most open, the resin is applied during the lowest temperature of the day. If the cracks are wider than 1 mm, they are filled with No. 50 sieve size silica sand before the polymer is used. The sealer should be applied directly to the cracks and a few minutes should be allowed to allow the sealer to seep down into the crack.

If more sealer is needed, then additional applications are made until the crack is filled. Material may be spread and worked into the cracked area using a broom or squeegee. The excess material is then brushed off the surface before the polymer hardens.

To improve skid resistance sand may be spread on the polymer-coated area on bridge decks. Formwork or sealing would be needed to contain the repair material in cracks extending to the bottom surface (ACI 345).

Pavements

Pavement cracks are always exposed to the elements and are affected by physical processes and chemical mechanisms. The physical processes include thermal contraction, drying shrinkage, wetting and drying, and freezing and thawing. Chemical mechanisms refer to the reaction of the aggregate within the concrete. The cracks start out being only continuous through an inch from the top or bottom surface (depending on the mechanism that initiates the cracks), but can increase to full depth cracks in rare cases when other forms of deterioration are present.

In addition, fatigue cracks that initiate either from the top or bottom surface depending on the location of the critical load and the superimposition of stresses due to environmental factors, progress top-down or bottom-up respectively with application of additional traffic loads during the design life of the pavement. The repair of plastic shrinkage cracks generally do not require major repair and can generally be sealed to protect the underlying concrete from infiltration of surface water, which has a direct effect on most deterioration mechanisms.

Lack of sealing major cracks can lead to spalling and other distress following freezing and thawing. Cracks where movement occurs are called working cracks. According to the American Concrete Institute, repair should cater for the anticipated movement. A suitably dimensioned recess should be cut along the line of the crack and then sealed with an appropriate sealant with a bond breaker. A surface seal made with a strip of formed sheet material may be appropriate in certain circumstances.

The choice of sealant depends on the amount of movement forecast, and the limitations imposed by the size of the recess which can be cut, together with the situation, i.e., vertical or horizontal.

There are three types of sealant in general use; mastics, thermoplastic and elastomers (ACI 345). Mastics are generally viscous liquids, such as non-drying oils, or low melting asphalts, with added fillers or fibers. They are usually recommended where the total movement will not exceed 15% of the width of the groove.

The groove should be cut so that it has a depth-to-width ratio of 2. Mastics remain plastic and will not withstand heavy traffic or solvents. In hot weather the mastic will tend to be forced out by the expansion of the adjacent structures and the surplus flattened and/or removed by traffic. Dirt and debris can become embedded in the material. Mastics are typically the cheapest of the sealants but their use should be restricted to vertical situations or those which are protected from traffic (Evans et. al., 2001).

Thermoplastics become liquid or semi-viscous when heated. The pouring temperatures are usually above 38°C (100°F). They include asphalts, rubber-modified asphalts, pitches and coal tar. The groove depth-to-width ratio is of the order of 1 and the total design movement is of the order of 200% of the groove width. Although these materials soften much less than mastics, they may extrude at high ambient temperatures and debris may become embedded.

Some of these materials are degraded by ultraviolet light and thus may become hardened and lose elasticity after a few years of exposure to direct sunlight (Evans et. al., 2001). Elastomers include polysulphides, epoxy polysulphides, polyurethanes, silicones and acrylics and may come as one part or two part materials. They can have considerable advantages over other types of sealants in that they do not have to be heated before application. In addition they typically exhibit favourable adhesion to concrete and are not susceptible to softening within the normal range of ambient temperatures.

Elastomers have a much higher degree of elongation than other sealants and many of them are capable of over 100% extension but in practice this should be limited to ±25%. The groove depth-to-width ratio should be 0.5. It is important to take steps to prevent the materials from adhering to the bottom of the grove; it should adhere to the sides only (Cady, 1995; Evans et. al., 2001).

5.6 Footings

The approach to repairing cracks depends on the effect the crack has on the structure. If structural stability is the issue, then repair with a high-tensile-strength material is necessary. If leaking is the problem, then crack filling is required. The USACE guidance (EM 1110-2-2002, 1995) on crack repair first directs that a crack in mass concrete be analyzed to determine whether it is active or not and whether there is a structural-stability problem or a leakage problem that must be repaired.

“Judicious neglect” is sometimes the chosen option. Crack arresting techniques are useful for stopping the propagation of a crack when it is caused by restrained volume changes. This repair has been used in mass concrete structures to prevent a crack from propagating into an adjacent placement. The simplest form of this repair technique is to place a grid of reinforcing steel over the cracked area, then place concrete over the grid.

According to Crumpton and Stratton, cracks that require repair because of structural stability problems are normally repaired either by adding reinforcing, stitching, or applying an external stress. The first method is to drill holes [commonly ¾ in. (19 mm)] perpendicular to, and through the crack [at least 18 in. (450 mm) deep]. These holes and crack plane are then filled with epoxy under low pressure [maximum 1.4 MPa (200 psi)], and reinforcing steel (commonly No. 4 or 5 bars) is inserted into the holes.

A large crack in the landside wall of the Eisenhower Lock was repaired by a similar method but using steel cable. Holes were drilled from a gallery above the crack through the crack and into the concrete next to the foundation. The cables were inserted from the gallery and anchored into the lower part of the structure, then tensioning from the gallery. Stitching is a method used to repair surface cracks.

Holes are drilled on both sides of the crack and anchoring “dogs” (staples) are inserted into the holes either with nonshrink grout, expanding mortar, or epoxy. The stitching should be variable in length and orientation so that loads are not transmitted to a single plane within the sound concrete. External stressing is a repair technique that may have some application in structural mass concrete.

Threaded steel rods are mounted on the surface of the structure using steel mounting plates to anchor each end of the rod across the crack. The mounting plates are bolted into or through the structure. Tension is applied along the rod with turnbuckles or by tightening the anchoring nuts at the end of the rod. (Crumpton and Stratton, 1983)

5.7 Behavior at Reinforcement Yielding and Beyond It.

Yielding of steel reinforcement occurs when a force of 94,000 N is applied. At this point in the response, the displacements of the beam begin to increase at a higher rate as more loads are applied. The cracked moment of inertia, yielding steel and nonlinear concrete material, now defines the flexural rigidity of the member.

The ability of the beam to distribute load throughout the cross section has diminished greatly Therefore, greater deflections occur at the beam centreline. Figure shows successive cracking of the concrete beam after yielding of the steel occurs. At 94,000 N, the beam has increasing flexural cracks, and diagonal tension cracks. Also, more cracks have now formed in the constant moment region. At 110,000 N, cracking has reached the top of the beam, and failure is soon to follow.

Strength Limit State.

At load of 114,000 N, the beam can no longer support additional load as indicated by an insurmountable convergence failure. Severe cracking throughout the entire constant moment region occurs. Noteworthy is that just before the collapse few splitting cracks (compressive cracks) appear at the upper part of the beam due to crushing failure of the concrete there.

5.8 Load–Deflection Response.

Load–deflection behaviour of concrete structures typically includes three stages. Stage I manifests the linear behaviour of uncracked elastic section. Stage II implies initiation of concrete cracking and Stage III relies relatively on the yielding of steel reinforcements and the crushing of concrete. In nonlinear iterative algorithms, ANSYS 8.0 utilizes Newton–Raphson method for the incremental load analysis.

The full nonlinear load–deformation response is shown in Fig. 10. The response calculated using FE analysis is plotted. The entire load–deformation response of the model produced well correlates with the hand calculated results. This gave confidence in the use of ANSYS and the model developed.

VI. CONCLUSION

Finite element models of 3.0 m ordinarily reinforced concrete beams, constructed in ANSYS V8.0 using the dedicated concrete elements have accurately captured the nonlinear flexural response of these systems up to failure. The dedicated element employs a smeared crack model to allow for concrete cracking with the option of modelling the reinforcement in a distributed or discrete ways.

In terms of using finite element models to predict the strength of existing beams, the assignment of appropriate material properties is critical. ANSYS is time saving and cost efficient tool that helps in simulation and gives satisfactory results using discrete approach.

REFERENCES

[1]. M. Y. H. Bangash, *Concrete and Concrete Structures: Numerical Modeling and Applications*, Elsevier Science Publishers Ltd., London (1989).

[2]. Y. Hemmaty, "*Modeling of the shear force transferred between cracks in reinforced and fibre reinforced concrete structures*," in: Proc. of the ANSYS Conf., Vol. 1, Pittsburgh, PA (1998).

[3]. ANSYS 8.0 Manual Set, ANSYS Inc., Canonsburg, PA (1998).

[4]. *ANSYS Theory Reference*, Seventh Edition, Swanson Analysis Systems (1998).

[5]. ANSYS – *Engineering Analysis System. Theoretical Manual (for ANSYS Revision 8.04)*, Swanson Analysis Systems (1998).

[6]. D. Kachlakev and T. Miller, *FE Modeling of Reinforced Concrete Structures Strengthened with FRP Lamiates*, Final Report SPR 316, Oregon State University (2001).

[7]. K. J. Willam, University of Colorado (Private communication) (1982).

[8]. . K. J. William and E. D. Warnke, "*Constitutive model for the triaxial behaviour of concrete*," in: Proc. of the Int. Association for Bridge and Structural Engineering, ISMES, Bergamo (1975), Vol. 19, p. 174.

[9]. K. J. Bathe, *Finite Element Procedures*, Prentice-Hall Inc., New Jersey (1996). W. F. Chen and D. J. Han, Plasticity for Structural Engineers, Springer- Verlag, New York (1988).