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Doctor of Philosophy

Deterministic/Reliability-Based Critical Earthquake Load Models for Linear/Nonlinear Engineering Structures
[Abbas Mohamed Babbas Moustafa; February 2002; Supervised by C. S. Manohar]

The problem of specifying ground motions for which engineering structures are to be designed to resist the action of earthquakes has remained a challenging problem in earthquake engineering research. Important engineering structures, such as large dams and nuclear power plants, are to be built so as to ensure probabilities of failure that could be as low as 10-5 to 10-'. In order that the engineer is able to predict such low failure probabilities at the design stage, elaborate and reliable models for the anticipated earthquake loads are needed. The construction of such models, however, is beset with significant difficulties that stem because of the following facts:

Lack of adequate engineering models that capture the complex physics involved in seismic energy built-up in the earth's crust and production of ground motions during earthquakes.

Paucity of adequate database of recorded strong motions for many parts of the world that constitutes a stumbling block in arriving at acceptable engineering models for strong ground motions.

Consequently, specifying design ground motions for important structures becomes essentially an il1-posed problem. In this context, it is of interest to note that the method of critical excitations has been developed in the existing literature as a notable counter-point to the more widely employed earthquake load specifications in terms of smooth design response spectra and power spectral density function models. The starting point in the method of critical excitations is the assumption that adequate description of earthquake inputs, that enable a desired response or reliability analysis to be satisfactory carried out, is not available, method advocates that the missing information in the earthquake inputs be determined such that a specified response Variable of a given structure is maximized. This leads to tailor-made earthquake load models that are least favorable to a given structure and at the same time they possess all the reliably known features of a future earthquake load. The development of critical earthquake excitation models, thus, depends upon the following influencing factors:

Framework adopted for response analysis: deterministic or probabilistic.

Dynamic characteristics of engineering structure including the effects that might arise due to the possibility of nonlinear mechanical behavior of the structure.

Nature of partial information available on the earthquake inputs.

The response variable chosen for maximization. In a deterministic analysis this could be the highest value of displacement, stress or stress resultant at a specified location in the structure over a given time period. In stochastic analysis, the response could be described either in terms of second order statistics or in terms of probability of violation of specified limit states.

Inclusion of spatial variability and multi-component nature of earthquake loads.

Possibility of earthquake loads appearing as parametric excitations in the governing equations of motion.

Research into development of critical earthquake excitations is now more than three decades old. A majority of these studies have focused on the analysis of single point seismic excitations for linear structures. Both deterministic and probabilistic frameworks have been employed in these studies. Notwithstanding these developments, currently there exists a need to develop critical excitation models that allow for spatial variability and multi- component nature of earthquake loads, possibility of earthquake loads driving the structure parametrically, nonlinear behavior of the structure and response characterization in terms of reliability measures. The present thesis, constitutes an attempt towards addressing some of these research needs. The thesis is organized into seven chapters and two annexure.

A review of literature covering existing random process models and critical earthquake excitation models is provided in chapter 1. The review begins by summarizing the salient features of random process models for earthquake ground motions encompassing issues pertaining to transient nature, spatial variability and multi-component nature of earthquake ground motions. The review of papers on critical earthquake load modeling covers, deterministic / stochastic models linear / nonlinear structural behavior and spatial variability of ground motions. It is observed from this review that literature on deterministic. The nonlinear optimization problem in both these approaches is solved by using the sequential quadratic programming (SQP) method. The procedures developed are illustrated by considering seismic response of a tall chimney and an earth dam. It is concluded that the have lower and upper bounds on Fourier coefficients in the first approach and constraints on amount of disorder in the second approach are crucial in arriving at realistic critical excitations.

The methods developed in chapter 2 are extended to determine vector critical earthquake excitation models for multi-supported linear structures in chapter 3. The formulation of structural equations of motion is carried out using the finite element method. The pseudo-static and dynamic components of the response are analyzed separately. Accordingly, response variables for maximization are chosen to reflect the decomposition of the total response into pseudo-static and dynamic components. The extension of deterministic procedures outlined in chapter 2 to multi-supported structures is fairly straightforward. Here, each component of support motion is expressed in terms of a modulated Fourier series with undetermined coefficients. Constraints on the input are ex w pressed in terms of these coefficients and are taken to reflect, as before, peak values of ground accelerations, velocities and displacements, total energy and upper and lower bound on Fourier amplitude spectra determining stochastic critical excitation models, the input is taken to be a vector of partially specified non-stationary Gaussian random processes. The critical psd matrix models that produce highest response variance are developed taking into account constraints on total energy, zero crossing rate and entropy rate. The numerical solutions to the nonlinear optimization problem is again obtained using the SQP method as has been done in chapter 2

The probabilistic critical earthquake load models in chapters 2 and 3 essentially the linear input-output relations for second order response statistics that are readily available in the standard random vibration literature. In the aseismic analysis of engineering structures, however, it is also of interest to characterize structural responses in terms of reliability measures. For linear structures under Gaussian inputs, theories based on extreme value statistics of Gaussian random processes can be employed for this purpose. Similar theories, however, are not available for nonlinear structures and for structures that are parametrically excited by earthquake loads. Studies reported in chapters 4 to 6 propose the use of time-variant reliability methods in arriving at critical earthquake excitation models. Accordingly, chapter 4 reports on deriving random critical excitation models for linear structures under single point Gaussian inputs. Here, the critical excitation is taken in the critical psd matrix models as well as in the excitation at the check point and the sensitivity vector. Chapter 6 describes the extension of reliability index based critical excitation models developed in the previous chapter to problems involving nonlinear structural behavior. This study covers both singlv supported and multi-supported nonlinear structures, but, however, attention is limited to single-degree-of-freedom (sdof) systems with cubic nonlinear force-displacement relations. As before, critical excitations are defined as those that minimize probability of violation of limit state defined on a specified internal force in the structure. This probability is again characterized indirectly in terms of the Hasofer-Lind reliability index that is derived from a quadratic response surface that fits the implicitly defined failure surface at the design point. The results on critical psd functions show a dominant peak at the linear structural frequency and also an additional peak at three times the linear structure natural frequency. This latter peak being attributed to the presence of structural non-linearity. For the case of the doubly nonlinear sdof system that is subjected to differential support motions, the governing equation of motion is shown to contain non-Gaussian parametric and external excitations. The results on critical excitations for this case are shown to reflect the influence of both parametric and nonlinear resonances. Issues related to treating structural capacities as being random are also examined in this chapter. Chapter 7 is the concluding chapter of the thesis in which a brief resume of new improvements to existing critical load modeling as well as novel elements of the thesis are given along with a set of suggestions for future research.

A few computational details of reliability indices and response surface modeling are provided in annexure A and B. It is hoped that these annexure improve the readability of the thesis.

Based on the work carried out in this thesis, the following papers, with Prof. C. S. Manohar as a co-author, have been prepared.

1. A comparative study on deterministic and stochastic critical earthquake load models, Proceedings of the International Conference the Civil Engineering, ICCE 2001, Volume II, Interline publishing, Bangalore, India, 173-180.

2. Investigation into critical earthquake load models within deterministic and probabilistic frameworks. Earthquake Engineering and Structural Dynamics. 2002. 31. 813-832.

3. Critical spatially varying earthquake load models for extended structures. Provisionally accepted, Journal of Structural Engineering SERC Madras.

4. Reliability-based critical earthquake load models for linear structures, to be submitted, journal of Sound and Vibration.

5. Reliability-based critical earthquake load models for nonlinear structures, to be submitted, ASCE, Journal of Engineering Mechanics.

6. Deterministic/Probabilistic critical earthquake load models for parametrically excited structures, to be submitted, Probabilistic Engineering Mechanics.

Vibration of Cables under Deterministic and Random Excitations
[G. Visweswara Rao; November 1989; Supervised by R. N. Iyengar]

Cables form important structural components in many engineering systems. The capacity of elastic cables to carry high tensile loads is well established by their wide application in suspension bridges, power lines and mooring cables. Stringent safety requirements of these systems necessitate rigorous analysis even in the determination of natural frequencies and mode shapes. The distinctive characteristics of a cable are the curvature and elasticity. While there are several investigations on the in plane response of cables under direct periodic forces, behaviour under seismic support excitations and non-planar response under lateral loads have not been understood well. In addition, since cables are by their very nature displacement sensitive, consideration of nonlinear effects would be necessary in some circumstances. In this context, it may be required to consider stochastic inputs also, since earthquakes and wind forces are essentially random. The present thesis is concerned with some aspects of linear and nonlinear phenomena associated with cables under both deterministic and non-deterministic inputs. The thesis is divided into six chapters.

Chapter I is devoted to a brief review of literature. Important past studies pertaining to linear and nonlinear dynamic analysis of cables are reviewed. This is followed by a critical discussion. The chapter ends with a summary bringing into focus the motivation for the present research work of the author.

In Chapter II, the effect of a lateral load on the linear dynamic behaviour of a cable is studied. When a non-uniform lateral load acts on a sagged cable, the resulting vibration pattern of the cable is non-planar. Numerical results on natural frequencies and mode shapes of non-planar vibration are presented. Non-planar behaviour can be viewed as a coupling between lateral and in plane motions which gives rise to further interesting problems. In particular, the effect of a periodic lateral load in inducing parametric instability is investigated. Numerical results on instability regions in the parameter space are presented for typical examples.

In Chapter III, the forced response of cables under seismic support excitation in studied, Both vertical and longitudinal components of motion are included in the analysis. The significant participation of the elastic modes of the cable in the response analysis is highlighted. Also, the influence of the propagation time between the supports is examined in detail and is shown to cause considerable variation in cable response. A modal superposition procedure based on the response spectrum is developed to estimate the peak additional cable tension under the seismic input motions. Results are presented for typical cables under a few real earthquake records.

The study of nonlinear behaviour of cables under external excitation is the subject matter of the next two chapters. In chapter IV, the planar and non planar responses of a cable to combined in plane and lateral excitation are studied. Due to the possible coupling between various modes, the nonlinear behaviour of a cable is quite complicated. As a first step, the interaction between the first symmetric mode of vertical and transverse displacement sis investigated. The input is an in plane harmonic forcing function acting along with a uniform lateral load. This type of excitation could be a model for the flow induced forces due to vortex shedding. The equations of motion contain both quadratic and cubic nonlinearities and are solved by the method of multiple scales. The steady state response near the condition of internal and external resonance is investigated in detail. Cables with even moderate sag-to-span ratio are shown to exhibit typical nonlinear resonant behaviour different from that of a system with cubic non-linearities. The complicating effect of internal resonance in producing possible non-periodic steady state solutions under periodic excitation is brought into focus.

In Chapter V, the response of cables under a stochastic excitation is studied. Two excitation models are considered, (i) a narrow band input and (ii) a combined periodic and white noise input. The equations are solved by the method of equivalent linearization using gaussian closure. It is found that the linearlized equations lead to multi-valued response moments in certain regions of the parameter space. A similar situation is known to arise in the case of Duffing's oscillator when analysed through equivalent linearlization technique. This is in fact a limitation the approximate procedure. However, the acceptability or otherwise of the results can be studied through a stochastic stability analysis. Such an analysis is performed for both the cases of excitations mentioned above. Digital simulation results are presented to support the theoretical results.

Analysis, Specification and Synthesis of Strong Motion Earthquake
[Krishna C. Prodhan; December 1987; Supervised by R. N. Iyengar]

Earthquakes cause destruction to life and property in catastrophic proportions. As a result, the constant aim of earthquake engineering has been to design structures that would suffer minimum or no damage in the event of an earthquake. In the design process, the most difficult and crucial problem is how best to specify the design seismic load. This problem assumes great importance particularly in the aseismic design of sensitive structures like nuclear power plants and emergency structures like hospitals and high dams. Here the engineer is confronted with a serious situation arising out of the randomness and uncertainty of the earthquake motion yet to occur. The currently available strong motion descriptors can be classified as either direct or indirect. For example, magnitude, maximum ground acceleration, duration, etc. are direct descriptions. Response spectra, Modified Mercalli Intensity (MMI) are indirect descriptors. Neither of the approaches is adequate by itself as it cannot fully reflect all the details associated with a shock. In either case, due to the inherent uncertainty, the methodology has to be statistical. With this in background, the present thesis aims at taking a fresh look at both the direct and indirect descriptors to evolve alternate approaches for studying and interpreting strong motion earthquakes. The presentation of the thesis is as follows: In Chapter I, a brief review of the direct and indirect methods of specifying and describing earthquakes followed by a discussion is presented. An attempt is made to bring out the limitations of the existing descriptors so as to facilitate the development of new approaches proposed in the succeeding chapters.

In Chapter II, the question of how to optimally combine the various descriptors like magnitude, a maximum acceleration, frequency content, duration, etc. is considered. For this purpose, a database of 92 strong motion earthquake records is selected. The method of multivariate statistics is used to arrive at a classification of the earthquakes. A new risk rating scale is also proposed. It is demonstrated that the risk rating is closely related to MMI.

The most common indirect method of specifying earthquakes is the provision of damped spectra in codes of practice. Whether these spectra are internally consistent so that they could be derived from each other, is studied in Chapter III. A linear regression analysis is carried out on paired spectra of 66 actual earthquake records. The regression results obtained are sued to define internal consistency in a statistical manner. With this, the internal consistency of the spectra of United States Regulatory Commission, Canadian Standard Association and Indian Standard 1893 (Fourth revision draft) is verified. It is shown that the spectra of the draft revision of IS-1893 are not internally consistent.

A major limitation of the classical response spectra is that they are obtained as responses of damped linear system. An alternate frequency domain description is the Fourier Spectra. The sine and cosine Fourier Spectra completely define any given earthquake record. In Chapter IV, the absolute values of 30 pairs of such spectra are normalized and statistically processed to arrive at their means and standard deviations. Thus a smoothened pair of these spectra could be sufficient to specify an earthquake at a given site. The relation of the two proposed spectra to the damped response spectra is also studied. It is further verified that time histories generated to be compatible with the new spectra do indeed have properties expected of actual earthquake records.

The time spent above given levels of ground acceleration is a characteristic feature of the accelerograms. Also, an important information required many times, particularly for nonlinear systems would be the time spent by actual or equivalent linear systems above specified response levels. These informations called here pulse characteristic are studied in Chapter V. The importance of the time spent by the accelerograms above their 20% level is examined. The time spent results for response acceleration of some linear single degree systems of different dampings are also presented.

The thesis concludes in Chapter IV with a summary and a set of conclusions.

The thesis ends with Chapter IV wherein a brief summary of the work with a set of conclusions is presented followed by a few suggestions for further research.

A paper published based on a part of the present work is enclosed in the Appendix.

Some Problems in Inelastic Response of Structures Subjected to Earthquakes
[B. K. Raghuprasad; 1977; Supervised by K. S. Jagdish]

The study reported in this thesis is concerned with two problems in the inelastic dynamic response of structures subjected to earthquake ground motions. The problems are:

(i) Vibration absorber behaviour in two-storey inelastic structures under earthquakes.

(ii) Torsional response of inelastic single-storeyed structures subjected to ground-motions.

Some relevant literature on the inelastic response of structures has been reviewed in Chapter I.

In Chapter II, 'The inelastic vibration absorber subjected to earthquake ground motion' has been studied. Two-storeyed, bilinear-hysteretic structures have been studied with a view to explore the possibility of using the dynamic vibration absorber concept in earthquake resistant design. The response of the lower storey has been optimized for the Taft, 1952, S69E earthquake accelerogram with reference to parameters such as frequency ratio, yield strength ratio and mass ratio of the two storeys. The influence of viscous damping has also been examined.

In chapter III, 'The inelastic torsional response of a single-storeyed structure with two degrees-of-freedom' has been studied. Here, the single-storeyed structure is assumed to consist of a rectangular slab, supported on series of portal frames, parallel to one another. The shorter side of the slab is assumed to be parallel to the span of the frames. The structure is assumed to possess two degrees-of-freedom, viz., a translation along the direction parallel to about a vertical axis through the mass center. The frames are assumed to follow bilinear-hysteretic, force-displacement law. The inelastic response of the structure to a horizontal component of ground motions studied numerically on the computer. The maximum ductilities of the various frames have been determined and the effects of various parameters like, eccentricity, yield strength and fundamental period have been studied for several earthquake inputs. The effect of strengthening the exterior frames has also been examined.

Chapter IV deals with the 'Inealstic Torsional Response of a single-storeyed structure with three degree-of-freedom'. The structure consists of a slab, square in plan, supported on four columns. In this problem, the two horizontal displacements of the structure and its rotation around a vertical axis through the mass center are considered. Interaction between the resistances of the columns in the two orthogonal directions has been considered. Two horizontal components of earthquake ground motion have been considered for the input. The parameters like, eccentricity, yield strength and period of the columns have been varied and their influence on the response behaviours has been observed. The responses of the structure to both the horizontal components of the quake and to only one of the components of the quake have been compared during the study.

Intelligent Optimal control of Earthquake or Wind Induced Flexural and Torsionally Coupled Vibrations in Buildings

[Anupam Singh Ahlawat; Supervised by Ananth Ramaswamy]

The protection of a building structure, the equipment housed within and the human occupants against damage induced by large environmental loads e.g., earthquake, strong wind gusts and waves etc., is without doubt, a worldwide priority. Requirements of safety of structures are addressed by the following design considerations, namely, reliable information on service loads, characteristics of the construction materials and efficiency and robustness of the analysis and design procedure employed. The uncertainty involved in the information about service loads, behavior and strength of the construction materials and the approximations involved in the analysis and design methods are such that these requirements can not be met completely.

Progress in material science and manufacturing technology has resulted in new construction materials characterized by higher strength and predetermined behavior, e.g., high strength structural steel and high performance concrete. Better quality control norms in the manufacturing process have led to lesser variability in the material proper-ties.

Availability of computationally powerful digital computers together with the use of computationally powerful and accurate methods of structural analysis, e.g., finite element method, to a great extent and the evolution of mathematical tools to handle uncertainties, e.g., probability theory, fuzzy sets and fuzzy logic, to some extent, have led to the design and construction of complex, slender structures such as high-rise buildings, long span bridges, deep water offshore platforms, etc.

To ensure both the safety and serviceability of the structure during the entire useful life of the structure, limit state design approaches have been developed. In this approach partial factors have been associated with live, wind, earthquake and dead loads, considering uncertainty levels in the peak magnitude of the various loads. Likewise partial factors have been associated with the variability in the strength of the materials or in other words resistance of the structure. This approach has been further improved by incorporating other reliability measures such as return period for environmental loads such as windstorm and earthquakes.

As the structures have become more costly, more complex and serve more critical functions, e.g., tall buildings, long span bridges, deep water offshore platforms, nuclear power plants, etc., the consequences of their failure are catastrophic. The safety of structures during the hazardous earthquake and wind loads applies not only to the structure but also to the life safety of the occupants. Hence, the conventional reliability criteria are no longer adequate. To enhance the safety requirements, most of the buildings are currently designed to yield during hazardous environmental loads without complete collapse, thus protecting the occupants within the structure. Inelastic deformation (yielding) is permitted as means of dissipating a portion of the energy transferred to the structure by these environmental loads. However, plastic deformation due to yielding results in permanent damage. Thus the conventional structural design is often based on providing sufficient strength and stiffness to limit the inelastic deformation to an acceptable level.

To meet the design requirements of economy, safety and serviceability, a new design philosophy has emerged, which is based on specifying the expected performance of the structural system during large environmental loads. Thus, rather than designing to ensure only the life safety of the occupants, one may ensure minimal damage to the structural system as well. The designs that follow this alternate philosophy are known as performance based structural designs.

Structures cannot be designed to withstand all possible external loads, however, some extraordinary loading episodes do occur, leading to damage or even failure of the structure. Higher flexibility and low damping characteristics of slender high rise structures have given rise to (i) higher material distress during large environmental loads, such as earthquakes and wind gusts, resulting in the failure of the structure and (ii) unacceptable levels of vibration causing discomfort to the occupant.

One way to mitigate the effects of hazardous environmental loads and to meet the stringent performance requirements is through the application of structural control technology. The of structural vibrations can be accomplished by various means, such as, providing counter forces (active control), isolating and dissipating the energy of the excitations (base isolation), absorbing and dissipating the energy of the structural vibrations (passive control). Structural control can be implemented using either passive, active or combinations of these strategies (semi-active, hybrid control).

Over the past three decades tremendous progress has been made to make control a viable technology for enhancing structural functionality and safety against natural hazards such as strong earthquakes and wind gusts. The passive and active control systems have been used in real application to reduce the earthquake and wind induced lateral vibrations of buildings.

Passive control systems operate without using any external energy supply. These systems either use potential energy generated by the response of the structure to supply the control force or dissipate the energy of the excitation through friction or viscoelastic deformation. Passive control systems include tuned mass dampers, tuned liquid dampers and a variety of energy dissipaters, such as, base isolation systems against earthquake loads, metallic yield dampers, friction dampers, viscoelastic Yi dampers, etc. Passive control system suffers from their limited capability to control the structural response, as it does not use any external energy source.

Active control systems operate using an external energy supply to apply the control force on the structure. Active control systems use sensors to measure the response of the system and/or excitation, compute the control command from the sensor output using a control algorithm and apply the control command to the structure by the means of actuators. Active mass dampers, active mass - drivers, active tendon systems, etc., are some of the active control devices developed and tested for actual structural application during the last two decades. The active control system is dependent on an external power supply and the power requirement is quite high in case of control of Civil Engineering structures. This makes such system vulnerable to power failure, which is always a possibility during a strong earthquake and windstorm. Moreover, due to the high power requirement, it is difficult to provide an active control system with its own dedicated power supply.

A hybrid control system is a viable solution to alleviate some of the limitations that exist in either a passive or an active control system functioning alone. The hybrid control system uses an active control component with a passive control component to supplement and improve the performance of the passive control system and to decrease the energy requirement of the active control system. In case of power failure or failure of the active control component, the passive component of the hybrid control system still offers some degree of protection, making the system fail-safe, an essential design requirement for life-line structures.

Active control system or the active control component of a hybrid control system computes the control command from the sensor output using a control algorithm. Performance of the control algorithms largely depends on the accuracy of the model in handling the dynamics of the structure and control devices. Uncertainties and nonlinearities in loads and material are inherent to most structures, limiting the accuracy of the model of dynamics of the structure.

This rotation in the control algorithms can be alleviated using an intelligent control system, e.g., logic control systems. An intelligent controller can be designed without specifying a very precise and an accurate model of the structural dynamics. Some of the characteristics of fuzzy logic appealing to control engineers are its effectiveness and ease in handling nonlinearities, uncertainties and heuristic knowledge.

Very few of the practical building structures have a zero eccentricity between the axis of rotation and the axis of inertia and are subjected to pure unidirectional excitation making them amenable for modeling as planar structures. A three dimensional structure with an eccentric location of the axis of rotation and inertia has coupled lateral and torsional responses, even when excited unidirectionally. Symmetric buildings, i.e., the buildings that do not have any eccentricity between mass and stiffness centres, respond with coupled lateral and torsional motion under wind excitations having an eccentricity between the aerodynamic centre of excitation and the mass \& stiffness centre of the building. However, two-dimensional plane frame structural models have been considered in most of the recent research on structural control technology. Thus most of the structural control methods that have been studied are not suitable for a majority of the practical building structures.

Behavior of the structural material is not always linear and time invariant, especially in the event of large environmental loads. A control system designed for a linear, time invariant structural system may not perform effectively and efficiently in the event of large environmental loads that lead to nonlinear behavior of the structural material. Use of an adaptive control system that has a capability of online tuning of the control system, based on the current dynamics of the structure; can alleviate the limitation of the fixed type control system.

In the present study an approach for an optimal design of fuzzy logic controller (FLC) driven active and hybrid control systems have been proposed. The proposed approach has been applied to both the plane frame equivalent 2-D models and torsionally coupled 3-D models of the building structure subjected to earthquake and wind excitation. An effective and efficient arrangement of the hybrid mass dampers has been presented for the torsionally coupled buildings. The safety of the structure mainly depends on the displacement and rotational response, while the comfort level of the occupants depends on the acceleration response. To ensure both the structural safety and serviceability (occupants' comfort), a multi-objective optimal design strategy has been formulated to minimize displacement, acceleration and torsional (in case of torsionally coupled building) responses of the structures. Genetic algorithm (GA) efficiently finds an optimal solution from the complex and possibly non-convex discontinuous solution space. A modified form of a two-branch tournament GA has been used in the present study for multi-objective optimization of the control system parameters, as the optimization problem is not necessarily convex.

The proposed approach has been further extended to design of an adaptive control system to improve the robustness of the FLC for nonlinear building structures. An online identification of the dynamics of the structure has been incorporated using artificial neuro- fuzzy inference system (ANFIS). Optimal changes in the FLC parameters have been computed for identified dynamics of the structure. A "currently available" time history of the excitation and the set of design input excitation have been incorporated in optimization problem to establish the required changes in the parameters of the FLC. Various hardware related constraints such as sensor noise, effects of quantization, saturation and sampling time of the analog to digital converter (ADC) and digital to analog converter (DAC), computational time delay to execute the main control algorithm and the supervisory control algorithm in case of adaptive control system, have been considered for a more realistic simulation of the digital implementation of the control system.

Effectiveness of the proposed control strategies has been investigated for the structural control benchmark problems and other problems for seismically and wind excited building structures, available in the literature. To make the comparison of the performance of the proposed control system with those that are reported in the literature, respective model of the buildings and the corresponding input excitations have been used in the present study. The performance of the proposed control strategies has been found to be better than the strategies reported in the literature. Multi-objective optimal design for FLC based hybrid control system provides a set of 'Pareto- optimal' designs that enable the designer to select an appropriate control system design for the desired performance requirements. Positions of the control devices and sensors have been optimized with the other parameters of the control system. Position optimization of control devices and sensors as a part of the controller design optimization become necessary in the case of nonlinear structures where mode shapes can not be used, to find out the optimal position of the control device. The proposed control system is a hybrid control system having fail-safe characteristic that makes the system suitable for lifeline structures where fail-safe system is an essential design requirement.

The thesis has been organized in seven chapters and appendices encompassing an introduction, a literature review, methodology and numerical results for fixed and adaptive control system and conclusions. References cited in the thesis have been arranged at the end. Appendices highlighting modeling issues available in the literature have been included for completeness.

A Nonstationary Random Process Model for Earthquakes and its Application
[R. Narayana Iyengar; May 1969; Supervised by K. J. S. Iyengar]

The interest of an engineer in earthquakes is mainly from the design point of view. He studies them so that the structures he builds can safely withstand the sudden earthquake shocks and the associated erratic ground motion. Though geophysicists have been studying the phenomenon of earthquakes since a long time, progress engineering-wise has taken place only recently, The first step in this direction has been the installation of strong motion recorders in seismic areas to record the ground motion near the epicenter. The importance of this needs no extra emphasis. Indeed, earthquake engineering essentially is the design of structures to respond to this ground motion with minimum or no damage. The designer is here confronted with a situation with serious difficulties. The irregularity exhibited by the ground motion cannot be quantitatively described in a simple manner. This induces uncertainly in the behaviour of a structure itself rendering design decisions doubtful. To crown these, the unpredictability of future earthquakes introduces extra uncertainty making the problem much more involved. The only way out of this seems to be by finding a suitable mathematical model for the ground motion. The development of a mathematical model for physical and natural phenomenon is not something new to engineering practice. This is undertaken in almost all fields by studying the underlying mechanism; for example, the foundation of a rotating machine is taken to be subjected to a sinusoidal excitation. In the present problem of modeling ground motion during earthquakes, an accurate analysis of the fundamental mechanism is beset with many complexities and may even be intractable. Anyhow, if the basic mechanisms of different earthquakes are similar one may expect a common pattern to exist among the recordings also. In the absence of a suitable analysis of the earthquake mechanism, this pattern is to be searched among a few available accelerograms.

Even a causal look at the past accelerograms will convince one that the most striking common feature is the randomness present in all the records. Thus the concepts of probability, statistics and random processes naturally find their way in an attempt to understand these records. This in turn makes the response analysis and design of structures also to be carried out in a statistical manner, applying the stochastic process approach throughout. In the present work attention is mainly focused on the modeling of ground acceleration as input to structural systems and the analysis of a single degree-of-freedom system with such an input. The presentation is as follows: A brief review of literature pertaining to the field of modeling of earthquakes followed by a discussion is presented in Chapter 1. Chapter 2 deals with the development of a new model in three steps. In the first stage many past records are analysed for what seem to be their particular and general characteristics. Based on the inferences of this analysis, in the second stage, a non-stationary random process suitable to simulate the important properties is proposed. In the last step an approximate method is worked out to estimate the parameters involved in the suggested model, so as to get quantitative simulation of some of the characteristics fixed beforehand.

After fitting in a model for such an irregular process it would be interesting as well as necessary to test it by generating sample functions. Chapter 3 is concerned with this aspect of the study. Four real records have been simulated by the above method of parameter estimation and the sample functions are presented in four ensembles. Response spectrum analysis is also carried out on all these. The realized results are compared with the expected ones.

The generation of the excitation samples is unnecessary when the response of a structure can be analysed probabilistically using only the statistical properties of the input process and the system characteristics. As an example of this approach, the analysis of a linear single degree-of-freedom system is undertaken in Chapter 4. After a mean square response analysis, an attempt is made to obtain the highest-peak statistical approximately. This is followed by an analysis of the response envelope. Numerical results are presented in detail for four types of earthquake like excitations.

The thesis ends with a chapter on conclusions and suggestions for future research. The following two papers have been prepared based on the material presented in this thesis.

1. A Non-stationary Random process model for earthquake accelerograms (To appear in the June 1969 issue of the Bulletin of the Seismological Society of America).

2. Probabilistic Response analyses to earthquakes (Sent for publication).

Master of Technology

A New Modal Combination Rule for Seismic Analysis of Multiply Supported Structures Using Critical Cross Power Spectral Density Functions
[K. Someswara Rao; January 2002; Supervised by C. S. Manohar]

Generally, for seismic analysis of multiply supported engineering structures design earthquake loads are specified in terms of response spectra. In the analysis of multiply supported structures subjected to multi component excitations, engineers are faced with the problem of combining maximum response quantities contributed from different excitations. The conventional method of solving this problem is by assuming mutually independent excitations which ignores the correlation effects between different excitations. In this work a new combination rule is developed using the critical cross power spectral density functions in which support excitations are modelled as stationary gaussian random process. The cross correlation effects between different excitations are brought in such a way that the response quantity of interest is maximised. This method is derived using fundamental principles of random vibration theory. It can estimate the maximum possible response of a structure under a set of incompletely specified seismic loading conditions.

Finite Element Vibration Analysis of Rotors Subjected to Transient Earthquake Loads
[Kamendra Singh; January 2000; Supervised by C. S. Manohar]

The equations of motion of a finite rotor element subjected to the most general seismic excitation with translational and rotational components has been developed by applying variational principles. The formulation includes shear deformation, rotatory inertia, gyroscopic and parametric terms. To evaluate the response of the system Wilson -0 method is used for direct transient dynamic analysis. To validate the results a no-spin case is considered and the results obtained in the package MATLAB 5.3 are compared with those of a-general purpose program ANSYS 5.5. Another important aspect, the effect of phase difference in excitation on the response, has also been considered and it is observed that the effect on response is quite considerable.

Natural Frequencies and mode Shapes of Brick Masonry Buildings
[P. R. Tevatia; January 2001; Supervised by K. S. Jagadish]

It is well known, how important is brick masonry in our lives. It is one of the most commonly used materials for the construction of single as well as double storied buildings. Owing to such great usage in our daily life, there is an imperative need to study the behavior of brick masonry, under the action of dynamic loads, and obtaining the natural frequency and mode shapes of such structures, so as to be able to visualize the after effects of natural calamities and take remedial measures well in time.

Response of the structure is influenced by the properties of the constituent materials, which actually varies largely from place to place. Studies have been carried out to understand the behavior of brick masonry, but the information is still scant. To supplement the existing studies, there is a need to carry out frequency analysis of masonry buildings.

In this dissertation, frequency analysis of single and double storied masonry structures has been carried out by idealizing masonry as an orthotropic material. An effort has been made to study all the possible combinations using different boundary conditions, considering the effects of openings, using clamped as well as simply supported roof thereby taking into account the complex4 of the structure.

The results thus obtained would be useful for dynamic analysis of masonry buildings particularly in context of out-of-plane vibration of walls.

Transient Earthquake Response Analysis of Liquid Storage Tanks using FEM and the Determination of Critical Earthquake Excitations
[Akhiliesh Mishra; January 2000; Supervised by C. S. Manohar]

The work aims at generating a critical excitation to be used in the design of elevated liquid storage tanks. The response analysis of the structure is carried out by using finite element models for the tank walls and the enclosed liquid. The general purpose FE program ANSYS is used. A class of benchmark problems on free vibration analysis of rectangular and cylindrical tanks is analyzed first and the results are verified with the exact solutions available in the literature. The lagrangian fluid finite elements are used to model the tank's content. Mode superposition method is employed to obtain the transient dynamic response due to earthquake motion. The critical excitation method is then used to obtain the excitation, which is least favorable to the structure, among all other excitations that can realistically be expected at that site. An optimization problem is formulated and solved using MATLAB to find out such an excitation. The response of the structure under critical excitation is compared with that under other earthquake of same intensity, and it is observed that critical excitation gives 50% higher response. The excitation is also shown to resemble realistic earthquakes in terms of duration, frequency content and transient characteristics.

Shock Table Studies on Brick Masonry Building Models Subjected to Base Motion
[K. Ravi Shakar; January 2000; Supervised By K. S. Jagadish]

In this project work an attempt has been made to study the failure pattern of a box-type unreinforced masonry building under the action of base motion. Prior to the testing, free vibration study was carried out to obtain the fundamental mode shape, frequency and damping. For the purpose of base motion simulation, a shock table was fabricated such that the cross walls (longer walls) of the box-type structure were subjected to out-of-plane motion. Also, due to the limitation of input energy, a scaling ratio of 1/6 was adopted. To reproduce the typical disposition of bricks, which is an important feature of a typical masonry building, scaled bricks were made. The scaled bricks were made of stabilized mud. The scaling facilitated drastic reduction m the mass on the shock table. Two scaled model buildings were tested; one made of cement mortar and the other made of lime mortar. The accelerations at the base of the model, and at two points on the building were measured, The strength and elastic properties of the masonry used were measured. This has been used in the linear finite element dynamic analysis. The experimental results were compared with FEA.

It has been concluded that shock table study is very useful in understanding the dynamic behavior of simple masonry structures. Further work needs to be carried out to achieve better scaling requirements for dynamic testing.

Studies on Response Spectrum based Methods for Earthquake Response analysis of Multi-supported piping Structures
[Sreecharana P. R.; January 1999; Supervised by C. S. Manohar]

The problems of Earthquake Response analysis of multiply supported piping structures in Nuclear Power plants are considered. Issues pertaining to the application of response spectrum based methods are examined. Specifically the question of residual errors in the analysis due to modal truncation errors is addressed. Numerical results based on the use of Dynamic Stiffness Method, traditional Finite Element Method using Time History analysis are presented. It follows from this study that determination of stresses using Response Spectrum

Method requires careful considerations to be given to the modal truncation errors.

Natural Frequencies and Mode Shapes of Brick Masonry Buildings
[R. Satish Kumar; January 1999; Supervised by K. S. Jagadish]

Brick masonry is one of the most commonly used materials for the construction of single and two storied buildings. There is a need to understand its behaviour under the action of c loads and obtaining the natural frequency and mode shapes of such structure is the first step towards it.

Since the response of the structure is mainly influenced by the properties of the constituent materials used, which varies largely from place to place, there is a need to study the behaviour of masonry structures made of locally available materials. The information regarding 'frequency analysis of masonry buildings is scant.

In this dissertation work, a parametric study of the frequency analysis of simple brick masonry structures has been done by idealizing masonry as an orthotropic material. It is obvious that for complicated wall layout the analysis would become difficult, hence frequency analysis of masonry walls with different boundary conditions has also been done. An attempt has been made to correlate the wall frequencies with building frequencies.

The effect of openings, boundary conditions, roof and its influence on the mode shapes has been discussed in detail.

Influence of Shape of a Building in plan on the bilinear inelastic dynamic response of framed structures subjected to earthquake ground motions
[G. R. Patil; January, 1998, Guided by Prof. B. K. Raghu Prasad]

Since the inception of the inclusion of the aspect of safety of the structures against the earthquake ground motion in the structural design, the available literature shows that not much study of the influence of the shape in plan has been taken into consideration.

About three and a half decades ago, the first thought to this consideration warned that an asymmetric plan shape might lead to torsional vibrations due to eccentricity between mass centre and the shear centre.

Biggs and Dowrick did a superficial study on asymmetrically planned buildings. Dowrick suggested that an asymmetrically planned shape can best be avoided rather than designed for. But a symmetrically planned shape is very difficult to achieve due to practical limitations such as shape of plot, soil conditions, Purpose of the building etc.

In the present study, aspects of the shape of the structure in plan have been studied in depth. The significant observations of the asymmetrically planned buildings undergoing torsional vibrations has been mentioned in the later chapter 4, Also influence of the eccentricity between mass center and the shear centre has been studied for various shapes of buildings.

Influence of period and aspect ratio on the response of rectangular building with two d.o.f and three d.o.f is also studied.

In this study, the record of EL-Centro earthquake, May 1940, has been used for the analysis.

Critical Cross Power Spectral Density Models for Earthquake Loads on Multi-Supported Structures

[Srinivas Chennapragada; 1997; Supervised by C. S. Manohar]

The thesis deals with the seismic response analysis of structural systems which axe supported multiple points. In this type of structures, the distance between the supports axe comparable to the characteristic seismic wavelength and, consequently, the supports suffer differential ground motions. Examples for this type of structures can be either land based structures like long span bridges, large dams, petroleum pipe lines or they can be secondary parts of primary system like piping systems, stairways, and multi-span rotors.

A review of literature on the methods for seismic response analysis of multi-support structures and on method of critical excitations has been presented in Chapter 1. A review of literature on the models for spatial variability and models for individual components of ground motions axe discussed. Also, the scope and limitations of currently available methods for seismic response analysis of multi-support structures namely, time history method, response spectrum method and random vibration method is presented.

The development of vector critical random earthquake excitation models is presented in Chapter 2. The input is modeled as a vector of non-stationary random processes. Each of components of this vector is obtained as a product of a deterministic envelope and a stationary Gaussian random process. It is assumed that the knowledge on auto-power spectral density functions is available; the cross spectral density functions are unknowns. These unknown functions axe determined, that, the variance of a specified response variable is maximized over time. The methodology developed is illustrated with reference to a Euler-Bernoulli beam supported on two linear springs. Two alternatives critical cross power spectral density function models are developed.

The dynamics of nonlinearly supported beam structures which axe subjected to differential random support motions is considered in Chapter 3. The beam is taken to be a linear Euler- Bernoulli beam and the support springs axe modeled as Duffing springs with cubic nonlinearity. The support excitations are modeled as a vector of stationary Gaussian random processes. The response analysis is carried out using the method of equivalent lineaxisation in conjunction with dynamic stiffness matrix method of structural analysis. The approximate results thus obtained axe validated by comparing them with corresponding results from Monte Carlo simulations based on finite element structural analysis. Furthermore, the problem of determination of critical cross power spectral density functions is also considered. The two models for critical cross spectra described in Chapter 2 are extended to account for system non-linearitys.

The conclusions resulting from the above studies and a few suggestions for further research have been presented in Chapter 4.

Appendix A describes three methods that are available to analyze the response of multiply sup- ported structures subjected to differential support motions. Brief description of simulation of vector Gaussian random processes with specified power spectral density matrix axe presented in Appendix B. Some useful terminologies on the description of vector random processes axe given in Appendix C.

Random Earthquake Response Analysis of Multiply Supported Nuclear Power Plant Secondary Systems
[Mr. R. Ravi; January 1997; Supervised by C. S. Manohar]

The safety of nuclear power plant structures under the seismic loading is one of the most important design requirements. A major hurdle in fulfilling this requirement lies in dealing with a significant level of uncertainty associated with the specification of the seismic load. This uncertainty arises, in turn, because of the complex nature of the earthquake source mechanism, wave propagation that affect the intensity of the ground motion at a given site and the effects due to soil structure interactions. The problem is further compounded by scarcity of recorded ground motions for different site conditions and focal distances. For the estimation of seismic responses, the deterministic methods such as response spectrum and time history methods have been developed with certain conservative assumptions to take care of the uncertain inputs. In the recent past, application of random vibration analysis techniques for the estimation of seismic responses is gaining acceptance in the nuclear industry. Nevertheless, for the critical structures such as nuclear power plant components, where the responses are to be estimated with a high degree of confidence, the uncertainties associated with the seismic loading makes the design an ill posed problem. The complexities are further enhanced in the case of multiply supported structures wherein a more detailed specification of the seismic loading at the supports are required. Also, it is worth noting that quantification of design seismic margins in the design is currently being carried out using probabilistic methods. The robustness and accuracy of such methods are open to question due to lack of available data.

Under such a situation, it is valuable to know what could be the maximum possible response of a given structure. The subject of critical excitation deals with this issue and offers a counterpoint to the traditional response spectrum based methods. Recently a methodology for optimal random process modelling of multi-support and multi-component earthquake motions has been developed at Indian Institute of Science. This method, called herein the Critical Cross Power Spectral Density (C-CPSD) method, has the potential for use in industry and therefore its performance merits a critical appraisal vis-d-vis the traditional methods of seismic response analysis. Furthermore, the method, as has been developed, is inapplicable if structural non-linearitys are to be taken into account. The present thesis, thus primarily aims at evaluating the performance of critical seismic excitation modelling in a realistic setting and contributing to the development of the methodology of critical excitations by extending the presently available procedures to nonlinear systems.

The thesis is divided into five chapters and the layout of the thesis is as follows.

Chapter I deals with a review of literature on the methods of seismic response analysis of secondary systems and the existing codes of practice. It brings out the scope and limitations of the various methods and codes of practice. The need to know the seismic margins available and the relevance of critical excitations in such a scenario is discussed.

Chapter 2 deals with the details of a multiply supported primary discharge pipe of the 500 MWe Prototype Fast Breeder Reactor, that has been selected for the purpose of the assessment of the C-CPSD method. The details of the finite element model used, results of the modal analysis and the generation of floor response spectra at support locations of the primary discharge pipe by time history and random vibration approaches are presented.

A critical assessment of the C-CPSD method with respect to the estimated responses such as dynamic stresses and displacements is reported in chapter 3 by comparing the results with those estimated by the conventional methods such as multiple response spectrum method, multiple time history method and envelope spectrum method. In the application of the critical excitation method, the seismic inputs are described in terms of the response spectra at the support points while the cross correlation between the support motions are taken to be unknown. The unknown cross correlations are found in such a way that the response variance at any given location is maximized. The results indicate that the critical excitations do not produce unduly high responses and they are about 1.3 times higher than the values that are obtained by multiple time history analysis. Also, the critical excitation method clearly establishes the high degree of over conservatism associated with the envelope spectrum method. In a multi-support excitation situation, as per the prevailing codes of practice, the allowable stresses for the dynamic part of the total stress is smaller than that due to the support displacements. In view of this, the critical responses were obtained by maximizing the dynamic part of the total response rather than the total response. Here, also, the robustness of the critical excitation method was established by changing the damage variable of interest and comparing the resulting responses over the structure. The results have indicated that the overall behavior of the relative response values between any two structural points remains unchanged irrespective of the response variable with respect to which the critical excitations have been established. The C-CPSD method uses a simple model for the phase characteristics between the support motions. It emerges from the present study that, since the actual cross coherence in a secondary system is more complex, there is scope for improving the method by allowing for more realistic models for phase spectra.

Chapter 4 considers the seismic response of a nonlinear, doubly supported, single degree of freedom system with cubic spring characteristics. The two supports are subjected to stationary Gaussian support motions. To start with, the support motions are taken to be completely specified. An equivalent linearization based random vibration approach for analyzing the system response is developed and the scope of the method is examined using digital simulations. A stochastic stability analysis of the approximate solution is also carried out to examine the validity of the equivalent linear models used. Subsequently, the problem of determination of the C-CPSD friction is considered and an approximate solution to this problem base don equivalent linearization is developed. The numerical results demonstrate the feasibility of the proposed approach.

The conclusions emerging from the above study and a few suggestions for further research are presented in the Chapter 5.

Critical Cross Spectra for Multi-Support and Multi-Component Earthquake Excitation
[Tangedipalli Srikanth; January 1996; Supervised by C. S. Manohar]

The work reported in this study pertains to the specification of earthquake loads for multiply-supported engineering structures. We model the earthquake motions as vector random processes and perform the response analysis within the framework of theory of random vibrations. Attention is focused on obtaining the description of power spectral density (psd) matrix of the vector excitation following the method of critical excitations. The study reported here is an extension of the recent work done by

Manohar and Sarkar (1995) and Sarkar and Manohar (1996) on seismic load specification using method of critical excitations. Before we proceeded with the details of the issues addressed in the study, we first present a brief review of available methods for handling multi-support and multi-component seismic excitations.

Critical Stochastic Seismic Excitation Models for Engineering Structures
[Abhijit Sarkar; August 1995; Supervised by C. S. Manohar]

Earthquakes constitute an important source of dynamic action on engineering structures. Considerable progress has been achieved over the last few decades in the aseismic design of engineering structures using time history, response spectra and stochastic process models for earthquake loads. More recently, stochastic field models which allow for spatial variability in earthquake loads on extended structures have also been developed. Seismic risk analysis procedures to assess the safety of important, structures are also available. Notwithstanding this progress, it is important to note that, in specifying the earthqu4ke,.lq4!k for the design of important structures, one has to reckon with three conflicting requirements:

- Scarcity of recorded earthquake accelerograms,
- A high level of uncertainty associated with mechanisms producing ground motions at a given location and
- High level of confidence with which the engineering structures have to be designed to withstand earthquake loads.

This would mean that, aseismic design of engineering structures is an ill-posed problem. The difficulties are further accentuated when one has to deal with multi-support and multi-component support motions which demands the description of loads at a much finer level for which the available data is all the more scarce. Thus, the robustness and accuracy of the available earthquake load models are open to question. In such a situation, it is natural to ask what is the worst which n-Light happen to a given structure under the action of an incompletely specified earthquake excitation. The method of critical excitation has been developed to answer this type of questions. This method is based on a realistic premise that earthquake inputs can only be partially specified with confidence and the emissing information in the input, which is essential for a complete response analysis, is that damage to a given structure is maximized. The term damage here denotes any unfavorable behavior of the structure. Critical excitations are, thus, by definition, dependent on the system, nature of partial information available and the damage variable chosen for maximization.

The present thesis contributes to the state of the art in the development. of method of critical excitations. The attention is limited to the linear system behavior. The thesis is divided into five chapters and an appendix. Firstly, the study of uniform support excitation is considered and subsequently, the analysis is extended to cover multi-support / multi-component seismic excitation problems. The layout of the thesis is as follows:

A review of literature on the method of critical excitations has been presented in Chapter 1. The analysis procedures and their applications reported in the literature have been surveyed and the need for investigation to develop the method further is discussed. A systematic I study of some of the open questions in this area of research is brought out in the subsequent chapters.

In Chapter 2, the study of spatially uniform critical excitation is carried out. The earthquake ground motion is modeled as a non-stationary random process obtained as a product of a prescribed deterministic envelope and a stationary Gaussian random process having an unknown power spectral density. The excitation is taken to satisfy constraints on the total average power and zero-crossing rate. In this case, the critical excitation is defined as the excitation which maximizes the response variance of a given linear system under the constraints of total average power and zero-crossing rate. The unknown optimal power spectral density of the stationary part of the excitation is obtained using linear programming methods. The resulting solutions are shown to display a highly deterministic structure and, therefore, fail to capture the stochastic nature of the input. A modification to the definition of critical excitation is proposed which takes into account the entropy rate as a measure of uncertainty in the earthquake loads. The resulting problem is solved using calculus of variations and also within a multiple objective linear programming framework. Illustrative examples on specifying seismic inputs for a nuclear power plant and a tall earth dam are considered and the resulting solutions are shown to be realistic.

The highest response of multi-supported structures subjected to partially specified multi-component earthquake support motions is considered in Chapter 3. The seismic inputs are modeled as incompletely specified vector Gaussian random processes with known auto spectral density functions but unknown cross spectral densities. This type of situations are easily conceivable when the seismic inputs are specified through a set of response spectra which, by definition, do not consider the effect of cross-spectral densities between different excitations. These unknown cross-spectral density functions are determined such that the steady state response variance of a given linear system is maximized. The resulting coherence functions are shown to be dependent on the system properties, auto spectra of excitation and the response variable chosen for maximization. It emerges that the highest system response is associated neither with fully correlated support motions, nor with independent motions, but, instead, specific forms of coherence functions are shown to exist which produce bounds on the response of a given structure. Application of the proposed results is demonstrated by examples on a ground based extended structure, namely, a 1578 m long, three span, suspension cable bridge and a secondary system, namely, an idealized piping structure of a nuclear power plant.

The problem of multi-support critical seismic excitations when the prior knowledge on the inputs is further restricted to only the first two spectral moments is considered in Chapter 4. A method for determining critical power spectral density matrix models for earthquake excitations which maximize steady state response variance of multiply supported extended structures and which also satisfy constraints on input variance, zero crossing rates, frequency content and transmission time lag has been developed. The optimization problem for this case is shown to be nonlinear in nature and solutions are obtained using an iterative technique, which is based on linear programming method. A constraint, on entropy rate as a measure of uncertainty which can be expected in realistic earthquake ground motions is proposed which makes the critical excitations more realistic. Illustrative examples on critical inputs and responses of single degree of freedom systems and a long span suspended cable which demonstrate the various features of the approach developed are presented.

Chapter 5 presents the conclusions emerging from the above studies and makes a few suggestions for further research.

In the Appendix, a newly developed computational scheme for determining the dynamic stiffness coefficients of a linear, inclined, translating and viscously/hysteretically damped cable element is outlined which takes into account. the coupling between in plane transverse and longitudinal forms of cable vibration. The numerical examples on cable systems considered in Chapter 3 and 4 are based on the algorithm outlined in this appendix. This computational scheme is based on conversion of the governing set of quasistatic boundary value problems into a larger equivalent set of initial value problems which are subsequently integrated numerically in spatial domain using marching algorithms. Numerical results which bring out the nature of the dynamic stiffness coefficients are also presented.

Based on the work described above the following papers (with Dr C. S. Manohar as co-author) have been submitted for publication:

- Critical earthquake input power spectral density function models for engineering structures (accepted for publication, scheduled to appear in October 1995 in Earthquake Engineering and Structural Dynamics, a copy of the paper is appended to the thesis).
- Critical coherence functions and the highest response of multi-supported structures subjected to multi-component earthquake excitations (under review, Earthquake Engineering and Structural Dynamics)
- Critical seismic vector random excitations for multiply supported structures (under review, Probabilistic Engineering Mechanics)

Dynamic stiffness matrix of a general cable element. by numerical integrations in spatial domain (under review, Archive of Applied Mechanics)

Vibration of Pipes Resting on Soil Medium

[S. Raghava Chary; April 1993; Supervised by R. N. Iyengar]

Pipelines are used extensively for transportation of fluids. Fluid velocity which depends on the intended purpose, imparts energy to the pipe making it to vibrate. Apart from this, pipes are supported in many ways. While indoor piping are supported on structures, cross country piping used for transporting petroleum products are either laid on ground or-buried. Good amount of literature is available in the area of pipes conveying fluid with emphasjs on stability aspects addressing critical flow velocities. However, the problem of pipe conveying fluid resting on elastic medium has not been fully understood. A modest attempt is made in this thesis to present an approximate analysis for the problem of pipe conveying fluid resting on elastic medium.

In chapter - I, a brief review of, literature is presented highlighting the previous contribution in the field of pipes conveying fluids. In addition the studies made in the area of a beam on elastic foundation closely representing the situation of a pipe on soil medium is presented. Various models used for this purpose have been covered. Based on the review, the scope for the present study is presented.

In chapter - II, vibration of pipe conveying fluid resting on soil medium has been studied modelling the soil medium as Winkler type.. Expressions are derived for critical flow velocity and fundamental natural frequency with flow velocity and soil stiffness as parameters for generally occurring pipe boundary conditions namely hinged - hinged, fixed - hinged and fixed - fixed. Numerical results are presented for various values of stiffness parameter, mass ratio and velocity utilizing the data of a typical pipeline like Trans Arabian pipeline.

Improvements to the model of soil are made in chapter III by including the inertia effect of soil. Frequency expressions obtained with this inclusion are highly non-linear and are solved using nonlinear methods. Numerical results are presented for various boundary conditions and values of soil inertia parameter, stiffness parameter and velocity parameter.

In chapter - IV, an approximate design office procedure is developed to compute the response of a pipe conveying fluid subjected to base excitation. Numerical results are presented for hinged - hinged boundary condition for, various values of velocity and soil parameters. The vertical component of the Taft earthquake (1952), is utilized in obtaining the pipe response.

The thesis ends in chapter - V, with a brief summary, a -set of conclusions and a few suggestions for future work.

Spectrum Compatible Random Processes as Earthquake Excitations
[M. Varadharajan; April 1992; Supervised by R. N. Iyengar]

An important step in the earthquake resistant design of structures is the specification of the induced ground excitation. For very important structures, the input specification obviously must be quite realistic and rigorous. In this thesis, some contributions have been made in the field of probabilistic specification of earthquake ground motion.

Chapter I, presents a brief review of literature on the methods currently available for specifying seismic inputs. Attention is focused mainly on earthquake specification through spectrum compatible power spectral density (PSD) functions. The concept of stochastic critical excitation has also been reviewed. While these developments are described in detail, limitations in the existing methods are brought out to state the motivation behind the present thesis. This is followed by Chapter II wherein an iterative procedure is developed for arriving at the compatible PSD function in a discretized form, from specified design response spectra. The procedure is based on a stationary random process model for the earthquake ground motion. Numerical results have been presented on the generation of PSD function compatible with typical available response spectra. The uniqueness of the generated compatible PSD function is examined by using two different mathematical representations for the PSD function. The internal consistency of the United States Nuclear Regulatory Commission (USNRC (1973)) and Indian Standards (IS (1984)) spectra with respect to different damping ratios has also been examined with the help of the compatible PSD function.

In Chapter III, the solution of the previous chapter is improved by including nonstationarity into the earthquake model in the form of a stationary random process modulated by a known function. The compatible PSD function of the stationary part is generated on a more rational basis by accounting for the probability level of exceedance associated with the design response spectra. It is shown that the incorporation of the precise probability level of exceedance associated with the design spectra into the analysis, ensures proper estimation of the compatible PSD function.

The determination of seismic threat for important structures through the critical excitation method is presented in Chapter IV. The investigation is limited to study the complicating factors involved in the application of stochastic critical excitation method to a multi-degree degree of freedom structure. The possibility of arriving at a common ground response spectra via an enveloping procedure is suggested. The thesis concludes in Chapter V with a summary and a few suggestions for further research.

Free Vibration of Rectangular Plates with Multiple Holes
[R. Ravi; November 1989; Supervised by R. N. Iyengar]

The study of vibration of plates occupies a central place in the dynamic analysis and design of many civil, mechanical and aerospace structures. While a large database is available on the free vibration characteristics of ordinary rectangular plates, information on plates with holes is limited. With this in view, in the present thesis free vibration analysis of rectangular plates with single and multiple holes is presented for various combination of exterior boundary conditions.

Chapter I is a brief review of available relevant literature in the area of circular and rectangular plates with openings. In Chapter II rectangular plates with a single hole is considered. Rayleigh-Ritz technique is adopted to find the natural frequencies and mode shapes for various important boundary conditions. Beam eigen functions are used as trial functions. The results of an all edges clamped plate with a single hole is verified by finite element formulation and the convergence of the results with beam eigen function is established. The analysis is extended to plates with several holes in Chapter III. Again Rayleigh - Ritz formulation is used with beam eigen functions as the trial functions. Results are presented in the form of charts for various hole sizes and exterior boundary conditions. .

Chapter IV is devoted to experimental verification of the theoretical results. Results on the free vibration of several aluminium cantilever plates with varying hole sizes are presented.

The thesis ends in Chapter V with summary, conclusion and a few suggestions for further research.

Non Linear Dynamic Analysis of Reinforced Concrete Beam-column Joints using Finite Element Method

[R. Basawaraja; January 1989; Supervised by B. K. Raghu Prasad]

The dynamic response of reinforced concrete beam-column joint is studied taking account of initiation, closing and reopening of cracks with strain softening effect. The computational procedure is based on two-dimensional non linear finite element method (as is at present restricted to two-dimensional situation). 8-noded iso-parametric elements are used for concrete as well as for steel. Perfect bond between steel and concrete is assumed. The validity of this assumption may be questioned but the nature of distribution of bond stresses near the contact surface between steel and concrete has not yet been exactly established. Von-Mi3es yield criterion is used for both steel and concrete. The non-linearity comes due to elastic-plastic behaviour of steel, concrete and cracking of concrete. The cracks are simulated by smeared crack modelling in which cracks are assumed to be uniformly distributed in the direction perpendicular to maximum principal tensile stress. Tensile strength criterion is used for the initiation of crack. After cracking has occurred, the cracked concrete is assumed to behave differently in two perpendicular directions and elasticity matrix (D-matrix) is suitable,, modified based on a modified stress-strain diagram for concrete in tension, taking into account strain-softening effect. This modified elasticity matrix contains positive shear modulus to account for aggregate interlocking. The equations of motion are integrated numerically using an explicit formulation with central difference scheme. The procedures outlined are demonstrated on a reinforced concrete beam column joint subjected to dynamic (sinusoidal) loading.

Non Linear Dynamic Analysis of Reinforced Concrete Beam Using Finite Element Method

[Shailesh Kumar Agrawal; January 1988; Supervised by B. K. Raghu Prasad]

The dynamic response of reinforced concrete structures (beams) is studied taking account of initiation and closing and reopening of cracks. The computational procedure is based on nonlinear finite-element method and is at present restricted to two-dimensional situations. 8-noded isoperimetric elements are used for steel as well as concrete. Perfect bond between steel and concrete is assumed. The validity of this assumption may be questioned but the nature of distribution of bond stresses near the contact surface between steel and concrete has not yet been exactly established. Von - mises yield criterion is used for both steel and concrete. The nonlinearity comes due to elastic-plastic behaviour of steel and concrete and cracking of concrete. The cracks are simulated by smeared cracking modelling in which cracks are assumed to be uniformly distributed in the direction perpendicular to maximum principal tensile stress. Tensile- strength criterion is used for the initiation of crack. After cracking has occurred, the cracked concrete is assumed to behave as an orthotropic material and elasticity matrix (D matrix) is modified. This modified elasticity matrix contains positive shear modulus to account for aggregate - interlocking. The equations of motion are integrated numerically using an explicit formulation with central difference scheme. The procedures outlined are demonstrated on a reinforced concrete beam subjected to different kinds of dynamic loading e.g., sinusoidal loading, step loading and initial velocity. The effect of various parameters such as area of longitudinal steel (As), area of web steel (Aw), grade of concrete, grade of steel, aggregate interlocking after cracking, cracking opening and closing, energy absorbed due to cracking opening and closing in performing hysterisis loops on the dynamic response of reinforced concrete beam is studied.

Seismic Response of a Power Plant with Base Allowed to Uplift
[N. Mahender; January 1986; Supervised by R. N. Iyengar]

The earthquake induced lateral forces on a structure, computed on the assumption that its base is bonded to the supporting soil, produce an overturning moment which may exceed the available overturning resistance due to dead weight, with the result a portion of the base of the structure would uplift temporarily. This phenomenon of partial separation of the base of a structure from the supporting soil during strong earthquakes has be6n observed in the past and widely reported in the literature.

The objective of this study is to investigate the effect of the lift-off-on the response of a nuclear Reactor structure resting on rock. The Reactor structure is idealized as a lumped mass system with ten degrees of freedom. . The supporting soil is represented by a Winkler model with spring-damper elements distributed uniformly. It is assumed that the springs can not take tension implying that lift.-off takes place when the upward displacement of a portion of the base is greater than the initial static deflection. The flexibility coefficients of the structure are determined by beam theory accounting for flexural and shear deformations.

Influence of shape of a Building in plan on the bilinear inelastic dynamic response of framed structures subjected to earthquake ground motions
[A. Saibaba; February 1985; Supervised by B. K. Raghu Prasad]

Since the inception of the inclusion of the aspect of safety of structures against earthquake ground motions in the structural design, the available literature proves that no significant study of the influence of the shape of the structure in plan has been taken into consideration during analysis.

About three decades ago, it was Luthers, who gave the first thoughts to it. He warned that an asymmetric plan shape might lead to torsional vibrations owing to the eccentricity of mass and stiffness centers of the structure. Later on, in the sixties, Biggs and in the seventies, Dowrick did a superficial study in this regard; Dowrick suggested that an asymmetric plan shape can best be avoided rather than designed for. But a perfectly symmetric plan shape is very difficult to achieve. It can be limited by the shape of site, soil conditions, purpose of the building and a variety of other constraints.

Hence in the present project, this aspect of shape of the structure in plan has been studied in depth and fairly good results regarding the influence of shape on the response have been obtained. Based on this, extensive studies can be continued in this regard, to develop some general criteria for designing structures with asymmetric plan shapes, subjected to earthquake ground motions.

Response of the Base Frame of a Circuit Breaker Subjected to Earthquake Ground motions
[Y. Bala Krishna; January 1985; Supervised by B. K. Raghu Prasad]

An attempt has been made to study the response of the base frame of an Electrical Circuit Breaker subjected to Earthquake Ground motion in horizontal and vertical directions. Digitalized earthquake record of Elcentro, 1940 has been taken for finding the response# The rotational effect on the response due to non coincidence of stiffness centre and mass centre has been taken into account. A bilinear hysteretic force and displacement relationship has been assumed. The circuit breaker has been idealized as a single mass unit resting on the base frame whose stiffness against horizontal and, vertical ground motion has been determined assuming the stiffness to be lumped at the four corners of the frame equally.

The response of the system has been obtained for

1. Horizontal ground motion with rotation in the vertical plane.
2. Vertical ground motion with rotation in the vertical plane.
3. Coupled horizontal and vertical ground motions-along with rotation in the vertical plane, The influence of eccentricity, of the frame* viscous damping on

the total response in the case of vertical ground motion has been studied and the response has been compared with that obtained from seismic coefficient and Response spectrum Methods. The response of the base frame for horizontal, vertical, coupled horizontal and vertical earthquakes has been compared for two kinds of connection, i.e. Rigid frame without braces and pinpointed frame with braces to know the effect of connections on the response. Also an attempt has been made to arrive at an optimum section for the base frame subjected to earthquake ground motions.

Response of Electrical Equipments fixed by holding-down bolts subjected to Earthquake Ground Motions
[Abdul Azeez; January 1985; Supervised by B. K. Raghu Prasad]

This thesis is an attempt to study the response of holding-down bolts of electrical equipment subjected to earthquake ground motions in horizontal and vertical directions. The translational and torsional effects which are created due to the eccentricity of mass center from the stiffness center, also obtained. The equipment is idealized as a single mass supported on the 4 bolts. A bilinear hysteretic force and displacement relationship has been assumed. The response of the idealized equipment is studied for horizontal and vertical earthquake ground motions input. The transnational response in vertical and horizontal directions and torsional response in vertical plane is evaluated. The influence of various parameters viz. eccentricity, stiffness, viscous damping, intensity of the earthquake has been looked into Comparison of the results with Response Spectrum and Seismic Coefficient method is done for some cases.

Inelastic Torsional Response of Offshear Platforms Subjected to Earthquake Ground
[V. Raviraj; January 1985; Supervised by B. K. Raghu Prasad]

The objectives of this paper are (i) to identify the basic parameters which control the earthquake response of torsionally coupled offshore gravity type platform systems composed of resisting elements providing force interaction during yielding. (ii) To clarify the differences in response between systems subjected to single component ground motion and systems subjected to double component ground motion. (iii) To clarify the differences in response between systems with the torsional stiff nesses of the columns about their own centroidal axes neglected and systems with the torsional stiff nesses of the columns considered in the yielding criteria. (iv) To evaluate the maximum ductility requirements in the effects of magnitude of eccentricities on the ductility.

A typical offshore gravity type of platform with a square deck and four resisting columns was used to examine these objectives First. Dimensionless equations of motion were formulated and a yield criteria to include the interaction of the torsional stiffness of the columns was assumed. ElCentro, May 1940, earthquake was used as input and the equations of motion were numerically integrated using linear acceleration-method.

Internal Consistency in Response Spectra
[H. V. Shankar; July 1983; Supervised by R. N. Iyengar]

This report is concerned with establishing a quantitative measure for internal compatibility of response spectrum for real earthquakes. This has been attempted by considering 30 real earthquake acceleration spectra. The data at Emery period for 5 Values of damping has been averaged after normalizing with respect to the zero damping spectra. Thus what has been obtained is the average of the ratio of the damped spectrum to the undamped spectrum. The standard deviation values also have been found. This instates for internal compatibility in what ratio the spectra showed decrease with damping.

The obtained results are compared with the standard spectra given in IS 1893. A comparison with the new-mark and blume spectra widely used in earthquake engineering design is also presented.

Response of Cantilever Structures to Earthquake Excitation
[T. K. Saha; 1976; Supervised by R. N. Iyengar]

Analysis of structures lateral forces is of considerable importance in engineering practice. Lateral forces caused by natural phenomena like wind and earthquake are random processes. Investigation of structural behaviour due to dynamic forces caused by such phenomena is a growing structural engineering problem.

Chimneys and stacks are an important class of civil engineering structures which demand an earthquake resistant in seismic areas. Although, the codes of practice provide some guide lines for the design of such structures there are several questions yet unanswered. One such question is about the effect of self weight and vertical acceleration on the bending moment and shear force developed in a structure during earthquake excitation. In this report an attempt is made to' study this effect to a limited extent.

In Chapter-1, the free vibration analysis of the uniform, cantilever beam including self weight is presented. In Chapter-2, the result of the free vibration analysis has been used to study the relative velocity response, spectrum which is normally sued as a basis for earthquake resistant design. In Chapter – 3, the forced vibration analysis of a uniform cantilever structure under several earthquake excitations has been presented. The effect of self weight and the vertical component of the acceleration has been included in this analysis.

Dynamic Properties of Concrete and Mortor
[R. Rudraprasad; 1976; Supervised by K. S. Jagadish]

The dynamic properties such as pamping constant and resonant frequency of concrete and mortar are important parameters in design of dynamically loaded concrete structures. In services, concrete could have suffered some internal micro-cracking due to stresses acting on them. Hence it is essential to know the influence of such cracking on the logarithmic decrement, etc. of concrete.

In the present investigation a total of 34 specimens cast out of two mortar mixes and two concrete mixes are tested using "Sonic Resonance Test". One mortar mix and one concrete mix each having six specimens were subjected to "Sonic resonance test" which is at minimum of five repetition for each specimen. In this type of test the order of difference for logarithmic decrement was 6% in case of mortar, and 15% in case of concrete which is due to heterogeneity of concrete and mortar mixes. From the other mixes tested for sonic resonance test before and after the application of different percentages of ultimate prior-stress. Logarithmic decrement decreases with increases of prior-stress up to 40% of ultimate stress, and increases with increase of prior-stress after 40% of ultimate stress. There was considerable scatter in the result.

The dynamic modulus, in general, found to be higher than static modulus and also found to decrease with increase of prior-stress.

Dynamic Properties of Concrete, Mortor and Hardened Cement
[P. W. Karkhedikar; 1975; Supervised by K. S. Jagadish

The dynamic properties such as logarithmic decrement and dynamic modulus of concrete are important parameters required in the design of concrete structures to withstand dynamic loadings. In service, due to the stresses acting, concrete could have suffered some internal micro-cracking. Hence it is essential to know the influence of such cracking on the logarithmic decrement etc. on concrete.

In the present investigation a total of 66 specimens cast out of three concrete mix, two mortar mix and cement paste were tested. Logarithmic decrement and dynamic modulus are obtained after subjecting the specimens to a prior-stress of different percentages of ultimate stress. These are determined by making 'sonic resonance test.' In the investigation, the logarithmic decrement is found to increase with respect to an increase of prior-stress, while in some cases it is found to decrease when the prior-stress is increased. The dynamic modulus is found to be higher by about 10% to 25% compared to static modulus.

Response of Inelastic Systems to Earthquake Ground Motion
[B. K. Mohanty; 1972; Supervised by K. S. Jagadish]

The inelastic response of a two-storey framed structure has been studied under the Traft Earthquake of July 21, 1952, N 69 W component. Idealized bilinear resistance-deformation relationship has been assumed for each storey. The non-dimensionalized equations of motion have been numerically integrated by the Newmark-b-procedure to obtain the response. The main system parameters varied are the frequency ratio and the yield ratio. A minimum value for the maximum response of the lower storey has been obtained in this range of values. The response history and the dynamic force-deformation curve has been presented for this optimum set of system parameters. The dissertation has been concluded with a few suggestions for further work.

Geometric Non Linear Effects on Dynamic Response of Suspension Bridges due to Earthquake Excitation
[Sudip Bhattacharjee; Supervised by Ananth Ramaswamy]

Cable supported bridges, being flexible in nature, respond more severely due to ground accelerations than do any other type of bridges. The response is greatly influenced by many parameters governing the bridge geometry and material. One of the parameter is the non linear behaviour of the cables and the deck. Although, the true non linear behaviour of the structure can be both material and geometric. the geometric non linearitys are more predominant in nature and affect the response of the structure. This geometric non linear behaviour arises due to the non linear force deformation relation of the cables. The state of the art technique in cable supported bridge analysis primarily involves a finite element modeling of the structure including nonlinear effects.

In this study, an attempt has been made to project the role of geometric non linear behaviour of suspension bridges on its dynamic response under earthquake excitations. A finite element model of a cable has been developed which incorporates geometric non linear features. In this study Both the cables and the deck- elements have been modeled considering geometric non linear effects. The effects of material non linearities have not been considered in this study. The findings of this study indicates that the construction sequences of suspension bridges induces significance nonlinearities in cable stiffness resulting a shifting in the dynamic response under seismic excitation. A brief review of the topics covered in different chapters are indicated below.

A brief review of the work has been presented in Chapter 1. A brief introduction has been given and the scope and limitations of the works have been indicated.

A critical review of the literatures have been presented in chapter 2. The basic geometric non linear behaviour of a single cable has been briefly explained. The various methods available for modeling the bridge super-structure including the deck an@ cables have been investigated. The use of the beam elements for modeling the deck of the bridges has been explained. It has been noted in this chapter that appropriate Placing of the beam elements in the finite element model is required to depict the exact behavior of the prototype structure. Several existing methods foifinite element modeling of cables have been discussed. The advantage of modeling the cable using truss elements and its limitations in simulating the geometric nonlinear behaviour have been presented in this chapter. The present. study uses a specially developed spar element which incorporates the geometric nonlinear behaviour with the idealized modulus of elasticity. Therefore, a discussion on the cable modeling has bee presented in this chapter which briefly reviews the existing model for idealized modulus of elasticity. Various analytical tools available for the geometric nonlinear forced vibration analysis have been discussed. The various method of simulating the ground motion acceleration has been explained. Lastly, the use of existing, strong motion databases for time history analysis has been indicated.

The development of a finite element model of a cable has been discussed in detail in Chapter 3. The bridge cable undergoes displacements at both the supports under both static and dynamic loads. Keeping this in mind, the cable element has been developed from the governing equation of a basic suspended cable under support displacement assuming the profile to be parabolic. The use of a idealized straight bar element with lengths equal to the length of the span of the cable has been discussed. The stress strain law governing the response of the bar element has been developed from the equilibrium equation for the cable. From the stress strain law, the idealized tangent modulus of elasticity of the bar element has been developed. The ability of the idealized modulus of elasticity to capture the true geometric non linear behaviour of the cable has also been explained in detail. The advantages and disadvantages of using the tangent stiffness modulus has been explained. A parametric study examining the influence of different cable geometric parameters on the stiffness modulus has also been projected. in this context, a few parameters have been identified which govern the equation of equilibrium of the cable. This form of idealized modulus of elasticity has been compared width the existing form and the different inherent inappropriate assumptions of the later one have been shown. Lastly, the same idealized tangent modulus has also been developed using the equilibrium equation of an exact catenary profile of the cable and is used in later chapters for the modeling.

The free and forced vibration response of the bridge have been projected n Chapter 4. It is a known fact that the stiffening behaviour of any structure shifts the natural frequencies of the structure towards the higher end. In this chapter, one of the source of increase in stiffness, namely, the gradual application of the deck load as done in construction process has been discussed. The step by step addition of deck loads in a construction process has been simulated using the finite element model of the bridge by non linear static analysis. The result of this simulation has then been validated by comparing with the results obtained by an analytical simulation of the process using th6 governing equilibrium equation of the cable which changes with each erection step. General recursive analytical formulae have been developed for this purpose. After the non linear static analysis has been per-formed, the free and forced liberation analysis of the structure has been undertaken starting from the stiffness obtained at the end of non linear static analysis. The effects of geometric non linear behaviour of the cable in free and forced vibration analysis have been discussed. Effect of different erection schemes followed at the construction site on the changes in stiffness and hence the response of the structure have been discussed.

Finally, chapter 5 based on the study, a broad set of conclusions have been projected. A few open areas for further research have also been indicated at the end of the chapter.