MATLAB & OTDR BASED DEFECT ANALYSIS

A THESIS SUBMITTED FOR PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF

MASTER OF TECHNOLOGY
IN
CONTROL AND INSTRUMENTATION

SUBMITTED BY:

HEENA
(2K12/C&I/29)

UNDER THE SUPERVISION OF

MRS.BHAVNESH JAINT

DEPARTMENT OF ELECTRICAL ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi, India

2015

DEPARTMENT OF ELECTRICAL ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042, INDIA

CERTIFICATE

This is to certify that the Thesis entitled, "**MATLAB & OTDR BASED DEFECT ANALYSIS**" submitted by **HEENA** bearing roll no. 2k12/C&I/29 is a record of bonafide work carried out by him, in the department of Electrical Engineering of Delhi Technological University, New Delhi, under my supervision and guidance in partial fulfillment of requirement for the award of the degree of Master of Technology in Control and Instrumentation Engineering during session 2012-2015.

Place: New Delhi

Mrs.BhavneshJaint

Date:

Supervisor

Electrical Engineering Department

Delhi Technological University

Delhi

ACKNOWLEDGEMENT

It is a great pleasure for me to acknowledge the assistance and contributions of few individuals to the successful completion of my Master's Thesis without whom it would be very difficult for me to complete the task.

I would like to especially to give my thanks to my adviser, **Mrs. Bhavneh Jaint**, Department of Electrical engineering, Delhi Technological University (formerly Delhi College of Engineering) for his valuable time and inputs during the project. He always stood by me during the problem session and despite their very busy schedule, he always gave priorities to my queries and problems. It is for his help and support that I am able to successfully finish the project and understand the concepts clearly.

Finally, I want to express my deepest regards to my parents and friends for being very kind and supportive towards me throughout the course of thesis completion.

Date: -------------------------- ---------

Heena

CHAPTER1

INTRODUCTION

1.1OVERVIEW

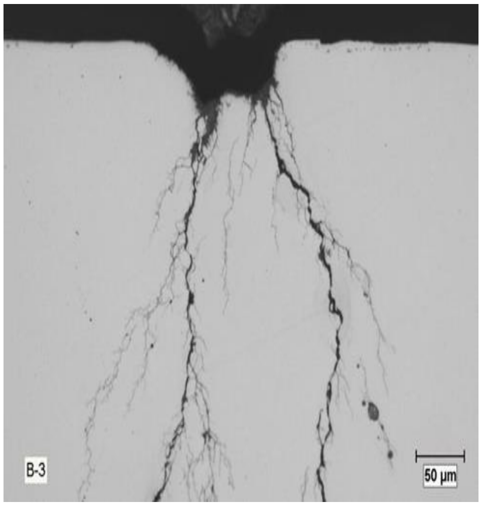
Structural Health Monitoring has been an important development for several engineering fields. Recent events remind us that the cost of a engineering structure collapsing is much more than economical, it affects people's life, as dramatically demonstrated by the collapses of the Laval's La Concorde overpass, in fall 2006, and, the Minneapolis bridge, in summer 2007.

Fig1.1(a)

Fig 1.1(b)

Fig1.1 showing the consequence of cracks

Damage occurs in a material when dynamic behavior of structural changes across a certain threshold. These damages eventually lead to cracking and failures. In general, Cracks can be termed as discontinuity within a material which is a sign of either its aging and / or its failure. Cracks can occur in a material such as concrete, metal, alloy etc. And it may occur under continuous harsh environmental exposure or due to in service loading or impact forcing.



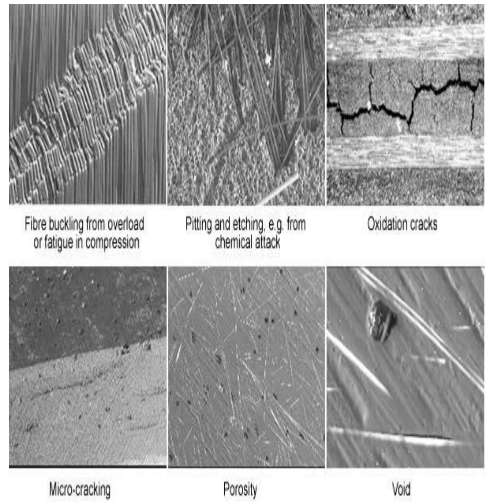


Fig 1.2(a) Fig 1.2(b)

Fig1.2 showing the propagation of cracks within structure.

All these cracks and structural deformation can degrade the integrity of a material. Thus when such cracks are left undetected, they may result in structural failure. Amongst the principal aims of SHM, the detection and localization of cracks appear as an essential task as they can lead to lethal faults and hence reduce the structure's life. An important challenge is to detect the location and orientation of crack which is difficult to predict due to material inhomogeneity and complexity. Therefore a large number of techniques have already been proposed and implemented for detection of cracks within a structure. The existing technology used for crack detection are Radio Frequency Identification (RFID) , Piezo-Electric Transducers (PZT), Ultrasonic method, Acoustic Emission, etc. However, these current sensing systems have certain disadvantages such as

- Susceptibility to Electro-Magnetic Interference
- Logistics for multiplexing
- Quasi-distributed
- Require a large number of sensors
- Reduced mobility

Fiber optics provides faster communications and recent advancement in fiber optic technology have significantly changed the telecommunication industry. Thus, over the previous few decades, Fiber Optics have found an increasing use in the field of sensor technologies as a viable and robust replacement for conventional sensing technologies.

Fiber Optic Sensors (FOS) are more sensitive than contemporary sensors and they are used for one of several types of applications. In smart manufacturing, they are attached or embedded to the component during the manufacturing process and are used to monitor temperature, pressure, viscosity, residual strain. During service, fiber optic sensor may be used for Non-Destructive Evaluation (NDE) to measure strain profiles, monitor delimitation or other changes in structural characteristics.

Fiber optic sensor with the ease of deployment and its ability to withstand harsh environmental condition gives it an extra edge over all the other available form of sensors and provide significant flexibility to SHM application.

Many fiber sensors are commercially available like, as intensity base fiber optic sensor, Extrinsic, Fabry-Perot Interferometer (EFPI), macro-bending sensors and fiber Bragg grating (FBG) which can be used for measuring the desired parameters even in a harsh environment. However, these fiber optic sensors have certain disadvantages such as all the above mentioned sensors are point sensors and hence cannot be used to sense over the entire length of structure. One of the major disadvantages of a Quasi-distributed system is the lack of coverage. Quasi-distributed sensing systems may not be able to determine the measurand information at the locations other than those, where the sensors are present Hence a large number of the sensors would be required to cover all possible regions which may not be possible for practical implementation.

Therefore, distributed sensors which can sense cracks over the entire length of the structure are highly desirable. Therefore, it is required to develop a Fully Distributed sensing system where each and every position along the length of fiber can act as the sensing element and can monitor the crack before it reaches the damage threshold. OTDR is used for the purpose of a fully distributed sensing system to find the position of discontinuity along the fiber.

We are proposing a fully distributed sensing system for the localization of crack in real time using the OTDR technique and single mode optical fiber. The unique feature of fully distributed fiber optic sensing system is the ability to perform measurement at thousands of locations along an optical fiber. For the fully distributed sensing system, the measurement techniques based on OTDR offer a viable solution for monitoring of distributed temperature, strain or pressure.

OTDR uses the principle of Rayleigh scattered light to measure the attenuation profiles of long haul fiber optic links. In the optical time domain coded technique, an optical pulse is launched into the fiber and a photo-detector measure the amount of light which is backscattered as the pulse propagates along the fiber. The detected signal so called Rayleigh signature present an exponential decay with time which is directly related to attenuation of fiber. The time information is converted to distance information provided that speed of the light is known.

Thus a highly reliable fully distributed sensing system with the use of commercial OTDR for structural health monitoring is facilitated without introducing any additional heavy component. The proposed fully distributed sensing system enables the user to find the crack or any perturbation along the entire length of optical fiber with the use of Rayleigh backscattering mechanism of OTDR.

1.2 Motivation

Real-time sensing of physical, chemical and biological stimuli is critical to maintaining safety and operational efficiency in today's complex civil infrastructure sites. Many of these applications, such as environmental pollution measurement, continuous harsh environmental exposure, or due to in service loading or impact forcing require various measurements at multiple locations, large spatial area coverage, capability of operation in harsh environments, low cost and in real-time. Therefore, there exists a critical need for technologies that can provide distributed measurement at multiple points. The motivation behind this thesis work is to develop a fully distributed sensing system using fiber optic sensors and OTDR to develop a reliable and robust sensing technique that can inform of the imminence of a engineering structure collapse or provide the measurement of multiple physical changes such as any cracks or perturbation within structure using single mode fiber. This system may be used to avoid such accidents and ensure their non-occurrence in the future.

Many kinds of sensors have been investigated for distributed sensing in the past two decades as mentioned above. Among these sensors, optical fiber sensors are well known for their intrinsic immunity to electromagnetic interference, high sensitivity, high resolution, resistance to chemical corrosion, small size, light weight, ease of installation and capability of operation in harsh environment thus attracting a great deal of research interest for distributed sensing.. Therefore, it is highly desirable to develop a new technology that can permit fully-distributed measurement of multiple physical, chemical and biological quantities using a single optical fiber.

1.3 Objectives

Fully distributed fiber optic sensing system plays a pivotal role in the monitoring of crack or any perturbation within the engineering structure or the collapsing of the structure due to presence of cracks. Not only because of its immunity to EMI (electro-magnetic interference) and light weight but also because of the ease with which it can be installed throughout the length of the structure, gives it an edge over other available form of sensors that can be used to measure the multiple cracks within the structure. In this work, we have surface mounted Fiber optic sensors that can be successfully deployed for structure monitoring. Our work focuses mainly on the following issues:

- To develop a Fully Distributed sensing system using OTDR and normal single mode optical fiber for crack detection and estimation of crack location and parameters.
- To investigate different fiber lay out mechanisms to increase the sensitivity of OTDR signal to cracks.
- To develop a digital signal processing system with backscattered signals for real-time detection of cracks in different structures.
- To develop a laboratory model for crack detection using OTDR.

1.4 Organization of thesis

The thesis is divided into the following six chapters. Each chapter is briefly discussed here to give an overview of the thesis.

Chapter 2: Literature Review: This chapter presents the literature review of the references which has been used for Fully distributed sensing system for detection of crack, and real time signal processing technique for measurand information.

Chapter 3: Distributed fiber optic sensing system: presents a basic theory on Fiber optic sensors for fully distributed measurement, its sensing principle, and optical source.

Chapter 4: Optical Time Domain Reflecotmetry: presents the working principle of Optical Time Domain Reflectometry and theory of crack detection**.**

Chapter 5: Experimental Setup: presents the experimental setup for real time monitoring of crack detection using Fiber optic sensors and Optical time domain reflectometry(OTDR) and highlights the methodology which has been used for the detection of multiple cracks..

Chapter 6: Results & Discussion: presents the results obtained from the simulations and experimental setups and the significance of each result is being discussed to achieve the desired objectives.

Chapter 7: Conclusion & Future scope: presents the conclusion of the thesis work and the scope for future work on the proposed field. This chapter is followed by references

CHAPTER 2

LITERATURE REVIEW

In order to avoid potential structural failure, due to crack development and propagation, it is necessary to detect, monitor and characterize the crack before it harms the structure. A large number of techniques have already been proposed and implemented for detection of cracks within a structure. A brief of some important research papers which I have used in my thesis work are discussed below:

Farhad Ansari. et.al [1] proposed a new fiber-optic sensor by which it is possible to directly measure the displacements associated with opening of cracks in cementitious composites, if their locations are known a priori. Hence, such sensors are most suited for experimental determination of crack tip opening displacements (CTOD) in notched specimens. Crack tip opening displacements are measured at the tip of notched FRC specimens by embedment of fiber-optic sensors in the specimens during mixing.

Christopher K.Y. Leung. et.al [2] has developed novel a novel optical fiber sensor for the detection of cracks and the subsequent monitoring of their openings. With this sensing concept, (i) no a-priori knowledge of crack location is required, and (ii) a small number of fibers can be employed to detect and monitor a large number of cracks. A theoretical model has also been proposed for the signal loss versus crack opening relationship developed through a combination of mechanical and optical analyses. Using concrete beams with embedded sensors, crack monitoring experiments are conducted.

BAO TengFei. et.al [3] proposed a fiber optic sensor with distributed crack sensing capability based on optical time domain reflectometry and experiments are conducted to obtain the optical power loss versus crack opening at different fiber inclination angles, and then a model is developed to quantify it. The test results show that detecting and monitoring cracks with the sensor do not require a-prior knowledge of crack locations and orientations.

K S C Kuang. et.al.[4] reported the use of Plastic optical fiber to detect initial cracks, monitor post-crack vertical deflection and detect failure cracks in concrete beams subjected to flexural loading conditions. And this intensity-based sensor system relies on monitoring the modulation of light intensity within the optical fibre as the sensor is loaded. These sensor design offers good signal stability and sensitivity to the monitored parameter and represents a cost-effective alternative to other more sophisticated health-monitoring systems currently used in civil engineering structures.

Chao Pan. et.al. [5] has developed a distributed optical fiber vibration sensing system based on differential detection of differential coherent optical time-domain reflectometer (DC-OTDR). In this paper multiple vibrations sensing and positioning along the long sensing fiber has been achieved by differential detection of series of Rayleigh backscattering signals produced by single optical pulse propagating in fiber. The experimental results are shown for the sensing range for more than 10km, the positioning error is less than +3m, and its signal to noise ratio is higher than 40.

Z. S. Wu. et.al.[6] discussed about the performance of a BOTDR optical fiber sensing technique for crack detection in concrete structure. This research proposed various optical fiber installation methods such as; one-round superposition, two-round superposition,overall bonding (OB) installation and point fixation (PF) installation. Experimental results has shown that the n-round superposition installation method can effectively and correctly detect the total crack width within a relatively local region.

Kai Tai Wan. et.al. [7] developed a distributed optical crack sensor based on OTDR measurement of bend loss. In this paper, the sensing principle and the fabrication of sensors for surface attachment and internal embedment has been described. Experimental results has been shown to demonstrate that the optical power loss versus crack opening relation at a particular point of bend loss is independent of the number of bends along the fiber.

N.M.P. Pinto.et.al. [8] proposed a quasi-distributed displacement sensor using an optical time domain reflectometer for structural monitoring. In this paper Four displacement sensing heads are placed along a standard single mode optical fiber in several locations with different intervals. And this configuration introduces power loss through the decrease of their fiber loop radius when displacement is applied. The decrease of the light intensity with displacement variation is reported. Results are shown for the 120mm displacement corresponding to 0.7mm of radius of curvature showing the losses of 9 dB with a sensitivity of 0.027 dB/mm. The quasi-distributed configuration is able to address sensors with 1m distance resolution between them.

Noah Olson.et.al. [9] introduces a sensing concept based on the bending loss of an optical fiber, Experiments have been performed to obtain the signal loss versus crack opening relation with the use of multimode fibers. A theoretical model for power loss versus crack opening has been developed to calculate the crack-induced curvature along the fiber with a finite element analysis. Power loss in the curved fiber is then obtained with the ray tracing technique. The theoretical prediction is found to be in good agreement with experimentally measured power loss.

Qian Wang.et.al [10] has investigated theoretically and experimentally for macrobending loss in single mode optical fiber(SMF28) and validating that the inner primary coating layer of SMF28 has a significant impact on the bend losses and most of the radiation field is absorbed in the inner primary coating layer of SMF28.

Yuelan Lu.et.al. [11] has developed a distributed vibration sensor by using heterodyne detection and signal processing of moving averaging and moving differential for the phase optical time domain reflectometry system. In this paper, Pencil break measurement has been done using distributed vibration sensor which is a standard technique to emulate the acoustic emission of cracks in concrete or steel bridges for early crack identification.

Da-Peng Zhou.et.al. [12] reported the use of time-resolved optical frequency-domain reflectometry for the measurement of distributed vibration or dynamic strain. The local Rayleigh backscatter spectrum shift of the vibrated state with respect to that of the non-vibrated state in time sequence has been used to determine dynamic strain information at a specific position along the fiber length. Standard single-mode fibers has been used as sensing head, and the result has been obtained using single mode fiber and are given for total length of 17m with the measured frequency range of 0-32Hz with the spatial resolution of 10m has been achieved.

A Masoudi.et.al. [13] proposed a distributed optical fiber sensor based on phase-OTDR to measure dynamic strain perturbations along 1 km of a sensing fibre. The technique is based on measuring the phase between the Rayleigh scattered light from two sections of the fibre and this allows multiple moving strain perturbation to be tracked and quantified along the entire length of the fibre. The demonstrated setup has a spatial resolution of 2 m with a frequency range of 500–5000 Hz and the minimum detectable strain perturbation of the sensor was measured to be 80 nε.

Robert R J Maier1.et.al. [14] has demonstrated Distributed transverse load sensing, along an extended length of polarization-maintaining (PM) fiber using using high spatial resolution (2 cm) optical frequency domain reflectometry (OFDR) which is based on recording a characteristic Rayleigh scatter ‘fingerprint’ of a single mode fiber.

Summary:

The above mentioned techniques have been successful in detecting the existence of the cracks but are quasi-distributed and reduced mobility. Fiber optic Sensors have recently gained acceptance in the sensing community for its inherent ability for multiplexing, immunity to EMI and inherent multiplexing abilities. Thus it is required to develop a fully distributed sensing system where each and every position along the fiber can act as the sensing element. Optical Time Domain Reflectometry (OTDR) has also been used for the purpose of fully distributed sensing system to find the positions of discontinuity along the length of fiber.

CHAPTER 3

DISTRIBUTED FIBER OPTIC SENSING SYSTEM

3.1 Overview

Fiber optic sensors respond to external perturbations by changing a property of the light flowing through them. This change can be used to measure the strength of the external perturbation. The principle of operation of the sensing mechanism of a fully distributed sensing system is discussed in this chapter.

3.1.1 Effects of crack on flow of light

It is known that flow of light within a waveguide will change due to change in properties of waveguide. Fiber optic sensing systems react to changes in their environment through a minute alteration of the properties of the light that travels through them. Light passing through a fiber that is attached to a wall, floor or other surface will remain undisturbed until the surface of the structure change. However any geometrical variation due to perturbation would cause physical shape variation in the optical fiber attached to the structure. These variations in shapes may induce the variation in the light path provided by the fiber. The way in which these changes are measured depends on the anticipated effect such as stress or temperature.

Usually optical-fiber contains buffer coating which allows the fiber to be bend insensitive. Once coating is removed sensitivity to external perturbation is increased and macrobending losses can be investigated.

3.1.2 Macro- bending effects

Macrobending of an optical fiber is associated with bending or wrapping the fiber. But for the slight bends, the loss is extremely small and is not observable. As the radius of curvature decreases, the loss increases exponentially until a certain critical radius of curvature loss becomes observable. So the amount of optical radiation from a bent radius depends on the radius of curvature and on the field strength at certain critical value along the radial axis. So for macrobending, the loss takes place when the radius of curvature of bend is larger then the radius of fiber cross section and it occurs in a fiber when it is turned around the corner. Coupling power from guided modes to radiation modes results in the signal strength loss. For any mode, some of the power travels in the cladding as the evanescent field. When a fiber is bent, evanescent field in the outer portion of bend must travels faster than the field in the core to remain in phase. As the distance from the fiber axis increases, the velocity of the evanescent field in that region must also, required to exceed the speed of light until some critical distance from the axis some amount of light is radiated away

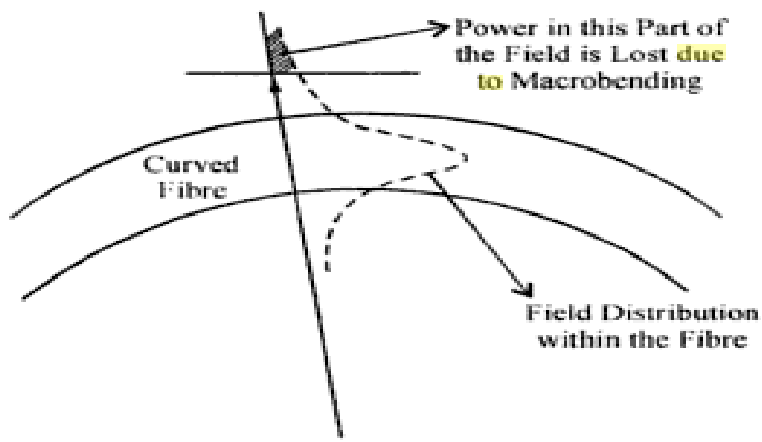


Fig. 3.1 loss mechanism in optical fiber due to macrobending

3.1.3 Light-intensity Perturbation in Optical Fiber due to Macrobending Effect:

Transmission of light through optical fibers can be explained by the Snell's law and the concept of total internal reflection. According to Fig. (3.2), as indicated by the refractive index 'n', when light travels from the fiber core that has a high refractive index into the cladding with a lower index, the light wave totally reflects back to the core. This is provided that the diameter of the core, and the refractive index of the core and cladding are chosen so as to force the light waves to propagate according to a certain critical angle of incidence. Many modes of light rays travel through a typical multimode optical fiber. Each successive mode propagates at an angle larger than the critical angle of incidence at the core to cladding interface. These modes stay within the core, and therefore no loss in optical intensity occurs. If the fiber is bent at any point along it's length, the change in the angle of incidence will cause some of the light rays to escape out by way of the cladding (Fig. 3.3). Consequently, higher-order modes that travel near critical angle of incidence enter the cladding and are lost. However, loss of higher-order modes does not significantly influence the intensity of light at the output end of the fiber.

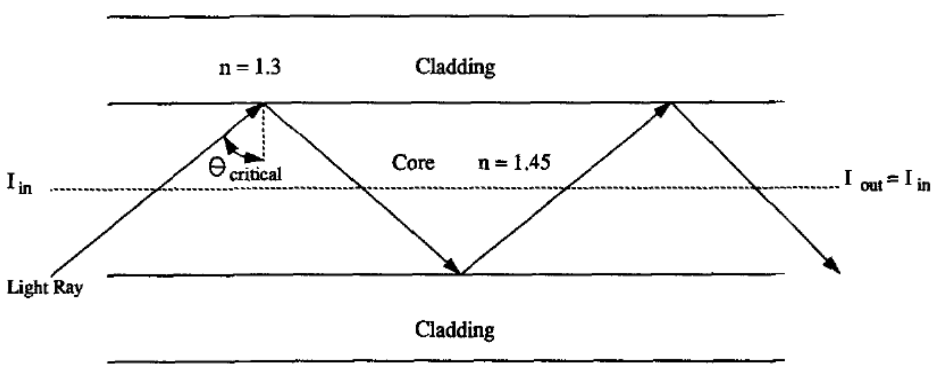


Fig. 3.2 basis for Light Transmission in Optical Fibers

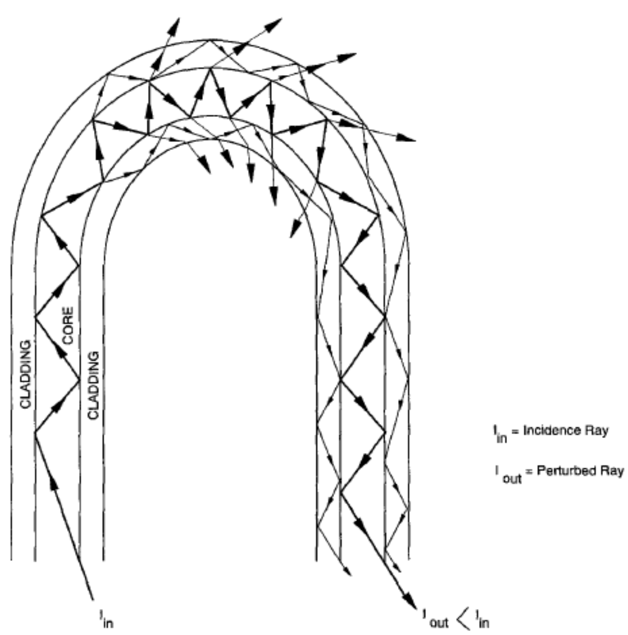


Fig. 3.3 light-intensity Perturbation in Optical Fiber due to Macrobend Effect

A major portion of the energy associated with the electromagnetic field is carried through the fiber by way of the fundamental modes. Fundamental modes of light propagate at angles much larger than the critical angle of incidence. These modes refract into the cladding only when the curvature of the bend is significantly increased beyond a critical level. The critical curvature varies from fiber to fiber, depending on the diameter as well as the optical and mechanical properties of the optical fiber. Reduction in the number of fundamental modes is associated with significant intensity loss at the output end of the fiber. Since fundamental modes propagate at angles within close proximity of one another, minute increases in the bend curvature beyond the critical level bring about large losses in intensity. The fiber-optic sensor developed measures the light intensity signal modulations due to crack opening displacements through a specific geometric arrangement. The curvature due to circular bend positions the propagation angles of the fundamental modes near the critical level. Crack opening displacements result in further bending of the bent optical fiber and a large decrease in light intensity. Optical fiber are made of thin silica glass strands, and therefore their embedment in structure will not alter or produce local damage to the material.

Macrobending is commonly modeled as tilt in the refractive index profile based on the radius of curvature of the fiber bend.

$$n_c^2(r,\theta) = n^2(r) + \frac{2n_1^2}{R} r\cos\theta \quad (3.1)$$

Where, n_c(r,θ) is a modified local refractive index dependent upon the fiber bend radius.

Effect of bend radius on macrobending is shown in fig(3.4). As for each curve the attenuation increases logarithmically as the bend radius decrease. In fig(3.4) attenuation increases at 1300nm for three step index profile are shown. The fibers have similar cutoff wavelength, but different refractive index delta value as measured by numerical aperture (A=0.253, B=0.188, C=.0.108)

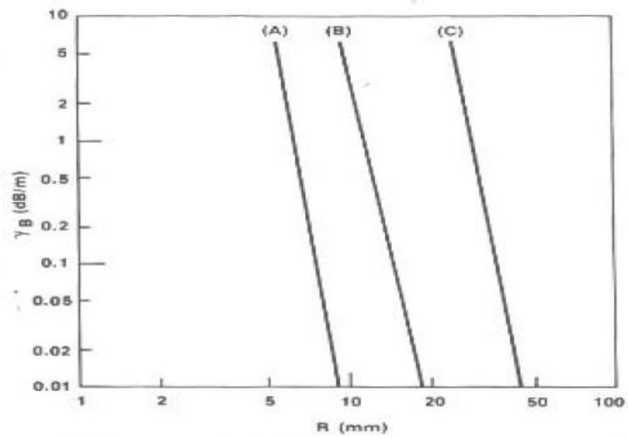


Fig.3.4 Macrobending attenuation

Macrobending attenuation at 1300nm for fibers with different numerical apertures. The attenuation increases exponentially as bend radius decreses. In general, as the refractive index delta or numerical aperture increases, the fiber can be bent to samller radius for similar loss**.**

3.2Distributed fiber optic sensing

Distributed fiber-optic sensing (DFOS) is a technique utilizing the very special properties of the optical fiber to make simultaneous measurements of both the spatial and temporal behavior of a measurand field. It offers a new dimension in the monitoring, diagnosis and control of large, extended structures of all kinds because of its capability of determining the spatial and temporal features of a measurand field with a medium which is non-intrusive, dielectric, passive, flexible and easy to install into existing structures.

Distributed fiber sensors can be divided into two types by the spatial continuity of the measurand:

- Fully-distributed sensors and
- Quasi-distributed sensors

3.2.1 Quasi-distributed sensing system:

A quasi-distributed fiber sensing (QDFS) system is one that only the prescribed sections of the fiber are sensitive to the measurand field. Fig (3.5).schematically shows examples of QDFS systems. Fig 3.5(a) illustrates time domain demodulation of the individual sensors and fig3.5 (b) shows the frequency domain demodulation system

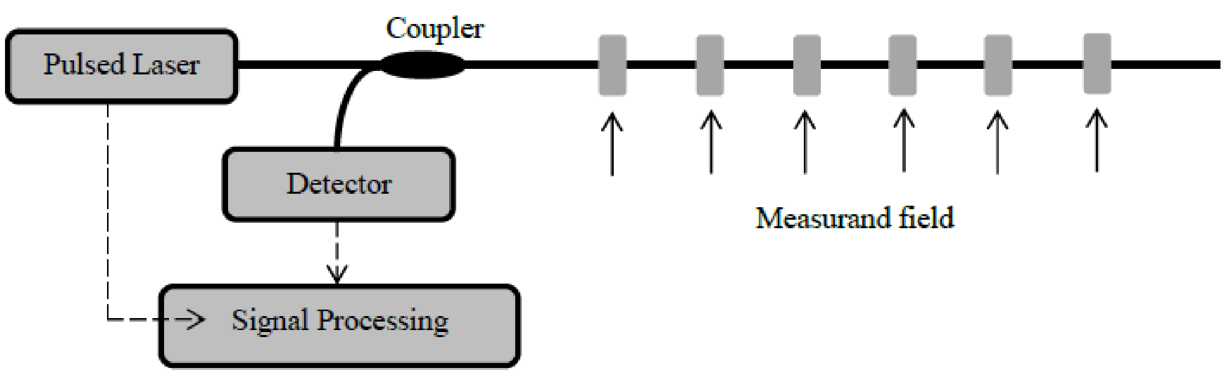


Fig. 3.5(a) QDFS systems illustrating time domain demodulation of the individual sensor

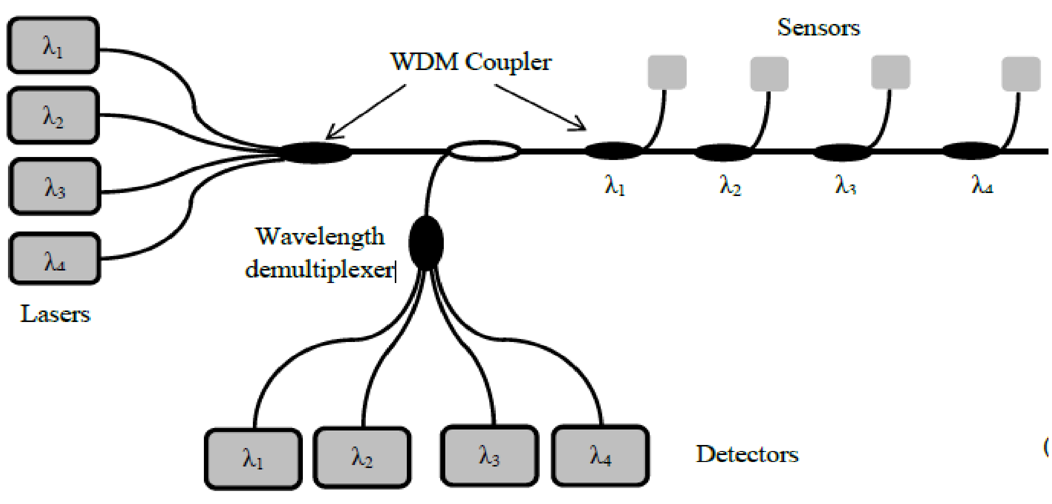


Fig.3.5(b) QDFS systems illustrating frequency domain demodulation system

There are several advantages of QDFS systems. The sensitivity can be relatively high because the sensors can be characterized specifically to the wanted measurand. The sensitive fiber section can be made arbitrarily small, leading to a good spatial resolution. Because the sensitive fiber regions are prescribed, their positions are known, leading to an easy identification of the spatial location of individual sensors

However, there are also some drawbacks in QDFS. The most important as well as the most obvious one is that all the sensing points in a QDFS system are fixed, which means the measurement can only happen in predetermined crucial locations. However, in practice, the need for detection is usually spatially random, especially in applications such as oil leakage detection, gas detection, and fire alarm. Also, there is always a limit on the maximum number of the sensors that can be multiplexed in a system, which is usually due to the attenuation of the interrogating light introduced by the sensing points or by the limitation of the demodulation techniques. And this makes QDFS not capable for long-span measurement, and even within the maximum multiplexing sensing points, to make a large number of sensors could be very time consuming and costly.

3.2.2 Fully distributed sensing sytem:

In order to overcome the limitation of QDFS, fully distributed sensing system come into existence in which instead of using a large number of point sensor, the entire length of the fiber act as a sensors. A fully-distributed fiber sensing (FDFS) system can detect parameters at any points along the fiber with a certain spatial resolution. Since the fiber is used for both sensing and light guiding, it is also called intrinsic distributed fiber-optic sensing.

The performance parameters which characterize a given DFOS systems are listed as follows, as illustrated in Fig 3.6.

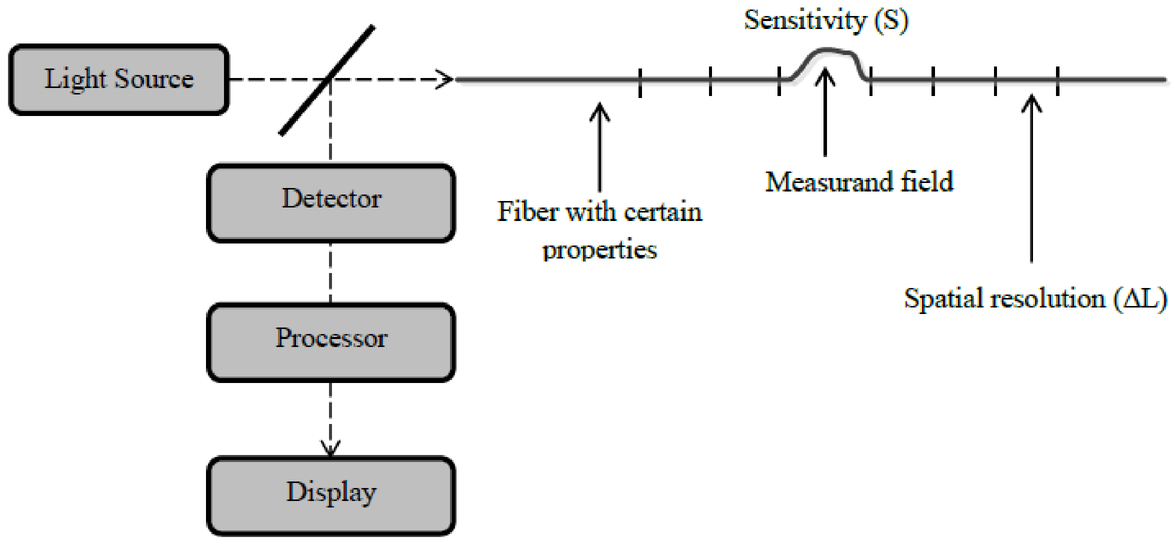


Fig. 3.6 fully distributed sensing system parameter performance.

(1) Spatial resolution (ΔL): is the smallest length over which any sensible change of the measurand can be detected (unit: meter). It is usually considered with the total fiber length (L).

(2) Sensitivity (S): is defined as the change in the detected optical power produced by a unite change of measurand field per unite length of fiber (unite: W/field/m).

(3) Measurement bandwidth (B): is the bandwidth over which the changes in measurand field can be measured for the full fiber length (unite: Hz).

(4) System bandwidth (W): is the bandwidth of the optical detector in the system (unite: Hz).

(5) Dynamic range (D): is the ratio of maximum to minimum values of the measurand field given the required accuracy (unite: dB).

(6) Measurement accuracy: is the accuracy with which the output power of the optical detector can be measured in the face of system noise levels (%).

(7) Fiber properties: the system specifications must include a specification of the fiber used in the system, such as the attenuation, geometrical properties, coating properties, and etc.

For any given specific application, there is always a strong trade-off among the above parameters in order to optimize the system performance. For any given specific application, there is always a strong trade-off among the above parameters in order to optimize the system performance. For example, the sensitivity will be greater when the measurement length is longer which means a worse spatial resolution. Therefore, there is a sensitivity/spatial resolution trade-off nearly in all measurement systems.

3.2.3 Advantage of fully distributed fiber optic sensing system:

- Having ability to measure over distance of several tens of kms without the need for any electric active component.
- Offer a great variety of parameter that can be measured so that multiple parameters can be mixed on same network.
- Cost effective as there are no special sensor embedded in cable making it very cost effective solution when large no. of measurement points are required.

3.2.4 Application of fully distributed fiber optic sensor:

As mentioned above, Quasi distributed sensing system are directional sensitive i.e; based on the position of placement of sensor on the structure. So in order to monitor a large structure it requires a large number of sensors which is quite inefficient method to monitor a large structure. Therefore to overcome this inefficiency Fully distributed sensing system come into existence which can monitor a large structure. Therefore fully distributed fiber optic crack sensor can detect multiple cracks and monitor their opening without any prior knowledge of crack location. Once the crack plane is known, an optical fiber can be coupled to structure so that it is making certain angle with the direction of crack opens, optical fiber needs to bend to maintain its continuity and this bend will induce loss of forward light power from the fiber core to the surroundings.

When the optical fiber is bent sharply, part of the light wave may leak into cladding and lost. An optical power meter can monitor the intensity in forward travelling light. However if only forward power is measured, the crack position cannot be located and cannot distinguish whether the loss is due to single or multiple opening. So it is required to monitor backscattered signal, the intensity of which is directly proportional to the forward light power in the core which will show a sharp drop across the crack. And this basic theory of distributed fiber optic sensor(DFOS) can be illustrated by an Optical Time-Domain Reflectometry (OTDR) system, which was the first effectively demonstrated DFOS system in 1976.

Summary:

In order to monitor a large structure quasi distributed sensing system requires a large number of sensors which is quite inefficient method to monitor a large structure. So to overcome this inefficiency, fully distributed sensing system come into existence which can monitor a large structure. Therefore, it is required to develop Fully Distributed sensing system for monitoring structure/material at each and every position of crack before it reaches damage threshold.

CHAPTER4

OPTICAL TIME DOMAIN REFLECTOMETRY

4.1 OTDR Principle

The OTDR characterizes a fiber-optic span, usually optical fiber sections joined by splices and connectors. The optical time domain reflectometer (OTDR) provides an inside view of the fiber, and can calculate fiber length, attenuation, breaks, total return loss, and splice, connector and total losses. Fig 4.1 (a) shows the schematic of an OTDR system, which consists of a pulsed laser, a detector, a coupler, data acquisition and a signal processor.

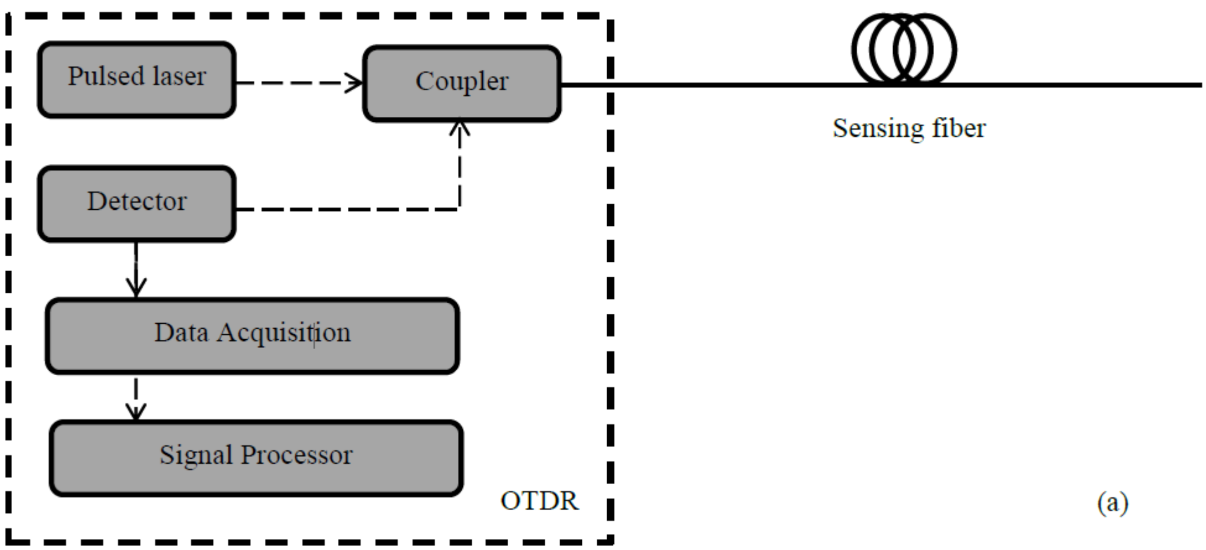


Fig.4.1schematic of an OTDR system

In this system, an optical pulse from the pulsed laser is launched into the fiber and the light is continuously backscattered as it propagates in the fiber because of Rayleigh scattering from the small inhomogeneities and impurities in the amorphous silica which is the fiber material. The backscattered light power was detected at the launching end and the distance it takes for the backscattered light to travel to the photo-detector is directly proportional to the time spent to travel within the fiber and is given by [23]:

$$d = \frac{\Delta t}{2v_g} \quad (4.1)$$

where d is distance traversed, Δt is time interval between sending and reception of pulses, v_g is the group velocity.

Backscattering of the light occurs due to the small variations in the refractive index of the fiber given by [23]:

$$P_{bs}(x) = P_{in}\left(\frac{v_g W}{2}\right)\alpha_r S e^{-2\alpha_r x} \quad (4.2)$$

where $P_{bs}(x)$ is the amount of backscattered light at any position along the length of the fiber, P_{in} is the amount of input optical power at the same position, v_g is the group velocity of the light, **W** is the pulse width, α_r is the Rayleigh scattering coefficient of the fiber and **S** is a backscattering coefficient given by [23] :

$$S = 0.38\left(\frac{N.A.}{n_1}\right)^2 \quad (4.3)$$

where N.A. is the numerical aperture of the fiber and n_1 is the refractive index of the core of the fiber.

At points of discontinuities within the fiber length, there is a strong reflection signal obtained in the OTDR spectrum which is shown in fig 4.2, which are denoted by peaks. These occur due to a rapid change in the refractive index of the core. The strength of the peak can be denoted by the Fresnel’s' reflection coefficient given by [24] :

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 \quad (4.4)$$

where R is the Fresnel’s' reflection co-efficient, n_1 is the core refractive index at any point along the fiber and n_2 is the core refractive index at the next position along the fiber length.

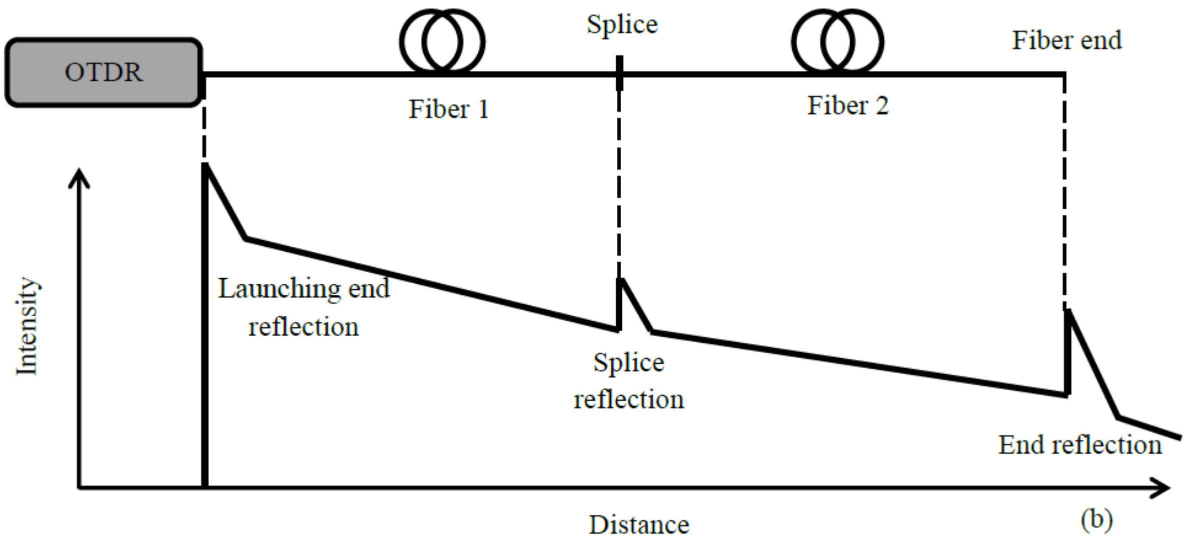


Fig. 4.2 a typical OTDR trace

Since the power of the received light decays as time increases, at the signal processor, the power of the back scattered light can be measured as a function of distance, by analyzing the time delay of the received light pulse compared with the reference point in the fiber. Figure 4.2 shows a typical OTDR return trace. The gradual decline of backscattered signal shown above without crack opening is due to attenuation or impurities present in manufacturing the fiber. The small drop correspond to bend loss at the fiber direction changing position. Those losses are negligible if the curvatures at those position are controlled to be small enough.

Therefore, if there is perturbation at any point along the fiber, the location can be determined by measuring the variation of the backscattering coefficient, and the spatial resolution depends on the temporal bandwidth of the light.

4.2Theory of Crack detection:

Following fig. illustrates the crack sensing principle with use of an optical fiber. When a light pulse is incident into the optical fiber from one end, the Rayleigh backscattered optical power is measured with an optical time domain reflectometer (OTDR) at the same end.

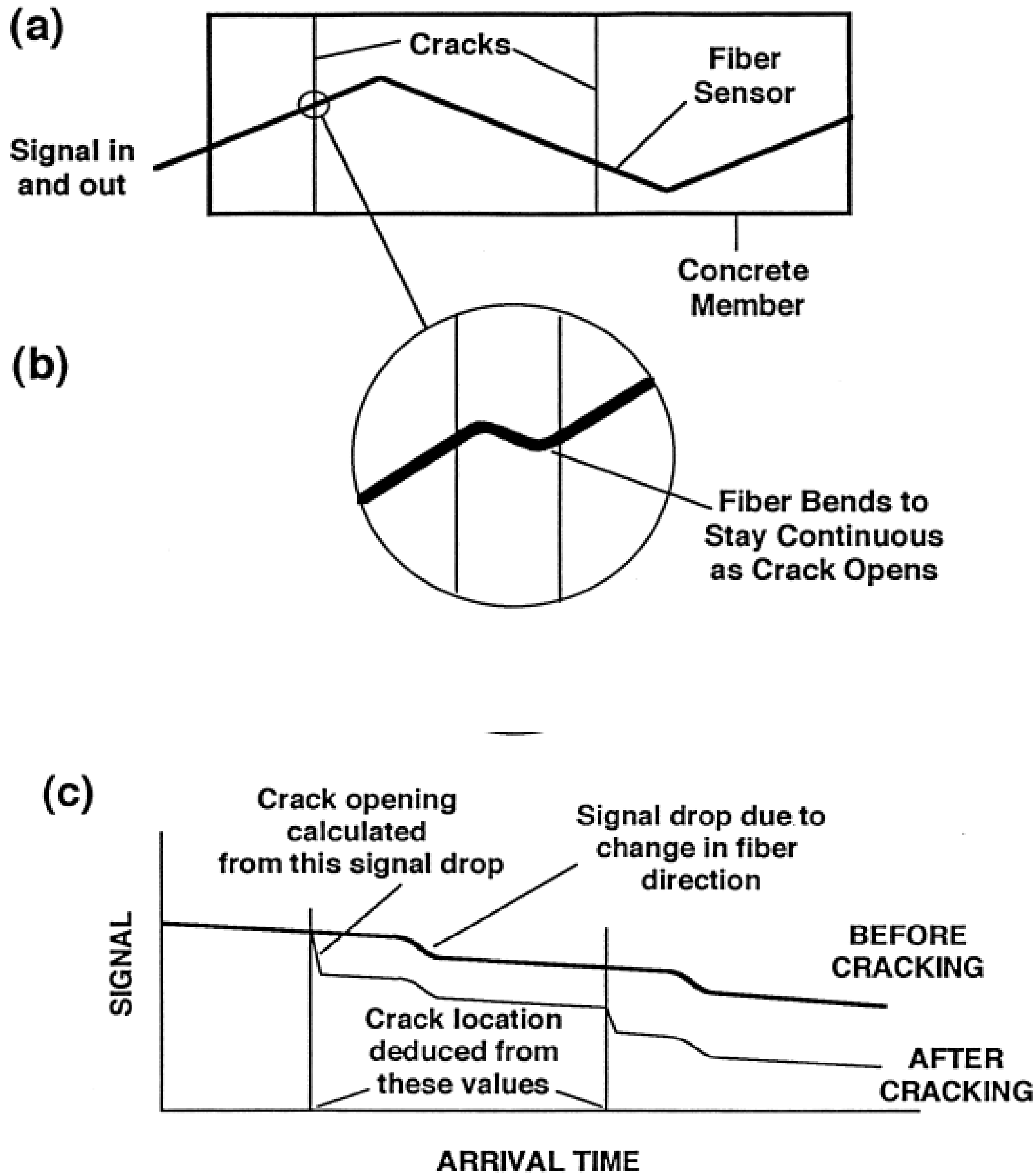


Fig. 4.3 illustration of crack sensing principle

Backscattered optical power at each and every position due to Rayleigh scattering is given by eq.(4.2). When the attenuation coefficient α is a constant from eq.(4.2), then its variation along the fiber is small without external perturbations such as strain, pressure, or cracks so curve will be relatively smooth and backscattered power in log-scale versus the distance travelled by light is a straight line as shown in fig 4.3(c).

But when crack intersects or cut the fiber then the fiber has to bend to keep its continuity and two bends will form in front of the crack faces as shown in Figure 4.3(b). This bend will cause the attenuation within the fiber and will induce optical power loss from the fiber core to its surrounding environment. As a result, the backscattered power will exhibit a sharp drop at the crack, as shown in Figure 4.3(c). The power drop due to macro-bending can be estimated in dB as [25];

$$loss = 10log_{10}\left(e^{-L\gamma_r}\right) \quad (4.5)$$

where *L* is the length of the fiber within the crack opening and bend loss coefficient is given by [25]:

$$\gamma_r = \sqrt{\frac{\pi a}{R}}\left(\left(\frac{V}{U}\right)^2 \frac{\sqrt{W}}{2a}\right)e^{\frac{4\Delta R W^3}{3aV^2}} \quad (4.6)$$

where ***a*** is the core radius, ***R*** is the radius of curvature of the fiber within the crack opening, *W* and ***U*** are the propagation constants derived from the Bessel function solutions, ***V*** is the normalized frequency of the light travelling through the fiber and ***Δ*** is the relative index difference.

When a crack opens in the structure, a fiber intersecting the crack has to bend to stay continuous (Fig. 4.3b). So in the curved portion (where the fiber changes in direction), bending loss may occur depending on the radius of curvature. When the fiber is bent, the increase in curvature may reduce the incident angle at the core/cladding interface to a value below the critical angle so some light energy will then move into the cladding and get dissipated. So the sudden bending of an optical fiber at the crack results in a sharp drop in the optical signal (lower line, Fig. 4.3(c)) and the resultant is reflected as an abrupt power drops in the OTDR spectrum.. From the time values on the OTDR record corresponding to the sharp signal drops, the location of each crack in the structure can be deduced by eq4.1.

CHAPTER 5

EXPERIMENTAL SETUP FOR CRACK DETECTION USING OTDR

The experimental setup for performing the experiment related to fully distributed crack sensing using OTDR and optical fiber is as shown in Fig.5.1

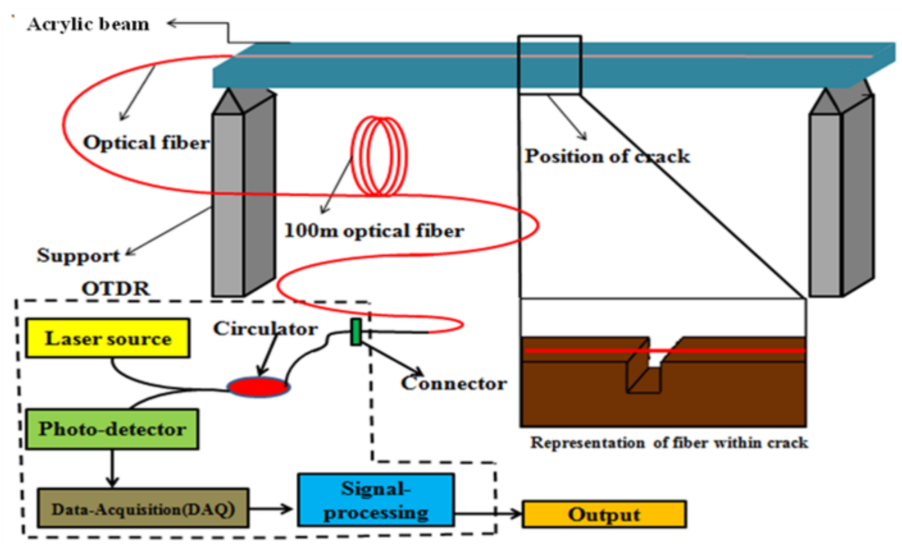


Fig 5.1 Experimental Setup for determination of crack characteristics

For the experiment we have used SMF28e single mode fiber. This single mode fiber has been attached to an acrylic beam having dimension of $20.5 \times 2.8 \times 0.3$cm. The fiber has been stripped of its acrylic buffer coating to increase sensitivity and attached with resin based adhesive to ensure the transference of strain without breakage in the fiber. Before attaching the fiber to the structure having a crack on it, a spool of 100m long length optical fiber has been placed. An EXFO FTB-150B hand held OTDR operated in continuous, real time mode with an input wavelength of 1550nm has been used to determine the position of cracks or any faults within the fiber. A spool of 100m long fiber is linked with the OTDR before it is attached to the structure so that very weak backscattered signals from the crack will not be overwhelmed by strong pulse created at the bulkhead connection. This 100m long length placed before the crack in order to reduce the pulse intensity and reduce the optical power and increase the sensitivity at the sensing position.

Light is injected in the form of pulses into an optical fiber from the laser source. The light propagating in forward direction along the optical fiber is modulated with the interaction of crack within the structure. The pulse of light is scattered at the position of cracks or on perturbation within the fiber. The amount of light that has been backscattered will pass through circulator and picked up by photo detector. As per the principal of OTDR, intensity of backscattered light provides the information of desired perturbation or crack along the fiber and the time difference between sending of pulses and reception of backscattered light yields the position of perturbation according to eq.4.1

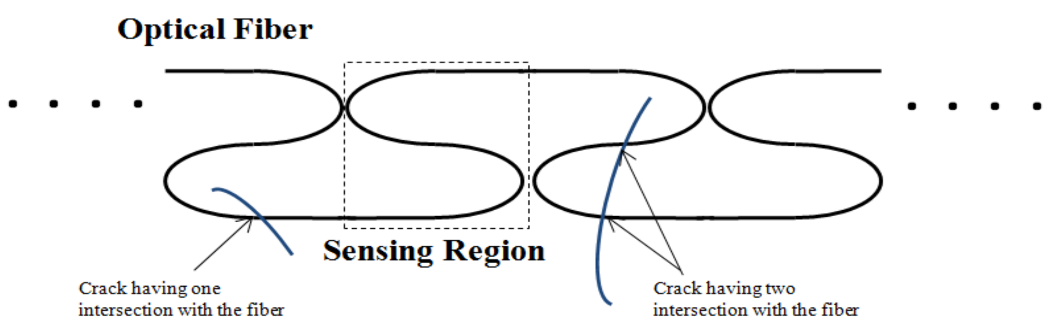


Fig. 5.2 Proposed fiber lay-out.

The proposed layout and sensing head mechanism consist of a fiber tied in the shape of 'S'. 'S' type configuration has been mounted on several acrylic beam as a fiber layout with the use of resin based adhesive to test its performance for crack detection. This 'S' type configuration has been proposed in order to increase the sensitivity for crack detection in a fully distributed sensor configuration. According to eq.4.5, when crack opening will increase, the radius of curvature will also increase causing the enhancement in macrobending losses. Thus in order to increase the sensitivity of distributed sensing system without sacrificing the resolution, this configuration has been used. As the spatial resolution of OTDR determines the sharpness of power drops obtained in OTDR spectra. Spatial resolution of EXFO 150B is given by $\pm(0.75 + 0.0025\%X)m$, hence this accounts

for more gradual losses instead of power losses. Thus in order to overcome this limitation 'S' type configuration has been used with the increment in sensitivity and keeping the resolution constant in a fully distributed manner in order to measure the multiple cracks. In this configuration, total length of fiber within a single 'S'configuration is chosen of order of the spatial resolution of OTDR used. When the crack develops and propagates, it intersect the different segments of the fiber in one 'S' configuration. Hence the amount of power drop shown in OTDR spectrum is dependent on the number of intersection that occur between the crack and fiber layout. The total loss can be estimated using:

$$Loss_{total} = I \times n \times 10log_n(e^{(-2L_r)}) \quad (5.1)$$

where '*n*' is the number of intersections between the crack and the fiber and '*I*' is the total losses incurred at the bends of the 'S'-structure.

Several samples have been fabricated by attaching optical fiber (without buffer coating) to the acrylic sheets using resin based adhesive along the axis of fiber. Sample used are:

- Specimen 1 contains fiber attached along the axis of structure.
- Specimen 2 contains fiber attached to the structure at certain angle.
- Specimen 3 contain fiber attached by using the 'S' type of fiber layout on structure..

Fig. 5.3(a): Specimen1

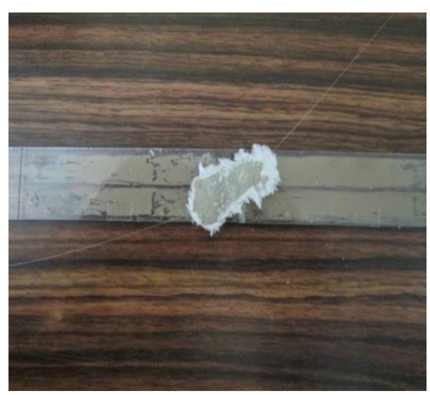


Fig. 5.3(b): Specimen2

Fig. 5.3(a): Fiber attached along the axis of structure

Fig. 5.3(b): Fiber attached to the structure at certain angle

Fig. 5.3(c): Specimen 3

Fig.5.3(c): Fiber attached using 'S' type fiber lay out

Specification of components:

The specifications of the instruments are listed below:

- **Single mode optical-fiber(SMF-28e):**

Performance characterization:

- Core diameter: 8.2μm
- Versatility in 1310nm and 1550nm application.
- Numerical aperture: 0.14
- Cable cut-off wavelength: $\lambda_{ccf} < 1260nm$
- Rayleigh backscattering-coefficient:

  1310nm- 77dB

  1550nm- 82dB
- Attenuation:

Wavelength (nm)	Attenuation(dB/km)
1310	< 0.35
1550	< 0.22

Acrylic beam:

Fig.5.4(a)

Fig.5.4(b)

Fig 5.4 showing acrylic beam and crack developed over beam.

Specification of Acrylic beam used:

All beams used are of following specification:

Length	62.9cm	95.9cm	96.5cm
Breadth	2.2cm	2.3cm	2.1cm
Height	0.6cm	0.9cm	0.5cm

Properties of Acrylic beam:

- Specific gravity- 1.19

Mechanical strength	Modulus of elasticity
• Tensile	400,000 psi
• Compressive	430,000 psi

- Refractive index- 1.49
- Light transmission- 92%
- Coeff. Of thermal conductivity- 5.104

EXFO- 150 FTB- Compact OTDR:

Main features of FTB 150:

- can be used with the FTB-400 Universal Test System (refer to *FTB-400* Universal Test System user guide) and the unit.
- offer impressive dynamic range with short dead zones
- perform quick acquisitions with low noise levels to enable accurate low-loss splice location
- acquire OTDR traces made of up to 128 000 points that provide a sampling resolution as fine as 4 cm
- Include a light source and can include an optional visual fault locator.

Fig5.5 EXFO 150FTB

Specification of OTDR used:

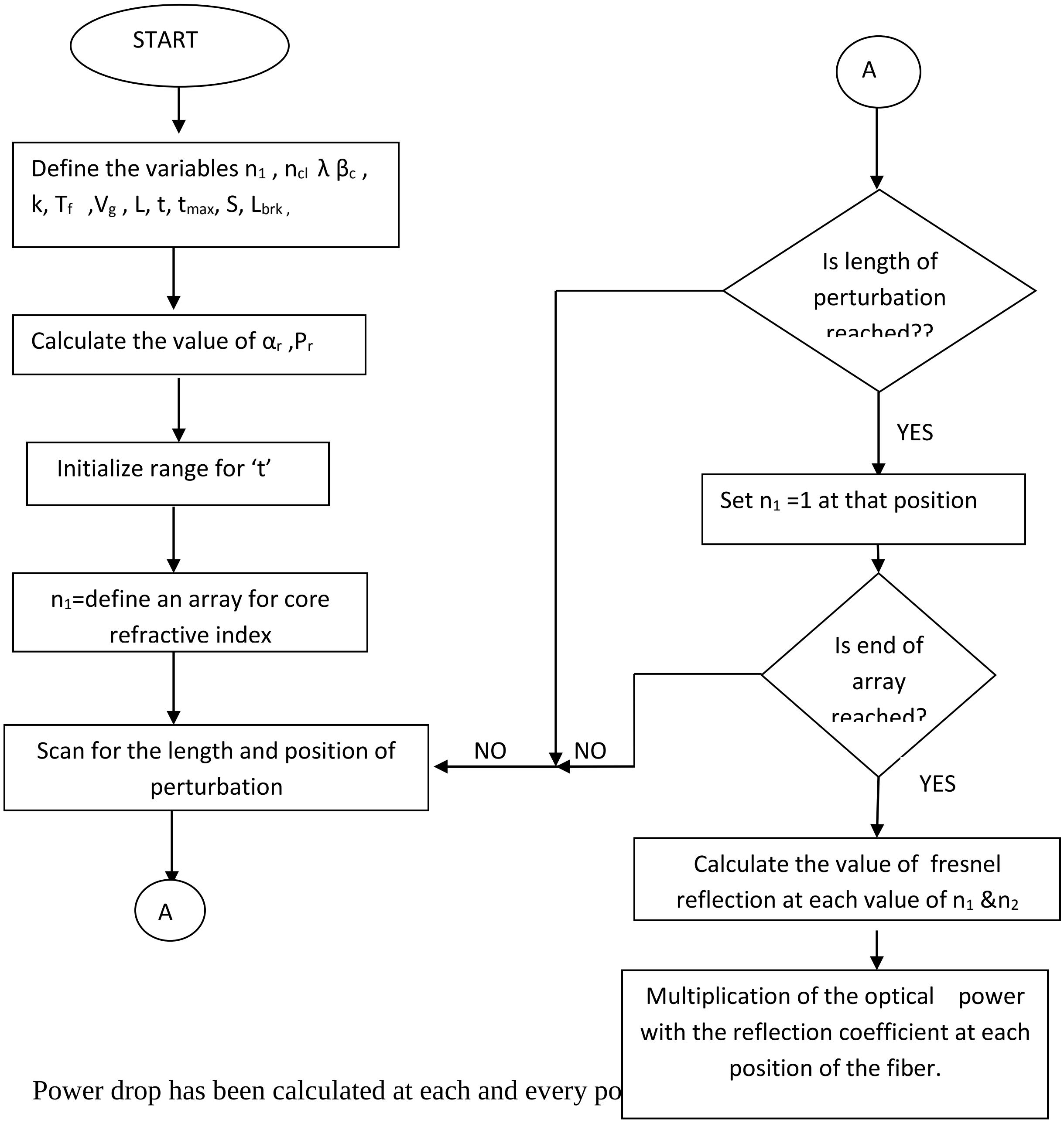
Model	**Wavelength used(nm)**	**Dynamic range(dB)**	**Event dead zone(m)**	**Attenuation dead zone(m)**
FTB-150-QUAD/FTB	$850 \pm 20/1300 \pm 20$ $1310 \pm 20/1550 \pm 20$	27/26 37/35	1/1 1/1	3/4 4.5/5
Distance range (km)	Multimode: 0.1, 0.3, 0.5, 1.3, 2.5, 5, 10, 20, 40 Singlemode: 1.3, 2.5, 5, 10, 20, 40, 80, 160, 260			
Pulse width (ns)	Multimode: 5, 10, 30, 100, 275, 1000 Singlemode: 5, 10, 30, 100, 275, 1000, 2500, 10 000, 20 000			
Launch conditions	Class CPR 1 or 2			
Linearity (dB) •	0.03			
Loss threshold (dB/ dB)	0.01			
Loss resolution (dB)	0.001			
Sampling resolution (m)	Multimode: 0.04 to 2.5 Singlemode: 0.04 to 5			
Sampling points	Up to 128 000			
Distance uncertainty (m)	$(\pm 0.75 + 0.0025\% of X distance)$			
Measurement time	User-defined (60 min maximum)			
Real time refresh(s)	Guaranteed<= 0.4			
Stable source output power(dB)	-1.5(-1300nm), -7(1550nm)			

CHAPTER 6

RESULT AND DISCUSSIONS

6.1 Simulation Results of OTDR Spectra

Simulations were performed to evaluate the nature of OTDR spectrum in the presence of several perturbations. The flow chart for the procedure is as shown in fig 6.1



Power drop has been calculated at each and every po

respect to Rayleigh scattering as given by eq 4.2. Entire fiber is characterized by singular

Fig. 6.1 Flow chart for simulation of OTDR spectrum

value of core ... ınical splice

there is smal ... ’. So at the

position of patch or mechanical splice refractive index array values are changed to ‘1’. To determine the reflection from this patch splice, Fresnel reflection has been evaluated at those position and multiplied with the power at that position.

Results:

Implementation of flow chart as shown in fig with the use of eq.4.2 & eq.4.4 yields the graph shown in fig6.2 for the condition stated in table no 6.1

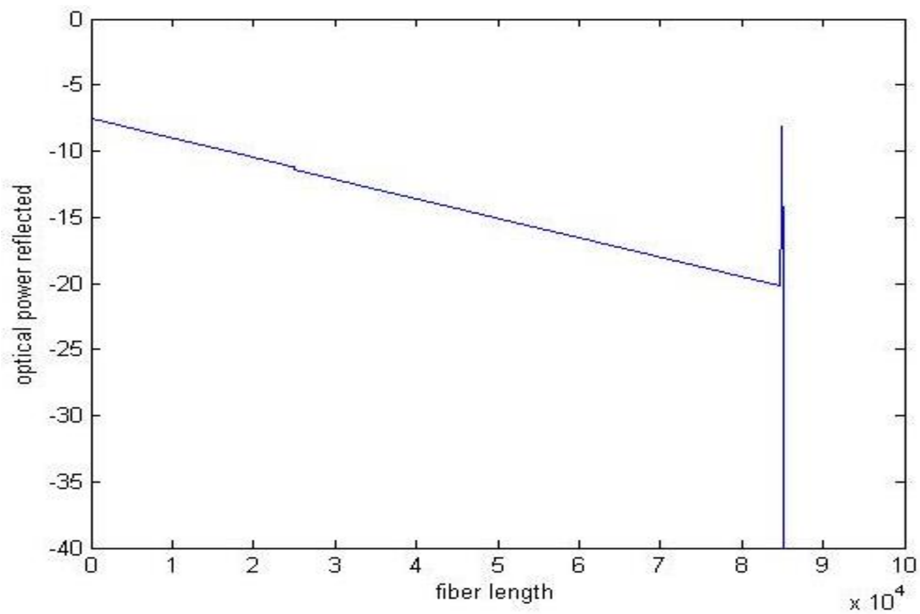


Fig6.2(a) Simulated spectrum showing fiber end break and splice position

Table 6.1: Amount of power loss with different parameters						
Wavelength	**n_{cl}**	**n_{co}**	**Fiber length**	**Fiber end break**	**Splice position**	**Splice loss**
1500nm	1.460	1.466	100km	85km	25km	0.20dB

Fig 6.2(a) shows the simulated result obtained from the flow chart that has been mentioned above (fig.6.1). Graph showing the splice loss and fiber end break. Due to splice loss it is showing a very small amount of power drop due to very small change in refractive index at the specified position of 25km. At the point of 85km i.e; fiber is

showing prominent peak due to rapid change in refractive index from core refractive index of 1.466 to 1.

OTDR spectra for splice loss and fiber end break:

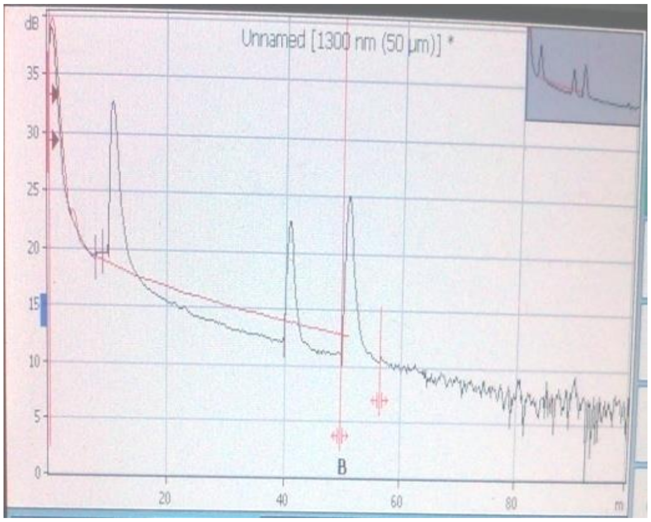


Fig.6.2(b) OTDR spectrum

The above figure shows the entry reflection loss, splice loss due to patch joint and fiber end break obtained in OTDR.

Table 6.2: OTDR spectrum for different patch joints and fiber end break.	
Fiber length	**Patch joint**
50m	10m, 40m

6.2 Simulation for crack:

Simulations were performed to evaluate the power drop due to the presence of several cracks. The flow chart for the procedure is as shown in fig 6.3

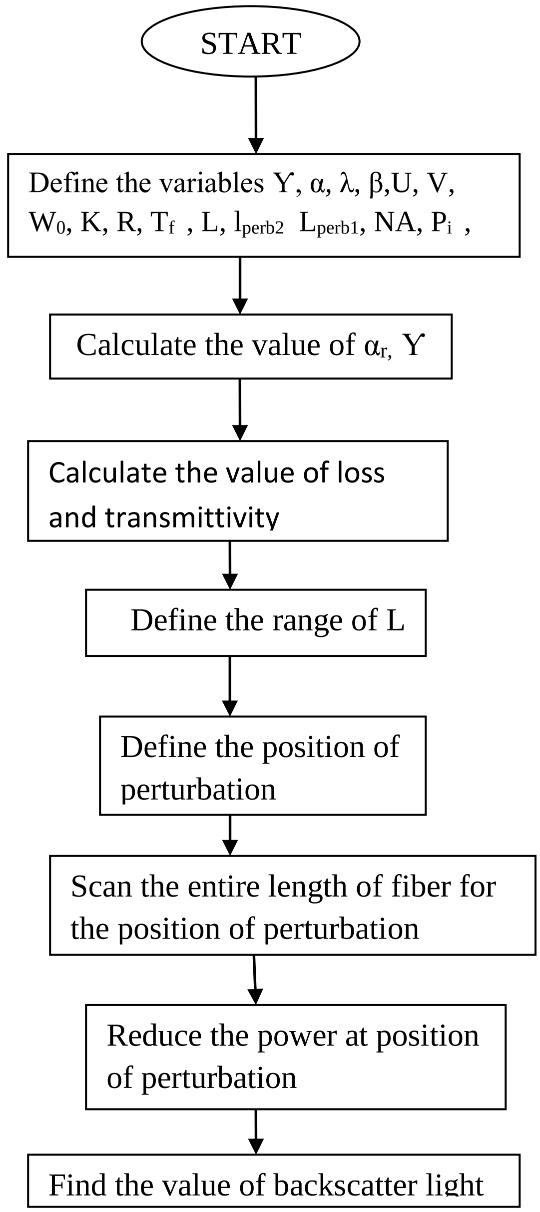


Fig.6.3 Flow chart for simulation of cracks

Amount of light that has been reflected back with respect to input power is termed as reflectivity and amount of light that has been refracted back with respect to input is defined as transmitivity and this transmitivity has been calculated at each and every position along the entire length of the fiber. But in the presence of crack, there will be loss in the initial that is being transmitted and will be calculated at that position by eq.4.2

Power loss due to crack:

Simulation has been performed for the detection of multiple crack shown in fig.6.4(a) & (b)

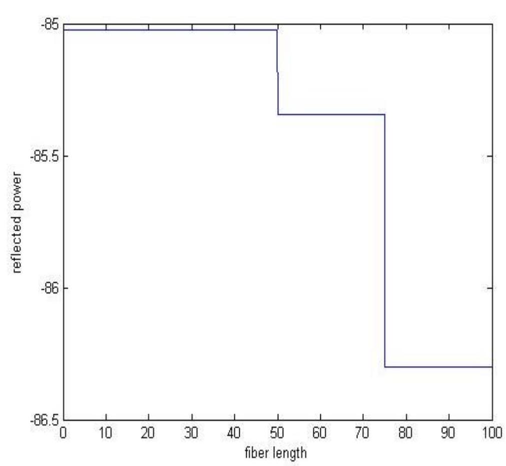


Fig. 6.4(a)

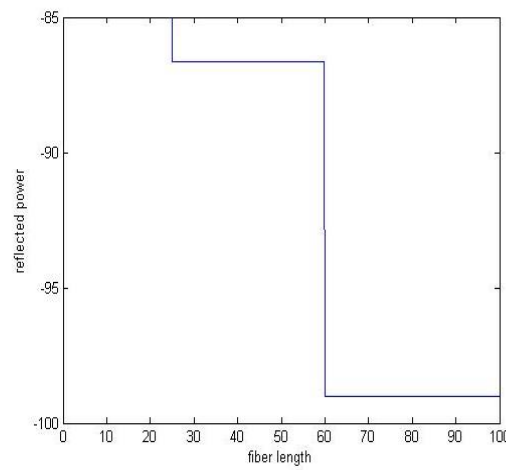


Fig6.4(b)

Fig.6.4. simulation of OTDR spectra with power drops due to crack at different position

Table 6.3: Power drops due to crack at different position		
Fig no	**Length of fiber**	**Perturbation position**
Fig 6.4(a)	100m	50m, 75m
Fig6.4(b)	100m	25m, 60m

Fig 6.4(a) and (b) showing the amount of power reflected back at different point of perturbation specified along the length of the fiber**.**

As for simulation of crack which has been shown in the flowchart of fig 6.3 , it is specified the position of perturbation at different points. And for a single mode bent fiber of length, pure bend loss has been described by eq.4.5. As the position of perturbation has been met along the length of fiber, there will be drop/loss which is calculated by the multiplication of the pure bend loss and transmittivity of the fiber given by following eq.(4.5). So above figure (fig6.4 (a) & (b)) shows a sharp power drop at the specified position of perturbation.

Power loss versus crack opening:

Fig. 6.5 showing Simulated loss of light in the presence of crack.

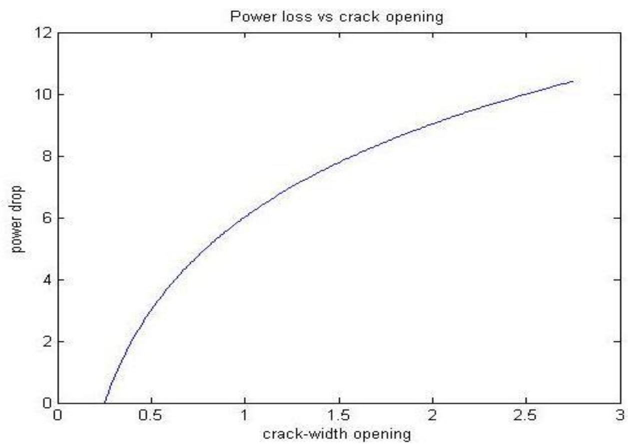


Fig6.5 Increase in power loss with crack face opening

Fig.6.5 validates the OTDR spectrum obtained by showing the relation between crack opening and power loss. As shown in fig 6.5 above for the initial crack with the little amount of opening power loss will be small but as the crack opening increases power loss will also increase depending up on fiber length within the crack space and radius curvature.

Power loss to amount of fiber within crack space:

Fig 6.6 (a) & (b) showing the power loss change by changing the fiber within crack space and keeping the bend radius constant.

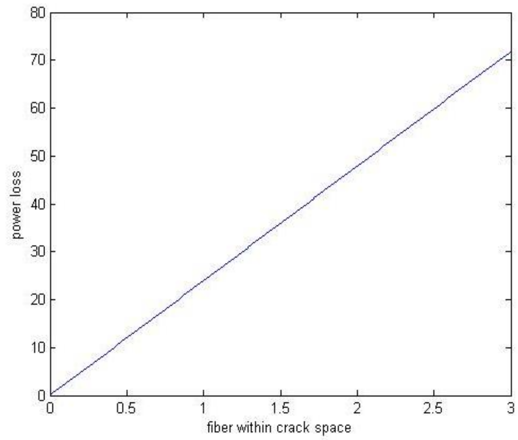


Fig. 6.6 (a)

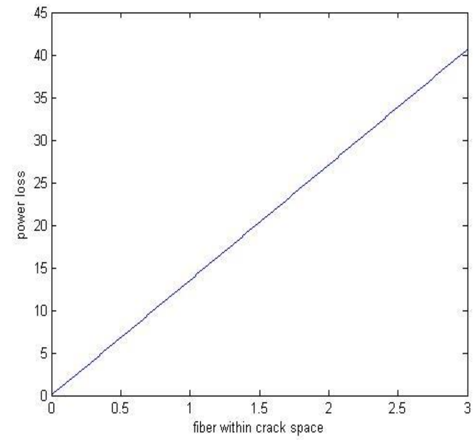


Fig.6.6 (b)

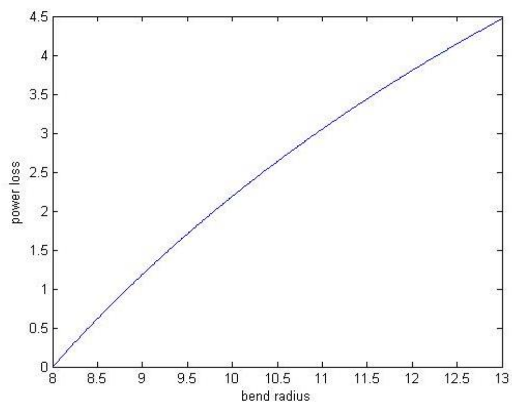
Fig 6.6 Increase in power loss with varying amount of fiber within crack space

Table 6.4: Power drops with varying amount of fiber within crack space.		
Fig no	**Fiber within crack space**	**Bend radius**
Fig6.6(a)	0.01-3mm	8mm
Fig6.6(b)	0.01-3mm	25mm

Graph shown above (fig 6.6(a) & (b)) is showing the power loss versus fiber within crack space keeping the bend radius constant. Bend loss due to perturbation given by eq(4.5) shows the relation between loss and fiber within crack space and radius of curvature. Fig 6.6(a) showing a greater power loss due to smaller bend radius and fig 6.6(b) showing a lower power drop with respect to larger bend radius as compared to smaller bend radius.

Relation of Power loss to Bend Curvature

Fig.6.7(a) &(b) showing the amount of power loss due to varying amount of bend radius and keeping the fiber within the crack space constant.



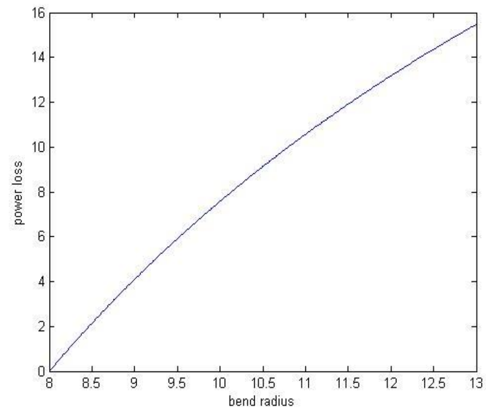


Fig6.7(

a) Fig6.7(b)

Fig 6.7 Increase in power loss with varying amount of bend curvature

Table 6.5: Power drops due to varying amount of radius of curvature		
Fig no	**Bend radius**	**Fiber within crack space**
Fig6.7(a)	8-13mm	0.866mm
Fig6.7(b)	8-13mm	3mm

Graph shown above is showing the pure bend loss versus bend radius relative to the fiber axis. As there will be any perturbation or crack in the structure then the fiber attached to it will also deformed or bend and due to this bend the radius of curvature will also reduce. And if the bend will increase, the radius of curvature will also reduce. Through this reduction in radius of curvature, bend loss will be calculated by eq.4.5. This bend loss coefficient will give the pure bend loss occur at the position of crack or perturbation given be eq4.6.

As from the interpretation of graph and from eq.4.6 mentioned above, power loss due to crack is dependent on both the factors i.e; fiber within crack space and radius of curvature. Fig(6.7) showing the constant value of fiber within the crack space and varying amount of bend radius and fig(6.6) showing the constant value of bend radius and varying the length of the fiber within crack space. Due to these two factors power loss is changing i,e while keeping the fiber within crack space constant and changing the bend radius from a lower value to higher value and power loss will increase i.e for smaller bend radius power loss will be more shown in fig 6.6(a) and for larger bend radius power loss will be small as compared to smaller bend radius as shown in fig 6.6(b).

6.3 Experimental Result:

6.3.1 Using Specimen 1 & 2 fiber layout:

Fig.6.8 (a) & (b) shows the experimental result obtained by specimen 1 with different amount crack openings.

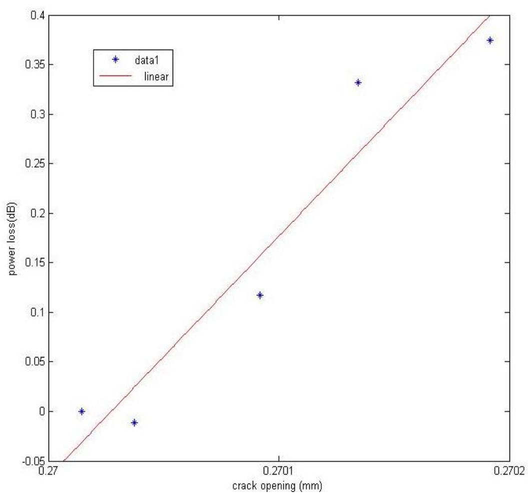


Fig.6.8(a)

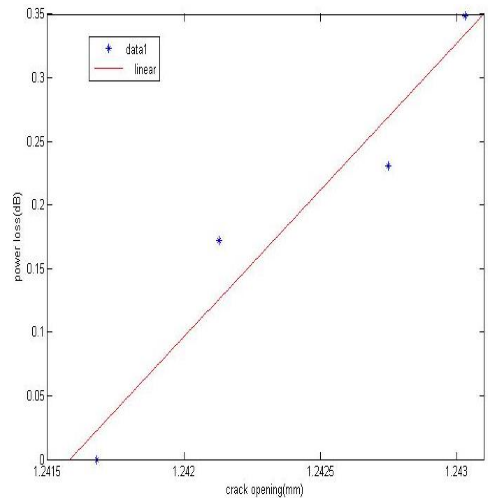


Fig6.8(b)

Fig 6.8 Increase in power loss with varying amount of crack opening by Specimen 1

Table 6.6: Power drops with the increase in initial crack opening				
Fig no	**Initial crack opening**	**Beam length**	**Breadth**	**Thickness**
Fig6.8(a)	89-88.73mm	95.9cm	2.3cm	0.9cm
Fig6.8(b)	85.31-85.22mm	62.9cm	2.2cm	0.6cm

Results has been obtained by performing experiment by laying an optical fiber over the acrylic beam having specified dimension above with the initial crack opening. Graph obtained showing the power loss with the different amount of crack opening. With the large amount of crack opening, power loss will also increase as shown in fig 6.8(a) depending on the amount of fiber within crack space and bend radius. Fig 6.8(a) and fig6.8 (b) has been obtained by specimen 1 with the different amounts of crack opening.

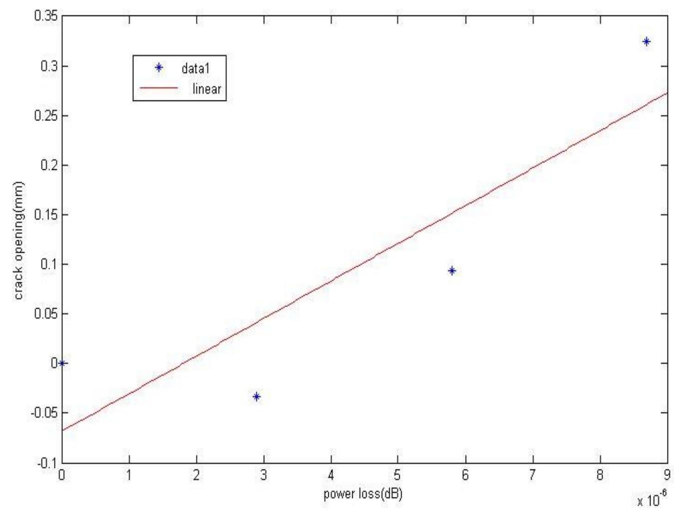


Fig. 6.8(c) Increase in power loss with varying amount of crack opening at certain angle by Specimen 2

Table 6.7: Power drop with increment in initial crack opening at certain angle					
Fig no.	**Initial crack opening**	**Length**	**Breadth**	**Thickness**	**Angle**
Fig6.8(c)	85.31-85.22mm	96.5cm	2.1cm	0.5cm	10degree

Graph shown above has been obtained by using specimen 2 inclined at an angle of 10 degree and having initial crack specified above. As shown in fig6.8 (b) above with the fiber layed along the axis of structure with the same crack opening has more power loss observed in comparison to the specimen 2. The reduction in power loss which is shown by eq.4.2 is dependent on both the factors i.e; length of fiber within the crack space and radius of curvature. As by using the specimen 2 length of the fiber within crack space has been increased and radius of curvature has also been increased so the cumulative effect of loss has been reduced with the use of specimen 2 according to the eq.4.6. Therefore it is showing the reduction in power loss with the same crack opening which has been used for the specimen 1

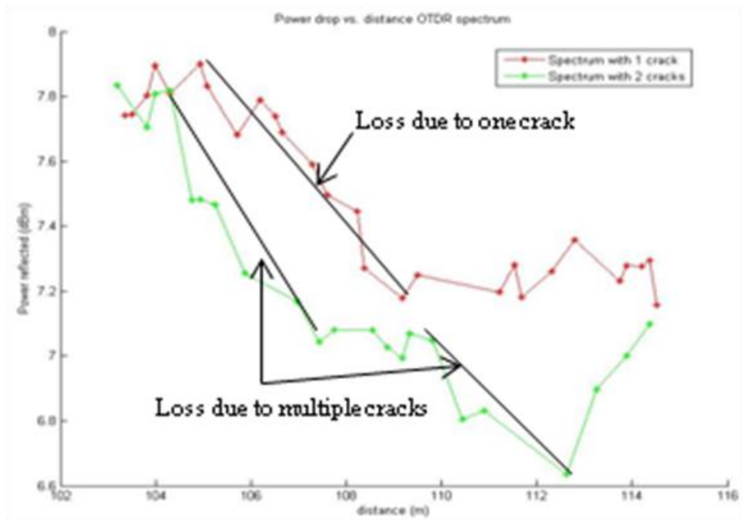


Fig.6.9 Practical OTDR spectra for crack location

Fig6.9 depicts the experimentally obtained spectra recorded in OTDR, for the localization of multiple cracks along the fiber length. In Fig.6.9, the red trace shows the power drop due to a single crack at approximately 106m, the green trace shows the power drop signature twice at 105m and 111m due to two different cracks. The amount of power drops for the two cracks of the green trace is also different due to variations in crack opening. The spatial resolution of the OTDR determines the sharpness of the power drops obtained in the OTDR spectra. In the present case, the spatial resolution of the OTDR is given by $\pm(0.75 + 0.0025\%\ x)m$. Hence, this accounts for the more gradual losses instead of sharp power losses as shown in Fig 6.4

6.3.2 Using S type of fiber layout:

Fig.6.10(a) & (b) shows the optical power losses obtained using the 'S'-layout with the crack intersecting the single strand and two strand of the configuration respectively.

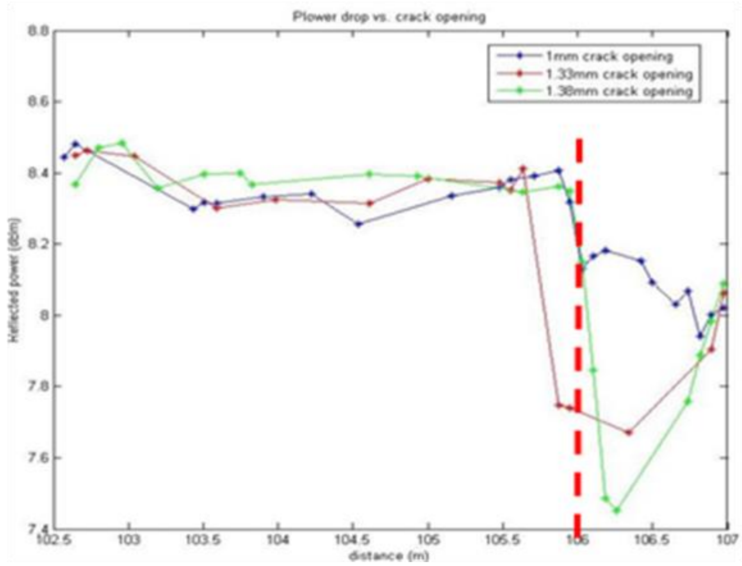


Fig 6.10(a) OTDR spectra for a single intersection of crack face and fiber.

Fig 6.10(a) shows the recorded OTDR spectra for a crack intersecting only a single strand of optical fiber over the crack opening. The power losses are shown to increase with an increase in the crack opening.

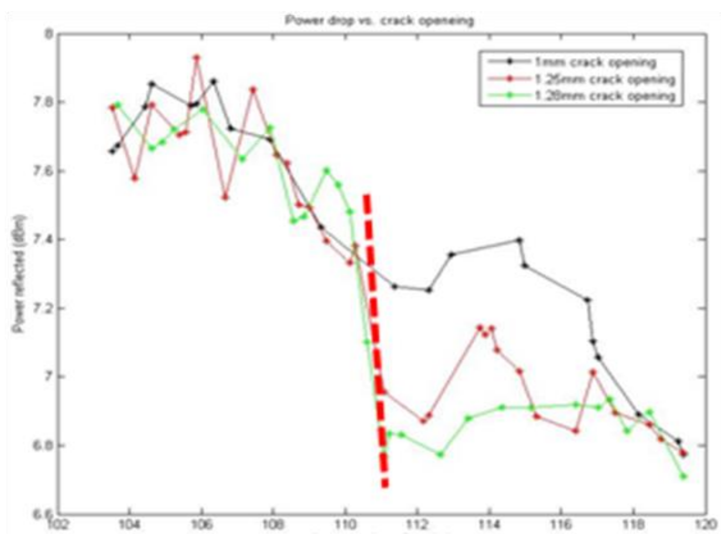


Fig.6.10(b) OTDR spectra due to two intersections between crack openings and the fiber.

Fig.6.10(b) shows the optical power losses obtained using the ‘S’-layout with the crack intersecting two fibers of the configuration. The 'S'-configuration increases the sensitivity by introducing a greater length of the fiber between the crack openings. The power drop in Fig 6.10(b) is significantly larger than for a single strand within the crack face.

Table 6.8: Increase in power drop with increase in crack opening			
For single intersection		**For Multiple intersection**	
Crack opening(mm)	**Power drop(dBm)**	**Crack opening(mm)**	**Power drop(dBm)**
1mm	8.1	1mm	7.25
1.33mm	7.75	1.25mm	6.85
1.38mm	7.5	1.28mm	6.5

Table 6.9: Summary of Sensitivity for ‘S’ type fiber layout	
Fig no	**Sensitivity**
Fig no 6.10(a)	1.97dBm/mm
Fig no 6.10(b)	2.83dBm/mm
Increase in sensitivity: 1.43dBm/mm	

The sensitivity has been increased from 1.97dB/mm to 2.83dB/mm, approximately 1.43 times with every intersection between the crack opening and the fiber. The total length of the fiber, within each of the sensing regions of the proposed configuration, is of the order of the spatial resolution of the OTDR. This enables enhancement of sensitivity, without loss of accuracy

CHAPTER 7

CONCLUSION

7.1 Conclusion

Development and propagation of cracks can be detrimental to the operation of an engineering structure and causes the failure of structure due to fatigue or harsh environmental condition. Many techniques has been proposed and implemented for detection of cracks within the structure such as Radio Frequency Identification (RFID) , Piezo-Electric Transducers (PZT) and Multiple Sequential Image Filtering . But there are several disadvantages of these techniques which prohibit the use and application of these techniques as fully distributed sensing system. Fiber optic Sensors have recently gained acceptance in the sensing community for its inherent ability for multiplexing, immunity to EMI and inherent multiplexing abilities.

The present work uses standard telecommunications optical fiber (SMF28e) and EXFO 150-TB commercial OTDR to demonstrate a multiple crack detection mechanism. Simulation has been performed to evaluate the response of light flowing through optical fiber in the presence of single / multiple cracks. Response of light and modulation of light propagating within the fiber in the presence of singular or multiple cracks has been practically obtained using OTDR

A novel 'S' type fiber layout has been developed for the crack localization in real time using the OTDR technique and single mode optical fiber. 'S' type layout has shown to have greater sensitivity to cracks and hence proven to be a more effective configuration for detection of cracks. The 'S' type configuration allows an increase in the sensitivity to the crack, while improving the spatial resolution of the OTDR. Results have shown an increase in the sensitivity by 1.43 times allowing a greater chance of signal pickup from the OTDR. Therefore such a sensing system would be highly useful in the determination of the position and characterization of cracks in an engineering structure.

7.2Future scope of work

In our work, we have developed fully distributed sensing system to detect multiple cracks. However this work can be extended to develop more efficient and reliable fully distributed sensing system with enhanced crack detection mechanism using different types of optical fiber sensor.

The novel ‘S’ type sensor that has been proposed for crack detection can be advanced so that the optimum shape and length can be determined according to an application without sacrificing resolution and sensitivity.

Artificial Neural Network and other pattern recognition methods can also be implemented to enhance the sensitivity, accuracy and noise immunity of the system for the crack detection system. Different pattern recognition methods can be implemented to determine the specifications of the crack, such as the crack opening, length and also for real time monitoring, in terms of crack propagation rate.

REFRENCES

[1]. Farhad Ansari, and Rajendra K. Navalurkar “Kinematics of crack formation in cementitious composites by fiber optics” Journal of Engineering Mechanics, Vol.119, 1993, pp.1048-1061.

[2]. Christopher K.Y. Leunga, Niell Elvinb, Noah Olsonb, Theodore F. Morsec, and Yi-Fei Hec “A novel distributed optical crack sensor for concrete structures” Engineering Fracture Mechanics, Vol.65, 2000, pp.133-148.

[3]. BAO TengFei1, WANG JiaLin & YAO Yuan “A fiber optic sensor for detecting and monitoring cracks in concrete structures” Science China Press and Springer, Vol.53, 2010, pp.3045–305

[4]. K S C Kuang, Akmaluddin, W J Cantwell1 and C Thomas “Crack detection and vertical deflection monitoring in concrete beams using plastic optical fiber sensors” Measurement Science And Technology, Vol. 14, 2003, pp.205–216

[5]. Chao Pan, Hui Zhu, Bin Yu, Zhu Zhu, Xiaohan Sun “Distributed Optical-Fiber Vibration Sensing System Based on Differential Detection of Differential Coherent-OTDR” PROC.IEEE sensors 2012, Taipei.

[6]. Z. S. Wu , B. Xu b , T. Takahashi & T. Harada “Performance of a BOTDR optical fibre sensing technique for crack detection in concrete structures”, Structure and Infrastructure Engineering, Vol.4, 2008, pp. 311 – 323.

[7]. Kai Tai Wan , Christopher K.Y. Leung “Applications of a distributed fiber optic crack sensor for concrete structures” Sensors and Actuators A, Vol.135, 2007, pp.458-464

[8]. N.M.P. Pinto, O. Fraza, J.M. Baptista, J.L. Santosa, “Quasi-distributed displacement sensor for structural monitoring using a commercial OTDR” Optics and Lasers in Engineering, Vol.44, 2006, pp.771-778

[9]. Noah Olson, Christopher K.Y. Leung, Aidon Meng "Crack sensing with a multimode fiber: experimental and theoretical studies" Sensors and Actuators A, Vol. 118, 2005, pp. 268–277

[10]. Qian Wang, Gerald Farrell and Thomas Freir "Theoretical and experimental investigations of macro-bend Losses for standard single mode Fibers" Optics Express, Vol.13, 2005, pp.4476-4484

[11]. Yuelan Lu, Tao Zhu, Liang Chen, and Xiaoyi Bao, "Distributed Vibration Sensor Based on Coheren Detection of Phase-OTDR" Journal Of Lightwave Technology, Vol.28, 2010,pp.3243-324

[12]. Da-Peng Zhou, Zengguang Qin, Wenhai Li, Liang Chen, and Xiaoyi Bao "Distributed vibration sensing with time-resolved optical frequency-domain Reflectometry" Optics Express, Vol.20, 2012, pp.13138-1314

[13]. A Masoudi, M Belal and T P Newson "A distributed optical fibre dynamic strain

sensor based on phase-OTDR", Measurement Science And Technology Vol.24, 2013, pp.1-7.

[14]. Robert R J Maier1,William N Macpherson, James S Barton, Scott McCulloch, and Benjamin J S Jones "Distributed sensing using Rayleigh scatter in polarization maintaining fibers for transverse load sensing", Measurement Science And Technology, Vol.21, 2010, pp.1-9

[15]. Koichi Morita and Kazuya Noguchi "Crack detection methods using Radio Frequency Identification and Electrically Conductive Materials", The 14th World Conference on Earthquake Engineering vol.14, 2008, pp.12-17

[16]. Seung Bum Kim and Hoon Sohn "Instantaneous reference-free crack detection based on polarization characteristics of piezoelectric materials", Smart Mater. Struct, Vol.16, 2007, pp.2375-87

[17].Abid A S, Yuri R, Sohichi H. "Nondestructive evaluation of damaged concrete using nonlinear ultrasonics", Mater & Des, Vol.30, 2009, pp.775-782.

[18]. Sandeep D, Piervincenzo R, Karthik R, et al. "Acoustic emission monitoring of CFRP reinforced concrete slabs.", Constr Build Mater, Vol.23, 2009, pp. 2016–2026

[19]. Hong-Nan Li , Dong-Sheng Li , Gang-Bing Song "Recent applications of fiber optic sensors to health monitoring in civil engineering" Engineering Structure,Vol.26, 2004, pp.1647-57

[20]. Harald Gnewuch, Emil Smeu, David A Jackson and Adrian Gh Podoleanu "Long range extensometer for civil structure monitoring using fiber Bragg gratings", Measurement Science and Technology, Vol.16, 2005, pp.2005-10.

[21]. S.K Ghorai., S.N Sengupta, S. Sidhishwari, and D.R Roy., "A hybrid fiber optic sensing system for structural health monitoring," in *Sensors*, IEEE, pp. 1667 – 1670, 2010.

[22]. Robert R J Maier,William N MacPherson, James S Barton, Scott McCulloch and Benjamin J S Jones "Distributed sensing using Rayleigh scatter in polarization-maintaining fibers for transverse load sensing" Measurement Science And Technology, Vol. 21, 2010, pp.1-7.

[23]. Masataka Nakazawa**, "**Rayleigh backscattering theory for single-mode optical fibers", Optic Info Base, Vol.73, 1983, pp.1175-80.

[24]. Michael Bass, "Handbook of optics – fundamental techniques and design", Vol. I, 2nd edition, McGraw Hill, Washington.

PUBLICATION

Neha Niharika, Mainak Basu, S. K Ghorai, " Detection And Monitoring Of Multiple Cracks Using Distributed Fiber Optic Sensing system" IEEE International Conference On Advanced Communication, Control & Computing Technologies (ICACCCT) 8-10th May 2014, Ramanthpuram, Tamilnadu, India