NONLINEAR DYNAMIC ANALYSIS OF STEEL FIBER REINFORCED CONCRETE BEAMS AND SLABS

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NONLINEAR DYNAMIC ANALYSIS OF STEEL FIBER REINFORCED CONCRETE BEAMS AND SLABS

by

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LIST OF ABBREVIATIONS AND SYMBOLS

A_c	Cross-sectional area of the concrete member
$\{A\}$	Flow vector
a_e	Area of the element
a_x	Distance from point load location to beam support
$[B]$	The displacement-strain matrix
$[B_i]$	The displacement- strain matrix related to node i
$[B]$	Linear part of B matrix
$[B_{nl}]$	Nonlinear part of B matrix
b	Concrete member width
b^n	Body force per unit element volume
$[C]$	Damping matrix of element
C	Damping parameter
C^0	Displacements continuity
D	Plate rigidity
D_c	Concrete cylinder specimen diameter
D_f	Steel fiber equivalent diameter
DIF	Dynamic increasing factor
$[D]$	Property matrix of the plate element
$[D]_{elasto-plastic}$	Elasto-plastic property matrix
$\{d\}$	Nodal displacements vector of the plate element
$\{d_e\}$	Eigen vector
$\{d_i\}$	Nodal displacements vector of node i
$\{\dot{d}\}$	Nodal velocity vector of the plate element

$\{\ddot{d}\}$	Nodal acceleration vector of the plate element
$\{d_{n+1}^{p}\}$	Predicted nodal displacements vector of node *i*
$\{\dot{d}_{n+1}^{p}\}$	Predicted nodal velocity vector of the plate element
$\{\ddot{d}_{n+1}^{p}\}$	Predicted nodal acceleration vector of the plate element
E	Modulus of elasticity of the plain concrete
E_{cf}	Modulus of elasticity of the steel fiber concrete
E_s	Initial elastic modulus of elasticity of the steel bar
$E_s^{'}$	Elasto-plastic modulus of steel bar
E_{ss}	Modulus of elasticity of steel fibers
F	Observed applied impact loading on structure
F_b	True bending load applied to the structure
F_i	The generalized inertial load
F_{max}	Maximum value of the impact force in kN
FRC	Fiber reinforced concrete
$F(\{\sigma\})$	Loading function
f	Stress function
f_{cf}	Compressive strength of steel fiber concrete
$f_{cf\text{-}reduced}$	Modified reduced compression strength of concrete
f_{tf}	Tensile strength of concrete
$f_c^{'}$	Compressive strength of plain concrete
f_y	Yield strength of the steel bar
f_{yd}	Dynamic yield stress for steel reinforcement layer
f_{1p}, f_{2p}	Biaxial tensile stresses
$\{f_e\}$	Vector of external forces applied to the element

$\{ f_i \}$	Vector of internal forces applied to the element
G	Uncracked shear modulus
$\overline{G}$	Cracked reduced shear modulus of the concrete
g	Gravitational acceleration
H	Hardening parameter of steel bar
H'	Hardening parameter of concrete
h	Concrete member depth (for beam) or thickness (for slab)
h_d	Dropping height from the striker to the top surface of the member
h_i	Distance from support location to the free edge of the member
h_p	Thickness of the plate element
I	Moment of inertia
I_1, J_2, J_3	Three stress invariants
I'_1, J'_2, J'_3	Three strain invariants
$[K]$	Element stiffness matrix
$[K_{nl}]$	Nonlinear geometric stiffness matrix of the plate element
$[K_{ta}]$	Tangential stiffness matrix of the plate element
L_n	Smallest length between any two nodes in the considered finite element mesh
L_c	Height of the cylindrical concrete specimen
L_f	Steel fiber length
L_f/D_f	Fiber aspect ratio
l	Concrete member length (measured from center to center of supports)
M	Generalized mass of the concrete member
M_c	Mid-span moment of simply supported member
M_{eff}	Effective mass of the concrete member in kg

M_s	The striker mass in kg
M_1, M_2, M_{12}	Moment resultants per unit length of the plate element
$[M]$	Mass matrix of structure
N	Shape function of the plate element
N_d	Total number of nodal translational degree of freedom for plate element
N_r	Total number of nodal rotational degree of freedom for plate element
N_i	Shape function of node i
OPC	Ordinary Portland cement
ORC	Ordinary reinforced concrete
P	Plain concrete member designation
P_c	Compression applied load along the cylindrical concrete specimen
p	External applied point load
q	External distributed applied dynamic load
R	Support reaction of the concrete member
S_1 , S_2	Shear forces of the Mindlin plate element
SFRC	Steel fiber reinforced concrete
Std. dev.	Standard deviation
SA	Steel fiber concrete member which contains long steel fibers only
SB	Steel fiber concrete member, where 1/4 of its volume fraction is short fibers and 3/4 of volume fraction is long fibers
SC	Steel fiber concrete member, where 3/4 of its volume fraction is short fibers and 1/4 of volume fraction is long fibers
se	Surface area of the element
T	Elastic fundamental period
Tol	Convergence tolerance

$[T]$	Transformation matrix
t	Time
t_m	Duration of the impact force
u	Displacement at any point of the Mindlin plate along x direction
V_f	Steel fiber volume fraction in concrete
V_s	Velocity of striker in m/s
v	Displacement at any point of the Mindlin plate along y direction
ve	Volume of the element
w	Displacement at any node of Mindlin plate element in z direction
w_c	Central deflection of the concrete member in z direction
w_{max}	Maximum central deflection of concrete member in mm
$\ddot{w}_c$	Central Acceleration in z direction at the specified location of the member
ψ	Loading parameter
x, y, z	Global coordinate system of the structure
x_i, y_i, z_i	Cartesian coordinate vector of i^{th} node of the element
α_c, β_c	Damping matrix parameters
α_f, β_f	Material parameters
α_2	ratio of principle tensile - compressive stresses
γ, β	Newmark parameters
δw_c	Virtual central deflection in z direction
Δd	Displacement increment
Δt	Time increment
Δt_{suit}	Suitable time increment
$\Delta\sigma$	Increment stress vector

$\Delta\varepsilon$	Increment strain vector
$\Delta_i \sigma_{n+1}^{ep}$	Incremental elasto-plastic stress
ε_c	Compressive strain of concrete
ε_{cuf}	Ultimate compressive strain of concrete
ε_e	Elastic incremental strain
ε_m	Ultimate tensile strain or limiting tensile strain of concrete
$\varepsilon_{oct}^{\bullet}$	Octahedral normal strain
ε_p	Plastic incremental strain
ε_{pf}	Concrete strain value at compressive stress
ε_t	Uniaxial tensile strain of concrete
ε_{tf}	Tensile strain value when the stress is equal to tensile strength
ε_u	Crushing strain of the concrete
ε_x, ε_y	Strains in x and y directions
$\varepsilon^{\bullet}$	Current strain rate
$\varepsilon_s^{\bullet}$	Strain rate value of concrete below which no rate effects are evident
$\ddot{\varepsilon}$	Strain rate of reinforced concrete steel bar
$\ddot{\varepsilon}_s$	Strain rate value of steel bar below which no rate effects are evident
$\{\varepsilon\}$	Strain vector of the plate element
$\{\varepsilon_l\}$	Linear strain vector
$\{\varepsilon_{nl}\}$	Nonlinear strain vector
ε_1, ε_2	Principle strains at the specified Gauss point
$\gamma_{oct}^{\bullet}$	Octahedral shear strain
γ_{xy}, γ_{xz}, γ_{yz}	Shear strains in directions x-y, x-z and y-z
σ_c	Uniaxial compressive stress of concrete

σ_o	Uniaxial equivalent hardening stress
$\sigma_{yd}(\varepsilon^P, \varepsilon^\bullet)$	Dynamic yielding stress
$\sigma_{ys}(\varepsilon^P)$	Initial and subsequent static yielding stress
σ_t	Uniaxial tensile stress of concrete
σ_x, σ_y	Stresses in x and y directions
σ_1, σ_2	Principle stresses at the specified Gauss point
σ_{1p}	Ultimate tensile strength of concrete in tension-compression zone of stress
σ_{2p}	Ultimate compressive strength of concrete in tension-compression zone of stress
${}_i\bar{\sigma}^e_{n+1}$	Effective stress vector of the element
$\{\sigma\}$	Stress vector of the plate element
$\{\sigma\}_s$	Uniaxial stress vector of the steel bar
υ	Poisson's ratio
$\{\lambda^i\}$	Residual load vector
τ_{xz}, τ_{yz}	Transverse shear stresses of the plate element
τ^n	Boundary traction per unit element area
ρ	Mass density of the concrete
θ	Transformation angle
θ_x, θ_y	Nodal rotations of the eight-noded plate element
$\varphi(\varepsilon^\bullet)$	Rate function
φ_x, φ_y	Transverse shear deformations of Mindlin eight-noded plate element
μ	Damping ratio
ω	Un-damped circular frequency of vibration of structure

ω_c	Compressive strength parameter when σ_1 / σ_2 is equal to one
ϖ	Compressive strength parameter when σ_1 / σ_2 is not equal to one
$\omega_{\max}$	Maximum circular frequency for the finite element mesh of structure
$\{\omega\}$	Eigen value vector
η, ξ, ζ	Local or natural coordinate system of the eight-noded plate element
η_i, ξ_i, ζ_i	Local or natural coordinate system at i^{th} node of the plate element
Π	Potential energy of the plate element

ANALISIS DINAMIK TAK LELURUS RASUK DAN PAPAK KONKRIT BERTETULANG GENTIAN KELULI

ABSTRAK

Penggunaan gentian keluli dalam konkrit telah menunjukkan beberapa faedah terhadap peningkatan kekuatan lenturan, kemuluran, kekukuhan, keupayaan kawalan keretakan dan penyerapan kapasiti tenaga terhadap beban dinamik yang dikenakan seperti hentaman dan letupan. Dalam analisis struktur dinamik menggunakan kaedah elemen terhingga, kesan hubungan juzuk bahan baru masih lagi tidak diuji dengan meluas sama ada konkrit gentian keluli biasa atau nisbah aspek bercampur konkrit bergentian keluli. Dalam kajian ini, satu percubaan telah dibuat untuk membangunkan satu elemen terhingga yang mengandungi lapan-nod untuk analisis dinamik tak lelurus bagi rasuk dan papak konkrit tetulang bergentian keluli dan biasa dengan menggunakan model bahan baru. Hinton program komputer telah diubahsuai dan dibangunkan menggunakan FORTRAN untuk analisis struktur dinamik unsur terhingga tak lelurus konkrit tetulang gentian keluli rasuk dan biasa seperti yang bahan dicadangkan dan mempertimbangkan dan ketidak lelurusan geometri. Kaedah Newmark telah digunakan untuk mendapatkan waktu integrasi persamaan gerakan. Ujian hentaman telah dijalankan untuk mengkaji gerak balas dinamik rasuk dan papak konkrit nisbah aspek bercampur gentian keluli. Keputusan-keputusan terhadap anjakan dinamik, pemecutan, halaju, tegasan dan ke patahan tenaga telah direkodkan. Keserasian dapat diperhatikan antara keputusan analisis dan hasil ujikaji makmal serta data-data lain yang berkaitan. Ia ditemui bahawa penggunaan pengerasan terikan mampatan model, model tegangan I, mula-mula retak modulus ricih dan bar keluli dwilinear model tingkah laku memberikan keputusan analisis yang terbaik.

NONLINEAR DYNAMIC ANALYSIS OF STEEL FIBER REINFORCED CONCRETE BEAMS AND SLABS

ABSTRACT

The use of steel fibers in concrete has shown a number of advantages such as the improvement of the flexural strength, ductility, stiffness, cracking control and energy absorption capacity against the applied dynamic loadings such as impacts and blasts. In structural dynamic analysis by finite element, the effect of new material constitutive relationships either for ordinary, steel fiber or mixed aspect ratios steel fiber concretes has not been investigated extensively. In this study, an attempt has been made to develop an eight-noded finite element for the nonlinear dynamic analysis of ordinary and steel fiber reinforced concrete beams and slabs using new material models. Hinton computer program was modified and developed using FORTRAN for the nonlinear finite element dynamic analysis of ordinary and steel fiber reinforced concrete beams and slabs according to the proposed and considered material and geometrical nonlinearities. Implicit Newmark method was used in these programs to obtain time integration of the equation of motion. Impact test was carried out to study the dynamic response of the mixed aspect ratios steel fiber concrete beams and slabs. Results on dynamic displacements, accelerations, velocities, stresses and fracture energies of the concrete members were recorded. Good agreement has been observed between analysis results and the outputs of experiment and other related data. It is found that the use of compressive strain hardening model, tensile model I, first cracked shear modulus and bilinear steel bar behaviour model gives the best analysis results.

CHAPTER ONE

INTRODUCTION

1.1 An Overview

During the progress of human civilization in the early centuries, constructing strong and durable structures was the problem which faced the human. Thus, the Assyrians and Babylonians have employed bitumen to bind the bricks and stones together as appeared in winged bull (Fig. 1.1a) which can be regarded as a primitive symbol for the columns to support structures. The ancient Egyptians started to mix the mud with straw to produce the binder material between the dried bricks in the building. In addition they also introduced the mortars of gypsum and lime in the pyramids construction which depicted in Fig. 1.1b. In China, people used the cementitious materials in the building of the Great Wall (Fig. 1.1c). The Romans produced hydraulic mortar using the brick dust and volcanic ash with lime. They also used the wood formwork in the construction. Later, Greeks used lime mortars which were much suitable than that used by Romans. Now, this mortar is also in evidence in Crete and Cyprus. The Greek temples (Fig. 1.4d) have been constructed based on the classical architecture rule of the safe span for stone beams which require closely spaced columns and proper proportions for lintels.

Fra Giocondo introduced pozzolanic mortar in the pier of the Pont de Notre Dame in Paris in 1499. This is considered as the first reasonable usage of concrete in modern times. In 1776, James Parker gained a patent for producing the hydraulic cement by burning clay that contained veins calcareous material. In 1800, William Jessop has used a concrete on a large scale to construct the West India Dock in Great

Britain. The first engineering application of Portland cement was credited by Brunel in 1828 that used the Portland cement to fill cracks in the Thames Tunnel. In 1891, George Bartholomew made the first street of concrete in Bellefontaine, Ohio in the USA which is still available today. The basic cement experiments have been standardized in 1900 (Youkhanna, 2009).

Fig. 1.1(a): Assyrian winged bull

Fig. 1.1(b): Egyptian pyramids

Fig. 1.1(c): Great wall

Fig. 1.1(d): Greek temple

Fig. 1.1: Ancient civilization symbols (Britannica, 2011; 123RF, 2006)

The employment of fiber reinforcement is not a particularly new concept. Fibers were employed in brittle building materials since old times. In fact, the use of dried grass in production of clay bricks regarded as one of the earliest inventions of mankind. Straws were used also in bricks in Assyria and Egypt. While Romans used horse hairs in plaster walls and clay made products (Youkhanna, 2009). Fibers have been used in concrete later in 1970. The reinforcement bars were firstly introduced in the concrete by Joseph Monier in 1849, who embedded a mesh of thin iron rods in concrete to make flower pots or rather large tubs for orange trees (Gordon, 1971). Then, the introduction of reinforcing steel bars, supported by design models for their use, turned concrete into one of the most significant construction materials and used more widely in various civil engineering structures. The efficiency, the economy, the stiffness and the strength of reinforced concrete make it an attractive building material for many structures. For its utilization as a construction material, concrete must satisfy the conditions hereunder:

I. The concrete structures must be safe and strong. The proper consideration of principles for basic analysis and studying of the mechanical properties of the concrete component materials lead to suitable and safe design of concrete structures to resist the accidental loading.

II. The structures must be stiff. Attention should be considered in analysis of concrete structure to control the deformation under loading and to decrease the cracking width.

III. Concrete structures must be economical. Because of high cost for reinforced concrete components, concrete material must be consumed reasonably.

Plain concrete has weak tensile strength compared to its compressive strength due to its low ductility and small resistance to cracking. Micro-cracks exist in the concrete during its preparation and even before application of loading, because of the changes in micro structure which produce brittle failure in tension. Thus, deformation and cracking reduced the using of concrete material. Therefore, the concrete experts tried to improve these weak properties of this material in order to suit the design requirements. The improvement of concrete properties was done in the last century (Bentur and Mindess, 1990) by introducing short fibers such as steel, carbon, glass etc to reinforce the concrete. In spite of the availability of construction fibers in various types according to producing material (as shown in Fig. 1.2), steel fibers are the most commonly used in concrete constructions than others. Further development has led to increase in usage of steel fiber reinforced concrete (SFRC) as a building material either with or without introducing of reinforcing steel bars. Steel fiber reinforced concrete was utilized at the first time in the construction of defense related buildings such as shelter structures. Nowadays, steel fiber reinforced concrete is commonly employed in diverse construction applications (Fig. 1.3) such as patios, slabs on grade, shotcretes for slopes and stabilization of tunnels, pre-cast concrete members, seaboard structures, airport runways, footing of machine, explosive and impact resistance structures and seismic resistance structures.

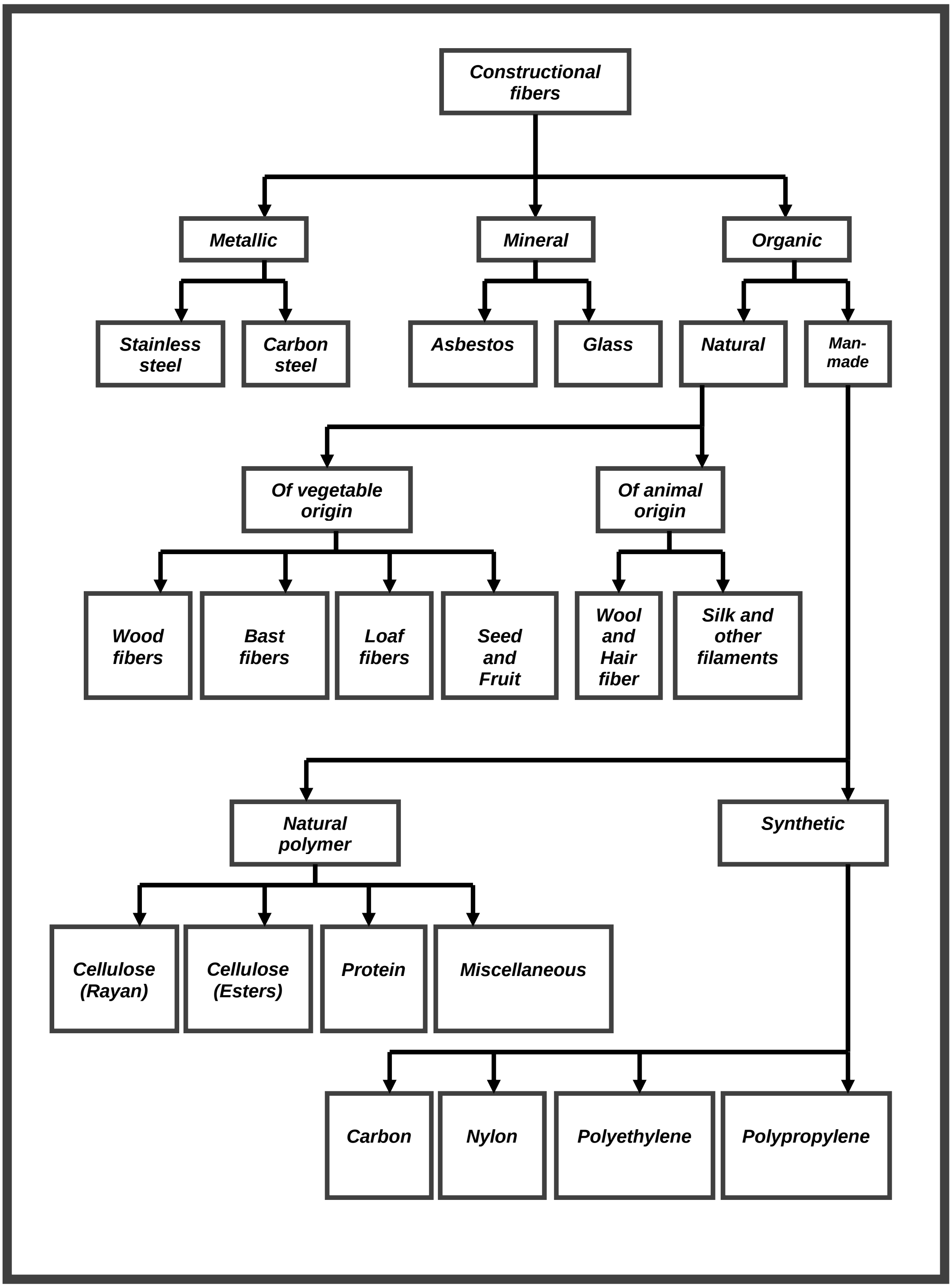

Fig. 1.2: Constructional fibers types and sources (Behbahani, 2010)

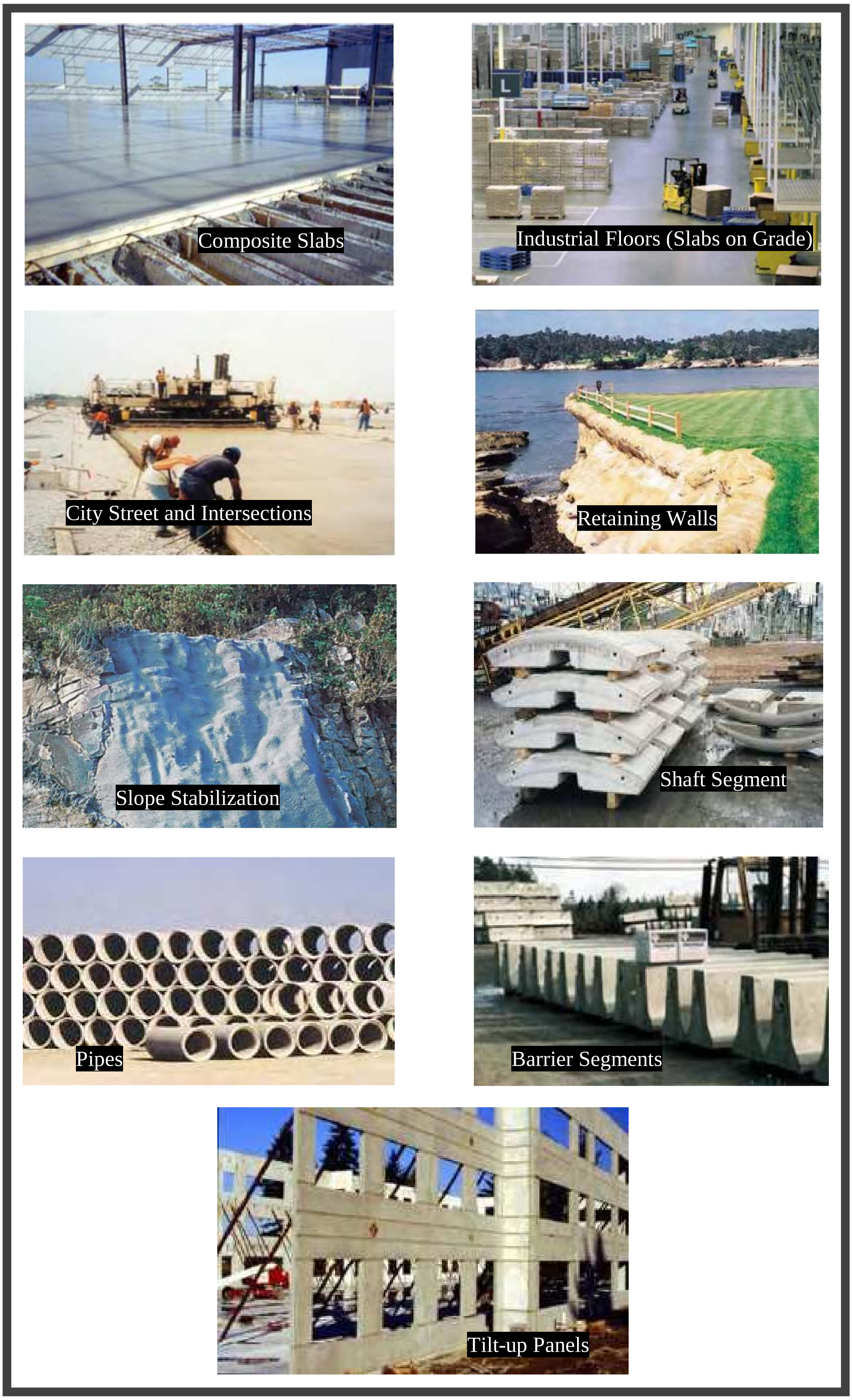

Fig. 1.3: SFRC applications facts (Maccaferri, 2011)

Worldwide use of these composite materials is reported at 150,000 metric tons per year (Banthia et al., 1998). The widespread utilizations of steel fibers in reinforced concrete members were in beam and slab structures.

While it is technically possible to produce a fibrous concrete of very high tensile strength using high fiber content (Tjiptobroto and Hansen, 1993; Li and Fischer, 1999), it is generally not feasible to do so for structural applications, mainly owing to practical reasons. The use of high fiber dosage may lead to severe reduction of the workability of the fresh concrete. Therefore, in load bearing structures, steel reinforcing bars are predominantly used while fiber reinforced concrete (FRC) is limited to applications where crack distribution and reduction of crack width are the main aims. However, the combined use of reinforcement bars and FRC may yield synergetic effects because of the improved bond properties (Stang and Aaree, 1992; Noghabai, 1998).

The positive effects of FRC are documented for such a large span of applications that it could be anticipated to be much more widely used than what is currently the case. It is often argued that the relatively high material cost of fibers is the reason for the low employment, but since the total production cost may be lowered in many cases, this is not the sole explanation. A more important reason is the current lack of design rules and guidelines, which fully utilize the advantages of fibrous concrete.

The use of FRC as a building material has been the goal of extensive researches during the last decades with numerous scientific reports as an output. Still, the resulting impact on existing codes of this material has been sparse in relation to the effort which was put into research (Groth, 2000). A reason for this, in a general meaning, may be that conventionally reinforced concrete is treated as an ideal elasto-plastic material characterized by only two parameters-stiffness and strength. On the other hand, fiber reinforced concrete is defined through its toughness, or softening, and in most practical cases it is assumed that it has approximately the resembled stiffness and strength as plain concrete. Therefore; fracture mechanic models can be used in order to establish design rules for fibrous concrete that consider the softening behaviour. However, the problem is that fracture mechanic models are till-now not fully implemented in the design codes currently in use. Furthermore, the use of fracture mechanical methods often leads to models that are not possible to be presented analytically. Instead, they are restricted to numerical treatment through finite element models, which in turn are not readily explained in design code formulations.

Another reason for fibrous concrete not being employed more plentifully is because of its still being a new construction material. This expression may be surprising concerning the large amount of research works that have been done till now, but it is important to discern different types of materials in fibrous concrete. In fact, the term covers a whole range of kinds of fibers which are mixed in as reinforcement.

Numerous reinforced concrete structures are available in society as natural infrastructure parts or as various types of military and civilian facilities (Magnusson, 2006). So in specific cases, reinforced concrete structures should be designed to withstand static and dynamic loadings. The possibility of exposure of the concrete constructions to dynamic actions like impact and blast is increased during their life span. The failure of concrete structures under dynamic forces is considered more complex than their failure which results from the applied static loading. However, it has been mentioned that the dynamic analysis of concrete structures can be performed via using of modified factor of safety or equivalent static loading case. There are many developed procedures led to so accurate investigation of the structural dynamic performance such as the imposing of more severe live loading cases as high speed machines which applied on the multi-story buildings, involving the extreme wind loading states in the analysis of high tower, big bridge structures etc, including advanced design of structures to resist high intensive blast load and improvement of specific structures to withstand earthquake actions.

Steel fiber concrete composite is able to absorb energy produced from the applied dynamic loadings on structure more than the conventional concrete material because of suitable high tensile strength of SFRC and its good resistance to failure under tensile loadings. Thus, SFRC material was utilized in many concrete constructions to resist severe dynamic actions especially in military or defense concrete constructions and concrete containments for nuclear materials. Hence, it is important to introduce the effect of many forms of dynamic forces in the analysis of these concrete structures to get more durable design.

Linear approach is usually used in the analysis of reinforced concrete structures, where geometrical nonlinearity is disregarded and small deformations are considered. In specific structural analyses, a plastic behaviour of the reinforced concrete material should be considered in the simulation of the structural performance. Thus many factors should be considered in analysis to represent this plastic nonlinear stress-strain relationship such as bonding between concrete and steel materials, cracking of concrete, yielding of the reinforcing bars, bond slip between concrete and reinforced steel bars or fibers and interlock of aggregate. The modeling of non-linear response of reinforced concrete material becomes more important for the analysis and design of SFRC structures (Thomee et al, 2005).

The formulation of reasonable analytical approaches to investigate the behaviour of concrete material is difficult because this behaviour include many nonlinear phenomena interact each another. The nonlinearity property produces several complexities in the analysis and design of steel fiber and conventional concrete structures because of their nonlinear behaviour, steel and concrete interaction, pull-out and debonding of steel fibers, and the effect of the concrete cracking under varying loads with time. Thus, the nonlinear response of concrete is mainly attributed to inelastic or plastic deformation and progressive cracking phenomenon. In structural analysis, it is preferable to introduce the geometrical nonlinearity influence because of large displacements that may produce changing in geometry of structures and their elements shape in analysis. Incorporation of these material and geometrical complexities into a mathematical formulation with depending on the continuum mechanics theories (Cervera et al, 1996; Hatzigeorgiou et al, 2001; Koh et al, 2001; Lu and Xu, 2004) such as the yield line theory is impossible because of the difficulty in consideration of in-plane forces and geometric nonlinearity in the analysis. New approaches of nonlinear structural analysis have been introduced with the invention of the developed and powerful computers, where the structural response can be investigated through the entire loading range of structure. The finite element approach is regarded as one of these advanced numerical procedures for analyzing structural problems with complicated boundary conditions and complex material behaviours which leads to produce a rational structural analysis with consideration of both material and geometrical nonlinearities. Thus, finite element method was used as an efficient technique in precise dynamic analysis and design of reinforced concrete members such as beams, slabs, shear-walls and box-girder bridges. The geometrical nonlinearity approaches have been already given and known in standardized manners. Hence, to provide a developed finite element procedure which suit the specified materials behvaiour of any structure it is necessary to propose new material constitutive nonlinear models. In other words, the numerical simulation of the actual material behaviours in the nonlinear finite element method lies primarily in the improvements of the mathematical material constitutive models.

Reinforced concrete beams and floor slabs are of particular interest, being common structural elements in building and bridge-decks which are exposed to the effect of blast and impact loadings. These structural elements are a form of the complex structures which are designed to serve for static and dynamic purposes by using finite element approach. The dynamic response of the concrete structures is significantly affected when steel fibers are added. Magnitudes and modes of the deflection are affected. The stresses and their directions are also influenced which leads to produce different modes of yielding and various cracking directions that occurred depending on the location, volumetric dosage and shape of the used fibers. Several works on steel fiber reinforced concrete beams and plates for static loads employing the finite element method have been carried out with some material models. Unlike conventional reinforced concrete, only a limited amount of information is available with regard to dynamic behaviour of steel fiber reinforced concrete. Investigations have been done to formulate the material constitutive relationships for concrete without checking the validity of these models in the case of both ordinary concrete and SFRC which contain various shapes of steel fibers. This formulation leads to unreasonable results.

1.2 Problem Statement

According to literature, only few studies have been conducted dealing with nonlinear finite element dynamic analysis of steel fiber concrete structures compared to conventional concrete structures. Most of the researchers who investigated the nonlinear dynamic analysis of SFRC structures used three dimensional finite elements rather than using of two dimensional elements especially eight-noded plate element. Thus, in this study, eight-noded elements have been adopted for dynamic analysis purpose.

The inclusion of the material constitutive relationships which are suitable for both conventional and steel fiber concrete materials is a case in point. Some material constitutive models have been proposed by many authors using specified type of fibers in their formulations. The reliability of several material constitutive models for SFRC material and plain concrete material available in literature has been investigated recently by many researchers. They proved that these available material constitutive relationships are valid and compatible only with specified experimental test results which are dependent in formulation of those material models, while these models do not give good agreement with other test results. Other researchers concluded that the formulation of new material constitutive models is needed for SFRC material, because the formulation of SFRC constitutive relationships is not limited and is dependent on the shape of steel fiber used. Hence farther investigations and studies in this direction are considered essential.

Varying level of sophistication and adoption of the appropriate material constitutive nonlinear models of concrete material depend on the problem to be solved, for example finding and selecting proper material constitutive models suitable for SFRC material should be made via the use of steel fibers of different shapes, aspect ratios and volume fractions. This is to formulate more sophisticated general models to fit most types of SFRC materials. Rarity of research is observed in proposing nonlinear material constitutive models suitable for both conventional plain and fibrous concrete materials. Thus, the role of new research must become clear to solve this problem which represented in the formulation of new material nonlinearities to suit the simulation of plain and different fibrous concrete material behaviours.

In this respect, the use of steel fibers has not been investigated widely for structural engineering purposes; therefore the analysis and design procedures of SFRC structures are still in the development stage, especially in dynamic analysis aspect. Thus, there was a scarcity of research works in the literature that deal with finding and selecting the proper new material constitutive models suitable for numerical dynamic analysis of both plain and SFRC members by using many shapes, sizes and volume fractions of steel fibers.

According to literature review no conclusive evidence has emerged to study dynamic performance of mixed aspect ratio steel fiber reinforced concrete members. Thus, experimental and theoretical studies are considered essential in this direction.

1.3 Aims of the Present Study

The main objectives for this work are four-fold:

1. To formulate of new material constitutive models for conventional and steel fiber concretes based on experimental results for uniaxial compression and splitting tension load tests and other biaxial loading tests. The effect of shape, size and volumetric fraction of the steel fibers are considered in formulating these new models.
2. To incorporate new material constitutive models in the finite element dynamic analysis procedure using degenerated eight-noded plate elements with consideration of geometrical nonlinearity.
3. To investigate experimentally the dynamic performance of mixed aspect ratios steel fiber reinforced concrete beams and slabs which are subjected to patch impact loading.
4. To check the validity of the present proposed finite element dynamic analysis results by comparing them with the outputs of both present experimental tests and other related studies considering three types of concrete members which are ordinary, single aspect ratio steel fiber and mixed aspect ratios (i.e. 0%

short fibers content, 25% short fibers content and 50% short fibers content) steel fiber reinforced concrete slabs and beams. Thus, find the best material models in analysis with respect to this comparison study.

1.4 Scope of Work

In this study, an attempt was performed to develop a procedure for the dynamic analysis of ordinary, single aspect ratio steel fiber and mixed aspect ratios steel fiber reinforced concrete members (i.e. simply supported or clamped slabs and beams). In the formulation of new material models, the considered steel fibers have different shapes, sizes, properties and volume fractions. The finite element method has been developed considering new material constitutive relationships which were used to investigate the dynamic behaviour of concrete member in the pre- and post-cracking levels of the concrete material. To overcome the problem of shear locking in dynamic analysis, the technique of reduced integration was applied in the formulation of degenerated quadratic thick plate element which is the general shear deformable eight-noded element.

Experiments have been performed to study the concrete behaviour under compressive and tensile loadings for formulating new material finite element models. Present models can be considered as general mathematical constitutive equations for developing finite element program required for dynamic analysis of fibrous concrete beams and slabs which contain different fiber shapes and volumetric fractions, in addition to investigate the dynamic response of ordinary concrete members. In the case of reinforcement bars the materials are considered to resist only the uni-axial loading condition. The stress-strain curves for steel bars are represented by the linear and bilinear elastic perfectly plastic models. In experimental and numerical approaches, the influence of steel fiber aspect ratio on the dynamic response of mixed shapes steel fiber reinforced concrete members subjected to impact loading has been studied.

In order to accomplish the objectives of the present study, a number of activities have been executed which included conducting experiments that are related with compressive and tensile behaviours of steel fiber concrete specimens (i.e. cubes and cylinders). These samples contained steel fibers in different shapes, sizes and volume fractions to formulate new material constitutive relationships related to the behaviour of the fibrous and plain concretes under uni-axial loading conditions. Then, data collection has been done for experimental secondary results from the literature for biaxial stress-strain curves of compressive and tensile behaviours for conventional and steel fiber concrete samples considering various steel fibers shapes and properties. After that a nonlinear regression analysis was performed in SPSS-Program of the available experimental data for concrete behaviour under uniaxial and biaxial loadings. Thus, suitable mathematical models for concrete behaviour under each loading case were found and the validity of these models was investigated. Hinton computer program coded in FORTRAN language was modified and developed to perform present dynamic analysis of conventional and steel fiber concrete members (i.e. slabs and beams). This modified program incorporates the effects of material and geometrical nonlinearities in eight-noded degenerated plate elements formulations. Implicit Newmark method with corrector-predictor algorithm was employed for time integration of the equation of motion. Experimental tests have been conducted for investigating the dynamic performance of the slabs and beams subjected to impact loading with considering mixed aspect ratio steel fibers. Finally, the validity of both present finite element procedure and the proposed material models have been checked via comparing the current numerical analysis outputs with the present dynamic test results and other outcomes available in the literature.

1.5 Thesis Outline

Present thesis is comprised of six chapters. A brief layout of each chapter is given hereunder:

- Chapter One presents general information on concrete containing steel fibers and the role of fibers in enhancing the concrete properties and performance under dynamic loading. It comprises of the problem statement, objectives, as well as the scope of work.
- Chapter Two presents the literature review on the areas of present research work. Nonlinear dynamic analysis of conventional and steel fiber reinforced concrete beams and slabs and development of degenerated plate element in structural analysis are reviewed and highlighted. This chapter also includes a review in the advancement of the fiber reinforced concrete as a constructional material and its properties in the fresh and hardened state with its applications.
- Chapter Three represents the core of this work. It covers the methodology for experimental and theoretical parts of the present research. Thus, explanation has been given for experimental process including uni-axial compressive and tensile loading tests of fibrous concrete specimens containing various shapes, sizes and volume fractions of steel fibers. The tests results are used in present material modeling. This chapter also introduces the formulation of the degenerated eight-noded plate finite element which has been adopted in present

study with explanation of the main procedure for nonlinear finite element solution and taking into consideration also the influence of the geometrical nonlinearity. The algorithm of the modified computer program coded in FORTRAN which assigned for current dynamic analysis of concrete beams and slabs has been given. The new material models were considered in the current analytical computer program. Details of the general degenerated plate elements using eight-noded elements with reduced integration rules and smeared idealization of reinforcement are also presented. The procedure of the dynamic analysis test for various SFRC beams and slabs containing mixed sizes of steel fibers are reported in details in this chapter.

- Chapter Four highlights the results and discussions on the material constitutive relationships for SFRC and ordinary plain concrete materials. Compression and splitting tensile tests results are utilized with other secondary published experimental data in preparation of developed and modified material constitutive relationships. There relationships are used to simulate the behaviour of both the ordinary and fibrous concrete materials under uniaxial and biaxial loading conditions based on the theory of plasticity. This chapter also involves the explanation of the considered material modeling of both steel reinforcement and concrete crack pattern approaches. Various material models for representing some concrete behaviours or properties are proposed for using in the current promised analysis. Furthermore, strain rate sensitivity and dynamic concrete properties of both concrete and reinforcement steel bar materials are also clarified.

- Chapter Five presents the experimental results for the current dynamic tests together with numerical applications in using the present finite element dynamic analysis procedure. Comparative studies, between experimental and computational results, as well as validation of the proposed formulations are given. Results of the present numerical procedure are also compared with other related studies. Parametric studies are also performed for nonlinear dynamic analysis of beam and slab structures with considering different variables. Preferable material constitutive models in analysis are found depending on the present dynamic analysis results.
- Chapter Six is the final chapter outlining the conclusions achieved from the current observations and some recommendations for further future researches.

CHAPTER TWO

LITERATURE SURVEY

2.1 General Introduction

As early as 2500 B.C., horse hair was reported to have been used in plaster to increase its tensile strength. Even straw and other vegetable fibers were also used to reinforce the sun baked bricks. Asbestos fibers had been used also to enhance the flexural and tensile strengths of ceramic in Finland. Thin and short length fibers are introduced into brittle materials to serve as crack arresting mechanisms to improve the properties of the concrete. Because of realizing the improved properties of the fiber reinforced concrete products, research and development works on fiber reinforced concrete (FRC) are initiated about four decades ago for many practical applications, such as reinforced concrete structures, pavements, overlays of bridge deck, offshore structures. Fatigue behaviour and endurance limits are significant because these kind of structures need to be designed for fatigue loading, and they benefit most from the addition of fibers to the concrete.

Since the early fifties of last century, the matrix theory was started to be applied in the analysis of structures. The stiffness and flexibility methods were developed as an extension of classical approaches. Later in 1956, the finite element method was proposed by improvement of the stiffness and flexibility methods. Until the late fifties of last century, most structural analysis methods were dependent on linear analysis approaches such as working-stress analysis method. Nonlinear plastic behaviour will consider for elastic materials when structure is analyzed based on its ultimate strength. Thus, the development of the ultimate strength methods has led to the consideration of the inelastic behaviour in analysis and improvement of linear elastic theory. This method enables engineers to predict the accurate structural strength and behaviour of structure under various loadings. Thus, after the first application of nonlinear finite element analysis to concrete structures in the late of sixties of last century (Rashid, 1968; Ngo and Scordelis, 1967), several new developments and improvements have been published and many researches were launched to introduce the finite element procedure in both static and dynamic analyses of reinforced concrete structures. During the past fifty years ago, various numerical studies have been performed to study the dynamic analysis of concrete structures with considering many structural parameters. Numerical analysis approaches in investigation of structural dynamic behaviour to the applied dynamic load are regarded inevitable to represent the performance of concrete structural members with proper degree of preciseness and validity. The numerical finite element approach was used successfully in the dynamic response analysis of concrete structures with taking into account the effect of both material and geometrical nonlinearities. The modification in the finite element analysis procedure of concrete structures was focused in developing new material nonlinearities. Thus, the formulation of the suitable material constitutive relationships for concrete material is considered as an effective scope of study in the field of structural engineering.

This chapter is devoted for presenting the historical background of both the use of fibers to reinforce the brittle concrete and the development in constitutive modeling of conventional concrete and SFRC. A survey is also reviewed nonlinear dynamic analyses of reinforced concrete members (e.g. beams and slabs) in both types of concrete, namely, conventional and steel fibers.

2.2 Steel Fiber Reinforced Concrete

In the development of concrete technology, concrete strength exceeding 100 MPa can be easily yielded to fulfill the construction requirements. However, the main concern with high strength concrete is the increasing brittleness with the increase of strength. Therefore, over the past few decades a new trend has emerged in the concrete industry. Fibers of different materials, sizes, and geometries have been added to the concrete mixture to produce a construction material which is generally defined as fiber reinforced concrete. Thus, SFRC is a concrete composite made of many components which are hydraulic cement, fine aggregates or coarse and fine aggregates, steel fibers and water (ACI Committee 544, 1988a). The concrete employed in the mixture is of the common sort, although the characteristics should be varied to obtain good workability as in the case of fibrous concrete. This may need limited size of aggregates, optimum gradation, high content of cement and introducing admixtures to get proper workability. The amount of steel fiber required for the fibrous concrete is usually measured as a portion of the total concrete volume. Generally, the fiber portions introduced into the concrete matrix can be classified into three groups, namely low, moderate and high volumes. Low volume of fibers composites are typically being used for applications which containing large volumes of concrete. The matrix is usually proportioned via following the procedures used for plain concrete, with slight modification done on the mixture. Volume fractions of fibers range from 0.5 to 2 percent or more for steel fibers, while 0.06 to 0.5 percent for polymeric fibers. The design of the fiber concrete mixture should consider the concrete's workability and good fibers distribution as well. Moderate fibers volume composites are usually being used for special applications. These composites normally contain cement and fine aggregates with fiber volume fractions usually