# Theses: IIT Kanpur

## Doctor of Philosophy

**Seismic Design of Strong-Axis Welded Connections in Steel Moment Resisting Frame Building**
*[Jaswant Narayan Arlekar; 2002; Supervised by C. V. R. Murty]*

Seismic design of welded connections in steel moment resisting frames (MRFs) has received considerable attention during the past decade. One of the main reasons identified for the poor performance of beam-column joints during earthquakes was the vulnerability of welds between beam flange and column to premature brittle fracture. The tri-axial state of stress in this region restrains the expected ductile yielding of the weld material there. The major emphasis of past research on this subject has been the improvement of design of beam-to-column connections to achieve superior performance of steel MRFs during strong ground shaking.

This research addresses welded strong-axis beam-to-column and column-to-foundation connections. Refined truss models are developed for representing the flow of forces near the joint regions. In beam-column joint region, the inelastic stress distribution is symmetric about the beam neutral axis. For the design of beam-to-column connections, the load flow is represented by an Improved K-truss model. But, in the column-foundation joint region, the presence of combined action of axial load, shear and bending moment results in an unsymmetric inelastic stress distribution. Hence, for the design of column-to-foundation connections the load flow is represented by a Twin Truss Model – one for axial load and bending moment and the other for shear.

New geometric configurations are proposed for welded strong-axis beam-to-column and column-to-foundation connections based on inelastic finite element analyses. The chosen connection elements reinforce the joint region and reduce the stress intensity, thereby improving the effectiveness of the connections to transfer loads without brittle failure in the weld region. Step-wise procedures are provided for the seismic design of both of these connections. These design procedures are based on capacity design concept, and incorporate the effects of material overstrength, strain-hardening and member instability.

Nonlinear finite element analyses are conducted to evaluate the performance of beam-column joint subassemblages, wherein the connections are designed using the proposed procedure. Monotonic pushover displacement-based analysis is used to compare the effectiveness of the beam-to-column connections in

transferring loads from the beam to the column. Assumptions made in the proposed design procedure are confirmed. Cyclic displacement-based pushover analysis is conducted for beam-column joint subassemblages and frame storey subassemblages. The proposed connection configuration designed using the proposed procedure showed excellent performance in contrast to that of the connection configuration currently being used in practice and designed by existing code procedures. Nonlinear finite element analyses of column-foundation joint subassemblage are preformed. Critical loading conditions encountered by these subassemblages during strong earthquake shaking are modeled. The column-foundation joints, designed using the proposed procedure, are found to be able to sustain lateral drifts larger than 4%, while retaining significant reserve capacity.

The seismic performance of steel MRF buildings can be significantly improved by adopting the proposed reinforced joint connection configuration in conjunction with the proposed procedure for their design. The connections so achieved are capable of avoiding the premature brittle fracture of the welds at the column face.

**Wavelet-Based Non-Stationary Seismic Response of Structural System**
*[Biswajit Basu; December 1997; Supervised by Vinay K. Gupta]*

This study proposes a wavelet-based approach for the estimation of the response of linear and non-linear structural systems which are subjected to an earthquake ground motion process modelled by its wavelet coefficients. An orthogonal wavelet basis function has been proposed for this purpose. The proposed formulation considers a more realistic modelling of the ground motion, and is thus more generalized as compared to the earlier methods based on the use of frequency-independent modulating functions. The linear structures have been idealized by single-degree-of-freedom (SDOF) and classically damped multi-degree-of-freedom (MDOF) systems for the purpose of formulation. Expressions have been derived for i) the representation of the input excitation through wavelets, ii) relationship between the wavelet coefficients of the excitation and response processes, and iii) instantaneous mean- square value and power spectral density function (PSDF) of the response. The moments of the PSDF of response are used to predict the response statistics of interest. Non-linear systems with non-linearity in stiffness or damping have been considered via linearization to systems with time-varying parameters. A Duffing oscillator has been considered to illustrate the performance of the proposed linearization in case of non-linear stiffness. For considering systems with non-linear damping, pure-friction (P-F) base-isolated structural systems have been considered. Those are modeled as i) a rigid block on a friction base, and ii) a two-degree-of-freedom

(2-DOF) base- isolated system. The effectiveness of the base-isolation system and the effect of the frequency non-stationarity on the non-linear response have also been studied in detail. It has been clearly shown how the ignoring of frequency non-stationarity in the ground motions may lead to inaccurate non-linear response calculations. Various formulations proposed in this study have been illustrated through comparison of the (wavelet-based) stochastic estimates with those obtained from time-history simulations.

**Stochastic Response of Suspension Bridges to Spatially Varying Earthquake Exicitations**

*[Manish Shrikhande; July 1997; Supervised by Vinay K. Gupta*

The stochastic response of a suspension bridge including the dynamic soil-structure interaction (SSI) effects to spatially varying earthquake excitations has been studied. Since the currently available procedures for the stochastic analyses of structural systems cannot be generalized to the case of suspension bridges, particularly when the SSI effects have to be accounted for, an alternative approach has been formulated in frequency-domain for the non-stationary seismic analyses of simple SDOF and MDOF systems. This approach is then extended to the formulation for suspension bridges by considering fixed-base modes and by modifying the excitations at different supports for the soil-structure interaction effects. The proposed formulation requires the characterization of ground motion in form of a coherency function, and the values of peak ground acceleration (PGA), Fourier spectrum and strong motion duration. The proposed approach has been validated via time-history analyses for two sets of synthesized spatially correlated accelerograms. For generating these accelerograms, a new approach based on the spectral decomposition technique has been proposed. This approach can be used to synthesize ensembles of realistic and spatially correlated accelerograms at several closely spaced stations. The accelerograms are made consistent- with a specified coherency function by using the duration spectrum and the phase characteristics of a previously recorded accelerogram. Further, the generated accelerograms at the reference station are also made consistent with the specified design spectrum in the mean sense.

It is found from a numerical study that the dynamic soil-structure interaction effects can considerably alter the response of suspension bridges founded on soft soils. Further, the suspension bridge vibrations in the vertical plane may not always be governed by the longitudinal ground motions as the relative contributions of the vertical ground motions increase with increasing soil compliance. It has also been found that the spatial variation of ground motion may significantly influence the response modification due to soil-structure

interaction effects. For soft soils, and more uniform and coherent motions, these effects may actually lead to substantial amplifications in the bridge response.

**Torsional Behavior of Elevated Water Tanks with Reinforced Concrete Frame-Type Stagings during Earthquakes**
*[Shekhar Chandra Dutta; October 1995; Supervised by Sudhir Kumar Jain and C.V.R. Murty]*

Elevated water tanks have filled during past earthquakes owing to large torsional response. Considerable torsional response may occur due to accidental eccentricity if the uncoupled torsional and lateral natural periods of the tanks are closely spaced. Torsional response of RC elevated water tanks supported on axisymmetric frame-type stagings has been studied in this thesis.

Such stagings are idealized as one-storey lateral-torsional coupled systems consisting of two or four lateral force resisting elements, depending on the lateral-to-torsional stiffness ratio and lateral-to-torsional strength ratio of the staging. Linear and non-linear responses of these systems are studied due to earthquake ground motions. This study focuses attention on the maximum element displacement. Between two systems having the same lateral and torsional natural periods, normalized eccentricity and modal damping, the one with a lower torsional-to-lateral stiffness ratio, i.e., tanks with small number of panels and columns, undergoes a larger torsional response. Also, in the elastic range the element displacement takes a minimum value at a torsional-to-lateral natural period ratio (t) very close to 1.0 and a maximum value each on either side of this minimum. The range $0.7<t<1.25$ is found critical from torsion view point.

Nonlinear behaviour is studied through a simple strength-deteriorating hysteresis model. In general, the idealized two-element systems (i.e., staging with low number of columns and panels) are found more vulnerable than the four-element systems (i.e., Stagings with large number of columns and panels). The element displacements are found to be significantly larger than those of the corresponding symmetric systems. If the rate of strength deterioration is large or if the ductility reduction factor used in design is 2 or more.

The dynamic characteristic of usually constructed elevated water tanks on a circular row of columns beams are studied. Approximate expressions for the torsional and lateral stiffnesses, and for the natural period ratio (t) are derived. These tanks are found to generally have t in the critical range identified in the linear study.

Four alternate staging configurations are studied: with redial beams, with redial beams and central column, with two circular rows of columns, and with diagonal braces. Expressions for estimating their lateral and torsional stiffness and natural period ratio (t) are derived. First three of these configurations are found to have higher value of t than that of the corresponding basic configuration, and the fourth configuration has a lower value. These configurations can be utilized to avoid large torsional response and to retrofit existing stagings.

**A Ductility And Displacement Based Design Procedure For Seismic Design of Reinforced Concrete Frames**
*[Gehad Ez-Eldin Rashad; November 1993; Supervised by Sudhir Kumar Jain]*

A displacement and ductility based design procedure (DDBDP) for reinforced concrete frames has been proposed which explicitly considers strength, stiffness, ductility, and structural configuration. The procedure satisfies the design requirements ate two limit states; serviceability limit state (SLS) and ultimate limit state (ULS). To obtain the outer envelop of base shear - roof displacement relationship, a displacement-control non-linear quasi-static analysis has been proposed. The analysis is carried out by imposing a lateral displacement profile on the structure in small increments. The displacement profile is proportional to the first mode shape of the structure, when it is elastic. Under inelastic conditions, the profile is also a function of mode shape of the "yielding" structure at that stage. A computer program has been developed to carry out this quasi-static analysis. The base shear - roof displacement relationship, so obtained is used to assess the suitability of design for stiffness, strength modelled by the ULS. To account for effect of low initial stiffness modelled by the non-linear analysis procedures on drift requirements at ULS, a correction based on a more realistic linear analysis has been suggested.

A limited parametric study has been conducted to assess the displacement-control quasi-static non-linear procedure with request to the time-history analysis. The displacement-control quasi-static procedure is seen to give reasonably accurate behavior and is more consistent than the force-control procedure

## Master of Technology

**Improved Seismic Coefficient Method to Incorporate Deformation Types and Higher Mode Effects**

*[Subhatosh Nandi, December 2005, Supervised by C. V. R. Murty]*

Current seismic code specifications for design of buildings use a design base shear spectrum based on single-degree-of-freedom (SDOF) systems and specify the lateral force profile using an assumed fundamental mode shape. The present study proposes an improvement to the above method, which is known as the Equivalent Lateral Force (ELF) Method, by incorporating the effects of deformation type and higher modes. The study idealizes buildings as uniform vertical cantilevers which; being continuum systems, have infinite number of deformation modes of which the significant modes are included in the analysis. A shear factor $\beta$ is used to characterize the relative contributions of flexural and shear deformations, $\beta = 0$ implying pure flexural behaviour and $\beta = \infty$, pure shear. Closed form solutions of the governing differential equation of cantilevers subjected to ground motion are obtained and time history analyses are performed. The base shear response spectra and lateral force distributions obtained from the study are compared with code provisions.

Code spectra are found to overestimate the base shear at low natural periods and underestimate at high natural periods. The effects of higher modes are significant for systems with high fundamental natural periods. Spectral ordinates are found to increase with increasing $\beta$ at low natural periods and with decreasing $\beta$ at high natural periods. Lateral force distribution profiles resulting from the study are seen to be considerably influenced by higher modes and $\beta$, especially at high natural periods. The study suggests the lateral force at the base be assigned a non-zero value, which is a departure from code profiles. In general, code profiles are seen to underestimate lateral force at lower storeys and overestimate them at higher storeys. Based on a limited number of ground motions, the study proposes analytical expressions to obtain the proposed alternative base shear spectrum and lateral force profiles.

A revised drift spectrum has been suggested as a complement to the response spectrum. The original drift spectrum was based on wave propagation analysis of a shear cantilever. This study recommends the use of modal time history analysis using the vertical cantilever mentioned above to derive the drift spectrum. This approach is closer to engineering practice and can give drift spectra for various deformation types while the original spectrum was limited to shear buildings. Moreover, the new drift spectrum requires ground acceleration records alone, while the original spectrum required ground displacement and velocity traces.

**Enahncement of Flexural Capacity of Undamaged RC Column by A Composiste Steel Caging Technique**

*[Pasala Naga Prasad, October 2005, Supervised by Sudhir K. Jain and Durgesh C. Rai]*

The upgradation of reinforced concrete buildings is frequently connected with requirements for their new utilization and for increasing load-carrying capacity of a structure. From the past earthquakes, most of the RC structures suffered damage or complete collapse mainly due to the inadequate strength and ductility of the column which play a vital role in the stability of the existing or deteriorated buildings. The existing vulnerable RC structures which have or could suffer damage due to inadequate strength can be repaired or upgraded by enhancing the ductility and/or capacity of critical column by any of the repair and strengthening techniques. Steel caging composite technique, is one of the various methods used for strengthening of rectangular reinforced concrete column. This technique is composed of steel angles and transverse steel flats as battens. In the present experimental study a rectangular reinforced concrete column is studied for flexural strength and ductility in the presence of axial load. The enhancement of strength of the column section is determined with the help of a theoretical model proposed for confinement which is similar to the confinement provided by the ordinary stirrups onto the concrete core. The present experimental study verifies the theoretically prediction strength of the strengthened column and studies the overall behavior, failure and ductility of the strengthened column.

In the present experimental study, three RC columns, one ordinary column and two strengthened columns with steel caging are subjected to constant axial load which represents 55% of design axial load and reversed cyclic loading and their performances are compared. The strengthened columns are designed for twice the flexural capacity of the ordinary column. It is experimentally observed, that the strengthened columns showed 1.98 and 2.42 times the flexural capacity of the ordinary column and ductility by 2.43 and 3.18 times the ductility of ordinary column. The confinement model predicted good results under the present loading conditions.

**Control of Out of Plane Deformation of Inelastically Buckling Aluminium Shear Panels**

*[Saiket Banerjee, October 2005, Supervised by Durgesh C. Rai]*

Yielding of the shear panels can be used to dissipate energy through hysteresis provided strength deterioration due to inelastic buckling is controlled. In the present study, aluminium shear link with confined web panels were examined experimentally under the application of cyclic lateral shear. Natural rubber block along with steel plate were used for the purpose of confinement. Soft alloys of

aluminium are less susceptible to web buckling problems because of their low yield strength which enables the usage of thicker webs. Widely available alloy 6063 and 1100 of aluminium for structural applications was used for fabrication of the I-shaped specimens with transverse stiffeners from plates using TIG welding process. Since this alloy was available in a harder temper, it was annealed in order to reduce it to soften temper O and also to relieve residual stresses developed due to welding. Six specimens of aluminium panels were fabricated with different geometric parameters, like web thickness, spacing of stiffeners and number of panels which affect the onset of inelastic buckling. All the specimens were tested under pseudo-static reversed cycle loading with increasing displacement levels using 500 kN servo-hydraulic actuator.

The specimens showed very ductile behaviour and excellent energy dissipation potential with unpinched and full hysteresis loops with shear strains upto 0.2. The confinement provided was effective in controlling the out-of-plane deformation of the web panel, although the onset of inelastic buckling did not improve much from that of the unconfined shear links. The experimental dataset of confined and unconfined shear links was used to obtain the proportionality factor in Gerard's formulation of inelastic buckling. This result is further used to obtain a relation between panel aspect ratio, the web panel depth-to-thickness ratio, and web buckling deformation angle for cyclic inelastic buckling, which can be used to determine the spacing of stiffeners.

Finally, eigenvalue buckling analysis and nonlinear static analysis of the aluminium shear link model were done in finite element analysis programme ABAQUS to verify the load deformation behaviour and the other aspects of experimental study.

**Review of Blast Resistant Buildings and a Case Study of Library Building at IIT Kanpur**
*[Lt. Col. Jasinder Singh Sodhi, June 2005, Supervised by Sudhir K. Jain]*

The word "Terrorism" in today's era has percolated in everybody's life. It has assumed a significant and dangerous dimension. The recent terrorist attacks the world over have demonstrated that the public buildings and the common man are as prone to such dangers as conventional security risk buildings. The most potent weapon any terrorist uses is RDX or TNT. These names have become as common as normal day to day words of English language.

Today no building is safe. Once conventionally regarded "soft targets" are being used by the terrorists in a big way to cause damage and gain publicity. Incorporation of certain blast resistant design features can reduce the damage to human life and property. The success of adaptation of these blast resistant design

features would be quite evident when an engineer or an architect working at the grass root level would imbibe them in planning and execution of his projects.

The existing Library Building at IIT Kanpur is an aesthetically designed building which is partly on stilts. This building houses one of the most renowned Libraries. Recently IIT Kanpur has been rated as the numero uno engineering college of the country. It is highly probable that any terrorist organization might try to cause a blast in this building to gain world wide attention.

This Thesis work comprises two parts, namely, enumeration of guidelines for blast resistant buildings and study of the impact of blast loading on existing Library Building at IIT Kanpur.

The Library Building was studied for blast loading using the software SAP 2000 Version 9.1.1. The blast load was modeled as a ramp function. On the basis of the bending moments obtained in the members, the Demand Capacity Ratio was calculated for two cases of blast loading and the impact of damage was assessed and the building was found to be vulnerable under 31.75 kgs explosive in the ground storey.

**Response of Buried Continuous Pipeline to Permanent Ground Deformation**
*[Suresh Ranjan Dash May 2005, Supervised by Sudhir K. Jain]*

The response of continuous buried pipelines to lateral spreading is studied mainly through the pipeline strain due to longitudinal and transverse PGD (Permanent Ground Displacements). The existing approaches of analysis of buried pipelines subjected to spatially distributed PGD are reviewed along with their results. A continuous pipeline resting on ground and subjected to transverse PGD and vertical settlement is modeled as a continuous beam resting on non-linear soil springs(axial, lateral and vertical) using SAP2000 structural analysis software. The responses so obtained are found to match reasonably well with those from the previous finite element model studies. The results show that the maximum strain induced in the pipeline is critically dependant on the width over which the ground displacement occurred. In addition, the pipeline is analyzed by both pseudo-static and dynamic analysis methods. The pseudo-static analysis underestimates the peak pipe strain compared to the dynamic analysis. Hence, for obtaining conservative force demands on the pipeline, the dynamic analysis is preferable with detailed modeling.

**Seismic Response of RC Frame Buildings on Stilts**
*[Perwez Ahmad, October 2004, Supervised by Sudhir K. Jain]*

Two frames three-story one-bay and five-story tow-bay were designed for loads corresponding to different zones as per Indian seismic code as well as for only gravity loads in one case. Frames designed for seismic loads were detailed as per ductile detailing code, else detailing was ordinary. Ground story columns of stilt frames designed for zone III were redesigned for 2.5 times forces coming from bare frame analysis. In the next case, first floor beams were also redesigned for 2.5 times forces. The masonry infill panels were modeled as equivalent diagonal struts. Nonlinear pushover analysis was performed on bare, stilt and infill frames. The performance of stilt frames were compared with bare and infill frames in terms of strength, stiffness, deformation capacity, and overstrength factor.

The study shows that deficit in ground story stiffness is 50-90% due to absence of infills; while overall stiffness deficit is 25-65% and strength deficit is 10-70%. Strength and stiffness deficit in ground story caused by absence of infills was more prominent if ground story height is more, while it is less significant in the frames designed for higher seismic zones. Both stilt frames in all design cases collapsed due to failure of ground story columns. It implies that ground story columns are more susceptible to failure than first floor beams in stilt frames. Increase in overstrength factors due to infills was more significant in infill frames compared to stilt frames. Overstrength factor due to infills was observed to decrease in frames designed for higher seismic zones. Column-overstrength factor decreases in higher seismic zones, as a result weak-column strong-beam mechanism was more likely. Deformation capacity was considerably increased due to ductile detailing in seismic design cases. In cases where, ground story columns & first floor beams of stilt frames were redesigned for 2.5 times of bare frame forces, an increase in stiffness and strength was noted; however, there was a decrease in deformation capacity.

**Forced Vibration Study of a Reinforced Concrete Building**
*[Lt. Col. Sanjay Adsar, September 2004, Supervised by Sudhir K. Jain]*

Forced vibration tests are performed on a reinforced concrete (RC) moment resisting frame (MRF) building with unreinforced masonry (URM) infill walls to determine its dynamic properties namely, the fundamental translational and torsional natural periods, the corresponding mode shapes and the structural damping. This three-storey building lies in the seismic zone III of India. An eccentric mass-shaker is used as force generator operating between 200 and 1400 cps, is used to apply a high level force and shake table for low level harmonic force at desired frequencies.

The building is analytically modelled using the FEM package, ETABS. Three models namely Bare frame model, Model with infill walls modelled as diagonal struts without incorporating the effect of openings and Walls modelled as diagonal struts after considering the effect openings struts. The dynamic properties of the building as derived using these models are compared with the experimentally obtained ones. The material properties used in the modelling, i.e., modulus of elasticity of brick masonry and reinforced concrete, are determined by in-situ tests. It is found that the analytical model with infill walls modelled as diagonal struts gave good correlation with the experimental results, whereas the bare frame analytical model ignoring stiffness contribution of masonry walls substantially overestimated the natural period in translational and torsional modes of vibration.
It is observed that the high-level vibrations produced by the eccentric mass shaker could excite the building fairly well thereby enabling better evaluation of the dynamic properties as the vibrations were not influenced by an ambient source of disturbance. Hence, this high force amplitude shaker can be very effectively used to study the dynamic properties for a variety of structures in the Indian subcontinent.

**Experimental Investigation of Inelastic Cyclic Buckling of Aluminium Shear Panels**
*[Sachin Jain, September 2004, Supervised by Durgesh C. Rai]*

Yielding of the shear panels can be used to dissipate energy through hysterisis provided strength deterioration due to inelastic buckling is controlled. In the present study, cyclic inelastic buckling of aluminium panels in shear was examined experimentally. Soft alloys of aluminium are less susceptible to web buckling problems because of their low yield strength which enables the usage of thicker webs. Widely available alloy 6063 of aluminium for structural applications was used for fabrication of the I-shaped specimens with transverse stiffeners from plates using TIG welding process. Since this alloy was available in a harder temper T6, it was annealed in order to reduce it to softer temper O and also to relieve residual stresses developed due to welding. Nineteen specimens of aluminium panels were fabricated with different geometric parameters, like web thickness, spacing of stiffeners and number of panels which affect the onset of inelastic buckling. All the specimens were tested under pseudo-static reversed cyclic loading with increasing displacement levels using 500 kN servo-hydraulic actuator.

The tendency of buckling of the panel is delayed on increasing web depth-to-

thickness ratio and reducing its aspect ratio. The specimens showed very ductile behaviour and excellent energy dissipation potential with unpinched and full hysterisis loops with shear strains upto 0.2. The experimental data set was used to obtain the proportionality factor in Gerard's formulation of inelastic buckling. This result is further used to obtain a relation between panel aspect ratio, the web panel depth-to-thickness ratio, and web buckling deformation angle for cyclic inelastic buckling, which can be used to determine the spacing of stiffeners, which will limit the inelastic web buckling at design shear strains.

**Effect of Soil Structure Interaction on Strength and Ductility Demands of Shaft Supported Elevated Water Tanks for Earthquake Loads**
*[Bhumika Singh, May 2004, Supervised by Durgesh C. Rai]*

Elevated water tanks supported on shaft-type stagings performed unsatisfactorily in past earthquakes. Codes recognize the lack of redundancy, overstrength and ductility in shaft-type stagings, and recommend larger design forces. In this study, strength and ductility demands of shaft stagings of eight tanks damaged during 2001 Bhuj (India) earthquake are re-assessed based on elastic and inelastic analyses considering soil structure interaction and sloshing motion of water inside the tank container. Shaft sections are found to fail at a higher base shear when soil-structure interaction is considered, than their fixed base counterparts. Also, ductility demands are less when soil-structure interaction is accounted for. Further, failure mode of a shaft *(i.e.,* flexure or shear) depends on its aspect ratio and natural period of the tank. The study identifies that shaft supported elevated water tanks designed considering (a) the effect of soil-structure interaction, and (b) *both* flexure and shear capacities depending on their aspect ratio, are likely to show improved performance during earthquakes.

**Battened Double-Channel Beam-Columns under Cyclic Load**
*[Dipti Ranjan Sahoo, December 2003, Supervised by Durgesh C. Rai]*

Double-channel sections are often used as beam-columns, which are connected to each other at few places by means of battens. The load-displacement behaviour of such members is adversely affected by compound buckling and large shear deformations. During seismic overloads, the local instability of components of battened beam-columns prevents to develop its full plastic moment carrying capacity and to allow the sufficient rotations required for expected ductility demands.

In the present study, the double-channel battened members subjected to constant axial compression and gradually increasing reversed cyclic lateral load. A specimen of double-channel battened beam-column, designed as per IS specifications, was tested experimentally and it failed due to lateral instability of the beam-column, prior to reaching its full plastic moment carrying capacity. However, the degradation of flexural strength and stiffness of the member started from the onset of local buckling of flanges and webs of channel section. The design of battened beam-column was modified in two stages by changing the configuration of batten in the plastic hinge region, i.e., a) reducing the spacing of battens in end panel by half, and b) "boxing" the end panel section by a wider batten. The modified designed specimens showed excellent performance in terms of flexural strength and stiffness, moment rotation response, ductility and energy dissipation capacity as compared to specimen designed as per IS Specification. However, the specimens having "boxing" configuration could able to reach its full plastic moment carrying capacity. The experimental results were verified by finite element analyses, using ABAQUS.

Seismic performance of battened double-channel beam-columns can be improved by closer spacing of battens in the plastic hinge region and further improvements can be obtained by "boxing" the plastic hinge region.

**Wavelet-Based Generation Of Spatially Correlated Accelerograms**
*[Kaushik Sarkar, July 2003, Supervised by V. K. Gupta]*

Consideration of spatial variability in seismic ground motion in the analysis of extended structures has been proven to be essential. For simple structures this can be conveniently incorporated in terms of cross power spectral density function during stochastic analysis. But for complex or non-linear structures, where time-history analysis is to be performed, a set of properly correlated earthquake accelerograms is required. In view of this, a new simulation approach for the generation of spatially variable seismic ground motions is presented. The simulated motions have realistic temporal variation in amplitude and frequency content and those are consistent with the design spectrum in the mean sense. Wavelet transform has been used for the time-frequency analysis and a new complex harmonic wavelet basis function has been proposed specially to deal with earthquake signals. Though a stationary coherency model has been chosen, but it can easily be extended for any other non-stationary model also, when they are made available. The proposed approach has been illustrated by two examples.

**Design Spectrum-Based Scaling Of Strength Reduction Factors**
*[Debasis Karmakar, July 2003, Supervised by V. K. Gupta]*

Strength reduction factors (SRFs) continue to play a key role in obtaining inelastic spectra from elastic design spectra (through response reductions factors) for ductility-based earthquake-resistant design. Despite several years of sustained research efforts, it remains interesting to explore how best to estimate these factors for a given design situation. This study proposes a new model to estimate the strength reduction factor (SRF) spectrum, in terms of a pseudo spectral acceleration (PSA) spectrum (normalized with respect to peak ground acceleration, PGA) and ductility demand ratio, with the help of two coefficients. The proposed model is illustrated for an elasto-plastic oscillator, in case of ten recorded accelerograms and three ductility ratios. The proposed model is more convenient to use in real-life applications and is able to predict SRF spectra reasonably well, particularly at periods up to 1.0 sec. Its parameters may be determined either by matching with the SRF spectrum for a single accelerogram or from the SRF spectra for a suite of accelerograms that are compatible with the same response spectrum. Those parameters are estimated in this study with the help of 1274 accelerograms recorded in western U.S.A., in case of design spectra for different combinations of earthquake magnitudes, site conditions and epicentral distances. A parametric study is also carried out for the explicit dependence of SRF spectra on strong motion duration, earthquake magnitude, site conditions, and epicentral distance. The Trifunac-Brady definition of strong motion duration is generalized for this purpose, and it is found that there is no clear and significant dependence of SRF spectra on strong motion duration. The parametric dependence on earthquake magnitude, site conditions, and epicentral distance conforms to the trends reported by earlier investigations. In particular, this study confirms that the dependence of SRF spectra on earthquake magnitude should not be ignored.

**A Statistical Study of Inelastic Displacement Ratio Spectrum For Existing Structures**
*[Debasis Karmakar, July 2003, Supervised by V. K. Gupta]*

Displacement-based design has been lately gaining importance due to the emergence of the performance-based engineering, and it is now becoming necessary to estimate maximum (inelastic) displacements of structures for different levels of seismic hazard. Being closely related to damage, displacement (or drift) has become an important parameter necessary to meet various performance goals. It is considered convenient to estimate the inelastic displacement demand in a structure by multiplying the elastic displacement demand of the structure with a ratio called as the inelastic displacement ratio. A comprehensive study has been conducted for the parametric dependence of the

inelastic displacement ratio in single-degree-of-freedom (SDOF) systems with known relative lateral strengths, on strong motion duration, earthquake magnitude, epicentral distance and geological site conditions. This study is more rational than the earlier studies of similar type as other governing parameters have been kept fixed while effects of variation in any particular parameter are studied. This study is based on the generation of ensembles of synthetic accelerograms from a database of 1274 accelerograms recorded in western U.S.A. for pseudo spectral acceleration (PSA) spectra of given source and site parameters. A new definition of strong motion duration has been proposed to overcome the limitations of the existing definitions in the context of the present study. It has been found that strong motion duration may influence the inelastic displacement ratios, depending on the hysteretic properties of the oscillator, in case of durations not much longer than 10 sec. Earthquake magnitude has a significant influence on these ratios for the SDOF systems of most time-periods while site conditions appear to be important for the stiff oscillators. A scaling model has also been proposed in this study for estimating the inelastic displacement ratio spectrum from normalized relative velocity spectrum of the ground motion. This model indirectly includes the effects of various governing parameters and has been shown to preserve the trends available from the direct study.

**Lateral Stiffness of Unreinforced Brick Infilled RC Frame with Central Opening**

*[Goutam Mondal, July 2003, Supervised by Sudhir K. Jain]*

Window and door openings are inevitable parts of infill walls for functional reasons. Currently publications like FEMA-273, ATC-40 contain provisions for the calculation of stiffness of solid infills mainly by modelling infill as a "diagonal strut". However, such provisions are not provided for infills with openings. The present study proposes a reduction factor for effective width of diagonal strut over that of the solid infill to calculate the initial stiffness of infills with a window opening. Parametric finite element analysis has been carried out on single-bay single-storey, single-bay two-storey and single-bay three-storey frames in order to examine the effect of central opening of different sizes on the initial stiffness of infill wall. The finite element model has been verified using experimental results of seven different specimens reported in the literature. Based on the parametric studies a reduction factor is proposed to determine the strut width for an opening present in the infill panel. The proposed strut-width reduction factor has been verified by changing some of the parameters and by applying the reduction factor on the experimental results of an independent single-storey single-bay specimen.

**Investigation of Seismic Shear Design Provisions of IRC Code for RC Bridge Piers Using Displacement-Based Pushover Analysis**
*[Rupen Goswami, August 2002, Supervised by C. V. R. Murty]*

Monotonic lateral load-deformation relationships of RC bridge piers bending in single curvature, designed as per the existing Indian standards, are analytically derived. For this, a static nonlinear displacement-based pushover analysis programme is developed. The analysis captures progression of plasticity, both along and across large pier sections using a fibre model. The effective shear stiffness considered accounts for both flexural translational and shear translational deformations of a general pier. Using an existing concrete confinement model, applicable for both circular and rectangular solid and hollow RC sections, appropriate hysteretic uniaxial constitutive relations for concrete and longitudinal steel are developed to account for unloading and reloading in fibres during redistribution of stresses in the sections. Buckling of longitudinal steel is also accounted for.

From analysis of a number of piers, transverse reinforcement requirements are found to be inadequate; shear capacities of sections are found to be lower than the shear demand due to flexure, except in slender piers. Increasing transverse reinforcement increases the deformability and ductility of the pier. Increase in the level of axial load reduces the ductility but increases the shear demand on the section. Providing additional radial links in hollow circular sections increases the ductility of piers.

**Investigation of IS Code Provisions on Seismic Design of RC Structural Walls**
*[Kaustubh Dasgupta; August 2002; Supervised by C. V. R. Murty and Shailesh K. Agarwal; CBRI, Roorkee]*

The compliance of wall sections, designed as per the current Indian Standard, with the capacity design philosophy is investigated. For this, the material characteristics during overstrength conditions are used for concrete and steel. The overstrength axial force-bending moment interaction curves are used to determine the flexural plastic hinge based overstrength shear demand that is compared with the design shear capacity. Structural walls of multistoreyed-framed buildings, designed as per the Indian Standard, are analysed to identify the possible modes of shear failure during flexural overstrength conditions. The top storeys of all the buildings and some storeys of the midrise buildings show vulnerability to shear failure. However no particular trend in the exceedance of shear demand over the design shear force is observed.

**Probabilistic Seismic Hazard Analysis of North-East India**
*[Sandip Das; August 2002, Supervised by Vinay K. Gupta]*

A probabilistic seismic hazard analysis has been carried out for the North-East India. Probabilistic seismic hazard maps have been prepared based on the uniform hazard response spectra for absolute acceleration at stiff rock/rock sites, as those represent a much more complete characterization of seismic hazard than the traditional maps prepared on the basis of peak ground acceleration. For doing the hazard analysis, a new attenuation model based on pseudo-spectral velocity scaling has been proposed by using 261 recorded accelerograms. The entire North-East India has been divided into $0.1^{o}$ grid size, and the hazard level has been assessed for each node of this grid by considering the seismicity within a 300 km radius area around the node. Using the past earthquake data, the seismicity for the area around each node has been evaluated by defining a and b values of the Gutenberg-Richter recurrence relationship, while taking care of the completeness of the earthquake catalogue. Each node has been considered to be disturbed by 50 annular source elements, for each of which the numbers of events in a magnitude class are estimated by distributing the total number as per the spatial distribution of past earthquake occurrences. Uniform hazard contours for pseudo-spectral acceleration as the hazard parameter have been obtained for a time-interval of 100 years and for 50% confidence level at different time periods for both horizontal and vertical components of ground motion. The trends reflected by these contours validate the seismicity model adopted for this study. Further, a comparison of the estimated hazard levels with those prescribed by the Bureau of Indian Standards code shows that (i) the assumed 50% risk level over 100 years service life in the code is not consistent with the peak ground acceleration specified for the North-East India, and that (ii) the present practice of specifying seismic hazard through peak ground acceleration and a fixed spectral shape may be inappropriate for structures in most areas of the North-East region.

**Experimental Investigation under Cyclic Loading of Brick Masonry House with Pre-cast RC Channel Flooring System developed by CBRI**
*[Jayanta Dutta; August 2001; Supervised by C. V. R. Murty and Shailesh K. Agarwal, CBRI, Roorkee]*

Extensive earthquake damage to masonry structures, in the past earthquakes demand better understanding of the responses of such structures under lateral load. The large stock of these vulnerable buildings also indicates urgent need for effective and economic techniques to strengthen them. In the present study, a single-room, single-storey full-scale brick masonry building with Precast RC roofing system was tested thrice under displacement controlled lateral cyclic

loading, to assess the effectiveness of the basic seismic repair and strengthening techniques. The in-plane diaphragm action offered by the Precast technology-based RC roofing system is also evaluated. A new strengthening technique was also introduced, and its effectiveness under lateral loading was evaluated. In the first attempt, the virgin building specimen was loaded laterally to failure. This damaged building was repaired by stitching across the cracks, and tested under the same lateral loading. The twice-damaged structure was repaired once more by stitching and strengthened by steel twin lintel belt and vertical corner reinforcement, and re-tested.

The building repaired by steel twin lintel belt showed better performance in comparison with the unstrengthened one under lateral loading and it could achieve strength well above that of the original one. However, the Precast roofing system studied seems vulnerable under strong earthquake shaking.

**Intensity Attenuation in Indian Earthquakes**
*[Sailender Kumar Chaubey; 2001; Supervised by Sudhir Kumar Jain]*

India has experienced a large number of earthquakes in the past. The number of strong motion records from these earthquakes is very small, and is not sufficient to be used for the development of attenuation relationships and to evaluate seismic risk for future earthquake. On the country, maps are available for a substantial number of earthquakes and it is prudent to use these for the development of attenuation relationships.

In this study, 59 earthquakes from different parts of the country have been considered. The isoseismals are collected from different sources. All the isoseismals along with their intensity distance data are presented in a tabular form. The Indian subcontinent is divided into six attenuation provinces, viz., Northwest, North, Northeast, Peninsular, Foredeep and Subduction. Different attenuation models are tried and best model has been found. For the first time, Indian subcontinent models relating magnitude and maximum intensity have been developed.

Intensity Attenuation relationships have been developed for each region. A single equation is also developed for entire Indian Subcontinent. Epicentral as well as hypocentral distance has been used and relationships are developed along the major and minor axes of the fault in addition to that for average attenuation (considering average radius of intensity Contour as distance parameter). The derived relationships are compared with that of India and other countries.

The approximate decay pattern of intensity for different provinces and distance Li to which the intensity decay curve follows a particular trend has been found. It has been shown, whether it is prudent to use the relationships developed in other Countries for seismic risk analysis in India.

**Scaling of Strength Reduction Factors for Degrading Elasto-Plastic Oscillators**
*[Arindam Chakraborti; August 2001; Supervised by Vinay K. Gupta]*

The inelastic (design) spectra characterizing a seismic hazard are generally obtained by the scaling-down of the elastic (design) spectra via a set of response modification factors. These factors depend on overstrength, ductility requirement, and structural redundancy of the system. The component of these factors, which accounts for the ductility demand ratio, is known as strength reduction factor (SRF). This factor represents the ratio of elastic strength demand to the inelastic strength demand of a single-degree-of-freedom oscillator with the inelastic deformations limited to a specified ductility demand ratio, and the variation of this factor with initial period of the oscillator is called as SRF spectrum. This study considers scaling of SRF spectrum in case of an elasto-plastic oscilator with strength and stiffness degradation characteristics. Two models are considered: one depending directly on the characterization of source and site parameters and the other depending on the normalized design spectrum characterization of the seismic hazard. The first model is the same as proposed earlier by Tiwari and Gupta (2000) in terms of earthquake magnitude, strong motion duration, predominant period, geological site conditions, ductility demand ratio, and ductility supply-related parameter. The second model is a new model pro- posed here in terms of the normalized pseudo-spectral acceleration values (to unit peak ground acceleration), ductility demand ratio and ductility supply-related parameter. For each of these models, least-square estimates of the coefficients are obtained through regression analyses of the data for 956 recorded accelerograms in western USA. Parametric studies carried out with the help of these models show that degradation characteristics significantly affect the way SRF spectra depend on strong motion duration and geological site conditions. It is also seen that these characteristics make a difference only for high ductility demands and lead to lower values of SRFs only when the oscillators are not very flexible.

**Wavelet-Based Characterization of Design Ground Motions**
*[Sushovan Mukherjee; August 2000; Supervised by Vinay K. Gupta]*

With the recent emergence of wavelet-based procedures for stochastic analyses of linear and non-linear structural systems subjected to earthquake ground

motions, it has become necessary that seismic ground motion processes are characterized through functionals of wavelet coefficients. While direct characterization in terms of earthquake and site parameters may have to wait for few more years, this study attempts such characterization through commonly available Fourier and response spectra for design earthquake motions. Two approaches have been proposed for obtaining the spectrum-compatible wavelet functionals, one for input Fourier spectrum and another for input response spectrum, such that the total number of input data points are 30-35% of those required for a time-history analysis. The proposed methods provide for simulating desired non-stationary characteristics' consistent with those in a recorded accelerogram. Numerical studies have been performed to illustrate the proposed approaches. Further, the wavelet functionals compatible with a USNRC spectrum in case of thirty five recorded motions of similar durations have been used to obtain the strength reduction factor spectra for elasto-plastic oscillators and to show that one may assume about ñ20% variation from mean to 5% and 95% confidence levels due to uncertainty in the non-stationary characteristics of the ground motion process.

**Seismic Response of Multiply-Supported Secondary Systems: Uncertainties and Decoupling Criteria**
*[Samit Ray Chaudhuri; August 2000; Supervised by Vinay K. Gupta]*

A mode acceleration formulation is presented to investigate the variability in the responses of a secondary system which is supported on a flexible-base primary system at multiple attachment points. The response functions are considered to be uncertain due to the uncertainty in the shear wave velocity and Poisson's ratio of the foundation soil. Both soil parameters are assumed to be independent variables with Gaussian distributions. A numerical study with the help of two example P-S systems and three example excitation processes shows that dynamic response should be considered for as many secondary modes as possible for the given formulation to work well, and that uncertainties in the soil parameters directly affect the transfer functions near the first few peaks and crests.

A perturbation approach is also formulated for determining the combined system properties in case of light secondary systems. A numerical study is carried out to illustrate the accuracy achieved with the proposed formulation, even when not all primary and secondary modes are considered. Considering that the input excitation is an ideal white noise process and that modal properties of the combined system are easily obtained, a primary system response-based decoupling criterion is proposed. The proposed criterion is found to be

applicable in case of several response functions of an example primary-secondary system.

**Experimental Investigation of Cyclic Behavior of Precast Exterior Beam-Column Joints**
*[Manoj Kumar Joshi; July 2000; Supervised by C. V. R. Murty and M. P. Jai Singh, CBRI, Roorkee]*

In spite of numerous advantages of Precast concrete construction, its use in high seismic areas is not popular, mostly because of the low level of confidence in its behaviour in these places. The joints between Precast elements are the critical regions in Precast structures from seismic considerations, as validated by their poor performance in many past earthquakes. Experiments are performed on four exterior beam-column joint sub assemblage specimen. Two of these are Precast and the other two correspond to monolithic ones, which serve as a benchmark for comparison. A pair of monolithic and Precast specimens has a different scheme for the anchorage of beam bars. In Precast specimens, the beam and column bars are anchored together through welding the exposed bars of the components. Displacement-controlled pseudo-static loading is applied on the specimens. The Precast specimen with beam bars anchored into the column performed better than the Precast specimen with continuous U-bars as beam reinforcement. The performance of the former was comparable to the corresponding monolithic specimen and is recommended for use in high seismic areas.

**Effect of Confinement on strength and Ductility of Large RC Hollow Sections**
*[Prabuddha Dasgupta; July 2000; Supervised by C. V. R. Murty]*

Ductile flexural behaviour of large reinforced concrete hollow sections is investigated. Effect of confinement in enhancing the strength and ductility of concrete sections is studied. For this, an existing confinement model applicable for both circular and rectangular solid sections is extended and modified to analyze large hollow sections of both shapes. An analytical method is proposed to quantify the effect of confinement in a hollow circular section where inner and outer hoops are connected by radial links. A number of sections are analysed to obtain the influence of axial load as well as various sectional parameters on the curvature ductility of the section.

From the analysis, links are found to have large effect on the ductility of a circular section, but the effectiveness varies with the wall thickness. For circular sections, lower wall thickness provides higher ductility, while for rectangular

sections wall thickness has no bearing on the ductility as long as transverse spacing of cross-ties is kept same. Also, rectangular sections can achieve much higher strength and ductility than circular ones do.

**Beneficial Effects of Brick Masonry Infills in Seismic Design of RC Frame Buildings**
*[Diptesh Das; July 2000; Supervised by C. V. R. Murty]*

An example three-storey residential building is designed for forces corresponding to Seismic Zone V of the draft Indian seismic code in accordance with seismic design philosophy given for RC frame buildings with brick masonry infills in the three current design codes. The building is also designed as per the Equivalent Braced Frame Concept given in literature. Non-linear pushover analysis is performed on these five buildings; the masonry infill panels are modeled as equivalent diagonal struts in all cases. The effect of the brick infills on the overall response of the structure is studied. The performance of all the five buildings are compared and the associated design procedure are evaluated.

The study shows that infills reduce the drift capacity and structural damage, and significantly increase the strength and stiffness of the structure. The columns, beams and infill walls in the lower stories are more vulnerable to damage than those on the upper stories. The role of the plinth beam is found to be significant when the contribution of infills are taken into account in the building design. The overall structural ductility is reduced, but the overstrength is increased with the presence of infills.

The building designed by the Equivalent Braced Frame Method showed both better overall performance and economy. It is recommended that this method be adopted for design of RC frame buildings with brick masonry infills.

**Experimental Investigation of Cyclic Response of Reinforced Connections for Earthquake-Resistant Steel MRFs**
*[Aniruddha Moitra; June 2000; Supervised by C. V. R. Murty]*

Studied using cyclic displacement loading. The connection details are designed using three different force models, namely (a) Truss Analogy Model, (b) Modified Three steel exterior-joint beam-column sub-assemblages with strong column weak beam are Truss Analogy Model, and (c) Improved Truss Analogy Model. The first and the third are adopted from literature, and the second is suggested in this study. This study also presents a simple beam-to-column

connection design method with beam flange as well as cover plate welded to the column flange.

The experimental study concludes that connection designs with single outer rib plate are always vulnerable to premature failure. On the other hand, connections with rib plates on both sides of the beam flange responded well. Two of the sub-assemblages are repaired with a pair of vertical rib plates on each side of the two beam flanges. In all the five cases, an average plastic rotation of about 0.02 radians only was developed in the beam as against 0.03 radians expected for connections suitable for high seismic areas. Hence, these connection configurations cannot be recommended for high seismic regions, but may be recommended for use in steel frames constructed in medium seismic zones.

**Experimental Investigation of RC Frames with Brick masonry Infills Having Central Opening Subjected to Cyclic Displacement Loading**
*[G. B. Pavan Raj; June 2000; Supervised by C.V. R. Murty and Sudhir Kumar Jain]*

Six 1:2.7 reduced scale one-bay one-storey RC portal frames with brick masonry infills are experimentally studied under displacement-controlled pseudo-static reverse cyclic loading history. Effect of window openings and unanchored long lintels in the infill are main focus of this study. One of the frames considered is a RC frame infilled with inclined brick course masonry, and another is a bare frame.

Frames with window openings in the infill showed reduction in ultimate load by 7%, initial stiffness by 47% and ductility by 32% than frames with full infills. Providing a long lintel does not show any major improvement over that when a short lintel is provided, except in increasing the initial stiffness by 29%. In frames with and without window frame around openings, the ultimate load, initial stiffness and energy dissipation are within 11%. In the latter, distortion of opening increased with displacement excursion, and the final collapse of the infill is in-plane from the sides of the opening. Progressive damage was almost similar in both the specimens.

The response of the frame with inclined brick courses in this study agree well with the favourable responses of previous study; the ultimate load, stiffness and energy dissipation in this study are within 10% of that observed in the previous study. Only outward buckling of longitudinal column bars at the bottom is observed in all infilled frames studied owing to increased axial in columns due to diagonal strut action of the infill and confinement of longitudinal column bars by the infill on the inner face.

**Empirical Relationships for Peak Ground Acceleration in Indian Earthquakes**
*[Roshan A.D.; 2000; Supervised by Sudhir Kumar Jain]*

Himalayan region in India is one of the most seismically active regions in the world. About 120 recordings from Strong Motion Accelerographs (SMAS) are now available from the recent Himalayan earthquakes in the magnitude (M range of 5.2 to 7.3 with the epicentral distances (R) ranging from 3 to 350kms. About 260 records from Structural Response Recorders (SRRs) from 5 Himalayan earthquakes are also available (M. 5.5-7.3; R: 4- 770kms). SRRs record spectral acceleration at natural periods of 0.4sec, 0.75sec and 1.25sec, for damping ratios of 5% and 10% of critical. The strong motion database available for Indian earthquakes can be enhanced by making use of records from SRRs.

The compatibility of responses from SRRs and SMAs from Indian earthquakes has been studied and the peak ground acceleration has been estimated from SRRs recordings. The estimates of peak ground acceleration from SRRs are in line with those from SMAs. The peak ground accelerations in Indian earthquakes are compared with those predicted by the existing attenuation relationships. It is seen that the relationships provide reasonable estimates for the earthquakes in Central Himalayas, but underestimate the motion for earthquakes in North-East India and Indo-Gangetic plains. It is seen that based on attenuation characteristics, the Himalayan earthquakes can be grouped into four categories: (a) events of Central Himalayas, (b) non-subduction earthquakes of ,North-East India, (c) subduction events of North-East India, and (d) Earthquakes in Indo-Gangetic plains.

Separate attenuation relationships for peak ground acceleration are derived for earthquakes in Central Himalayas, Indo-Gangetic plains, North East Indian Non-subduction zone earthquakes and North East Indian subduction zone earthquakes

**Experimental Investigation of Brick Masonry Infill Walls in RC Moment Resisting Frames for Earthquake Resistant Design**
*[Kiran Jagannadharao Akella; June 1999; Supervised by C. V. R. Murty and Sudhir Kumar Jain]*

Six 1:2.7 reduced scale one-bay one-storey RC portal frames with brick masonry infills are experimentally studied under displacement-controlled pseudo-static reverse cyclic loading history. Effect of window openings and unanchored long lintels in the infill are main focus of this study. One of the frames considered is a RC frame infilled with inclined brick course masonry, and another is a bare frame.

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**Experimental Investigation of Welded Beam-to-Column Connections in Steel Structures for Earthquake-Resistant Design**
*[Mukul Pant; June 1999; Supervised by C. V. R. Murty]*

Beam-to-column connections are steel MRFs have a major responsibility of transferring the loads safely between the beams and columns without compromising on the ductility of the frame. Experiences from the past earthquakes have shown that frames designed to remain ductile had failed in a brittle manner owing to brittle fractures of the welds at the connections. Further, a majority of the connections damaged, had been designed in accordance with the classical Bernoulli beam theory, which assumes that the flanges primarily carry bending and shear force is transferred through the web. The recent studies have shown that this is not valid in the neighborhood of the beam-column junctions, where the beam webs at the column flange are devoid of stresses.

In the present experimental study, four sub-assemblages of the exterior joint are studied under reverse cycle loading under displacement control in the post-elastic regime. The specimens are representative of both strong-column/weak-beam and weak-beam/strong-column design conditions. The connection details have been designed using the Truss Analogy Model available in literature as per the Allowable Stress Design method given in the Indian codes. The objective of this experimental study is to evaluate the suitability of the designed welded specifications in the Indian standards has also been highlighted.

Three of the four sub-assemblages sustained more than 40 cycles of displacement loading and showed excellent energy dissipation characteristics. The plastic rotation capacity of the sub-assemblages satisfies the FEMA criterion. Also it was seen that panel zone can contribute significantly to the inelastic response. And even in strong-column/weak/beam sub-assemblages, brittle fracture of welds may occur if the column is very stiff.

**Experimental Investigation of In-plane Diaphragm Action of the CBRI Precast Plank and Joist Flooring System for Earthquake-Resistant Constructions**
*[Rajesh Agarwal; July 1999; Supervised by C. V. R. Murty and R. N. Iyengar]*

The inertia generated during earthquake shaking are transmitted through the floor slab to the different lateral load resisting elements such as walls and frames. Thus, the floor slabs provide the critical in-plane action. In the past, numerous studies have been conducted on the in-plane behavior and characteristics of cast-in-situ floors. However, the in-plane diaphragm behavior of precast floors is still not understood. Most of the seismic design codes either assume floors to be rigid or attempt to make them rigid. But, efforts to make precast system resemble a cast-in-situ system may take away the economic advantage for the precast systems.

Two full-scale specimens of the precast plank and joist floor systems developed by the Central Building Research institute, Rorkee, are tested under in-plane monotonic loading to study their in-plane diaphragm behavior. The in-plane stiffness and relative displacements in the slab system and the performance of joints between the precast elements and between the slab and walls are investigated. The specimens are tested both the orthogonal principal directions, because the presence of joist in the slab along one the direction makes the stiffness characteristic considerable different in the two directions. A sliding test is performed on one of the specimen to obtain the load at which the floor slides off atop the masonry wall. The test shows that the CBRI system does provide the adequate in-plane diaphragm action. However, the slab system is vulnerable to sliding from atop the masonry wall under earthquake shaking.

The above slab system is also modeled using the finite element program, NASA. In analytical study, both linear and non-linear analyses are performed using solid and shell elements; elastic perfectly plastic behavior of the concrete is included in the latter.

The analytical study shows general agreement with the experimental results.

**Overstrength and Ductility Capacity of Reinforced Concrete Structural Walls**
*[Ranjith Kumar Reddy Jogla; July 1999; Supervised by Sudhir Kumar Jain]*

Shear wall systems have shown excellent performance in the past earthquakes. Lateral load response of reinforced concrete shear walls has been studied here. A computer program has been developed to obtain moment-curvature relationship for walls considering the boundary elements with confined concrete. This has been used to develop the lateral force-roof displacement relationship for building systems with shear walls.

An example building system, with six- and nine-storeys, has been used to study the behaviour. It is assumed to be located in seismic zone IV or V of Indian seismic zone map. The walls are designed in two ways: with boundary elements having special confining reinforcement as per IS: 13920-1993 and with boundary elements having only nominal shear reinforcement as per IS: 456-1978. Response is studied in terms of ductility, drift capacity, over strength and response reduction factor.

Initial stiffness, yield curvature, and over strength are found to be insensitive to the confinement in boundary elements. Due to confinement in boundary element, drift capacity increased by 20% to 70% and the response reduction factor by 25% to 70%. Over strength of the walls in seismic zone IV is found to be higher by 15% to 23% than that in seismic zone V. It is also noted that nine-storey buildings have higher over strength (15% to 25%) than the six-storey buildings. No particular trend was observed in the response reduction factor with the variation in seismic zone and number of storeys.

Performance of the wall buildings is compared with the available results in the literature for a similar R.C. frame building. Wall systems clearly have lower drift capacity. Six-storey wall buildings are stiffer than the frame structures and have lower over strength where as lateral stiffness and over strength are quite comparable for the two systems in case of nine-storeys. These results are also extrapolated to Study the expected response of a dual system consisting of walls and frames. Individual walls clearly had more lateral stiffness than tile frames. The walls and frames yielded at about the same lateral displacement level in case of nine-storey building, while in the six-storey building the frames were well-within elastic limit when wall yielded. Limited results of this study indicate that such dual systems should be designed based on tile nonlinear push-over analysis.

**Nonlinear Push-Over Analysis of Flat Slab Buildings With and Without Seismic Retrofitting**
*[Tirandas Srikanth; July 1999; Supervised by Sudhir Kumar Jain]*

Many existing flat slab buildings may not have been designed for seismic forces. It is important to study their response under seismic conditions and to evaluate seismic retrofit schemes. Two-dimensional nonlinear push-over analysis is carried out on a typical flat slab building. The building considered is designed only for gravity loads and wind loads. Comparison with similar conventional beam-column frames shows that the flat slab buildings have low lateral stiffness, low drift capacity and have hardly an ductility, while the overstrength is of similar order. The yielding of slab in sagging is significant in flat slab buildings because of insufficient bottom reinforcement. By making the column strip bottom reinforcement continuous, the yielding in sagging can be reduced considerably, but no improvement in drift capacity is obtained. Considering all these factors it is concluded that many existing buildings in high seismic lesions may need retrofitting.

The performance due to retrofitting by a) column jacketing, b) addition of beams at floor, and c) column jacketing and addition of beams are also studied by push-over analysis. The retrofitting of ground storey by column jacketing is a good cost effective technique but is adequate only when seismic deficiency is small. The beam retrofitting reduces the sagging hinging significantly. Increasing the number of storeys of retrofitting by either column retrofitting alone or beam retrofitting alone does not improve the behavior significantly. With increase in number of storeys retrofitted with addition of beam alone, there is decrease in drift capacity, without much increase in strength. When column jacketing and addition of beam are adopted simultaneously on more number of storeys, large increase in lateral strength and stiffness can be achieved.

**Effect of Seismicity Model on Design Force Ratio Spectrum**
*[V. Srimahavishnu; July 1999; Supervised by Vinay K. Gupta]*

Design force ratio (DFR) spectra give the ratio by which the design force level of a single-degree-of-freedom structure has to be increased such that the damage caused by a number of earthquake events expected to occur during its lifetime is limited to a specified level. In this study, the DFR spectra are compared for three different seismicity models. In the first model, the return periods of earthquakes are assumed to follow exponential distribution over the entire range of magnitudes. In the second and third models, the numbers of large earthquakes are estimated by time-dependent hazard function based on lognormal and Weibull distributions of return period. Different values of seismic gap length, i.e.

time elapsed since the last large event, are considered for these two models. The expected magnitudes of earthquake events expected to occur during the lifetime of the structure are estimated by applying the order statistics approach. It has been found from the numerical study on a hypothetical seismic region that the seismicity model may significantly influence the DFR spectrum. Further, there is a seismic gap length for which the DFR spectra for the second and third models become close to the DFR spectrum for the first model, and then, the DFR spectrum becomes somewhat insensitive to the seismicity model.

**Considerations in Seismic Design of Steel Moment-Resisting Frames**
*[Sudip Paul; June 1998; Supervised by C. V. R. Murty and Sudhir Kumar Jain]*

This thesis has been organized in four parts. In part I, the state-of-the-art review of seismic design of steel moment resisting frames for both American and Indian codes are discussed. Deficiencies in the seismic resistant design of steel structures by Indian codes are studied.

In Part II of this thesis three two-dimensional moment resisting steel frames are analysed to see the effect of panel zone deformation on the elastic drift. The analysis results show that in all cases the final design is governed by drift criteria rather than strength criteria. In addition to that the stability requirements of different structural elements are also studied and incorporated. An approximate method of estimating panel zone deformation is discussed and the results are verified by writing a linear analysis program including joint panel element. Finally a drift based resizing steps of the moment resisting frames are proposed.

In Part III of this thesis two important issues related with stability of steel structures are studied. It's well known fact that due to the presence of residual stresses in rolled section, it yields at an early stage i.e., half of its yield stress or so and also reaches to its full capacity when the extreme fibres strain is much higher than the yield strain. Here, three Indian standard sections are studied to see the effect of residual stresses on flexural capacity of the section. The other issue discussed in this Part is the local buckling of compression flanges. It's very difficult to quantify the local buckling issue with analytical modelling, in fact past results based on analytical study do not correlate with that of experimental results. Here a study is made to estimate the buckling stain of compression flange both in elastic and inelastic range for Indian standard wide flanged sections. The effect of local buckling on flexural capacity of these sections are studied by just bringing the compressive stress of the buckled flange to zero corresponding to their buckling strain. A computer analysis program including both material and geometric nonlinearity, large deformation and small strain, interaction is developed for a beam-column element by deviding it into a number

of segments along its length and into a numbers of fibres along its cross section for these studies. Part IV of this thesis gives a brief overview over the code provisions to be adopted in Indian design practice of design of steel structures. Some of these provisions are already exiting in plastic design code of Indian steel structure [SP: 6 (Part 6) 1972] but needs to be included in allowable stress design approach [IS: 800-1984] for seismic resistant design of steel moment resisting frames.

**Ambient and Low-Level Forced Vibration Tests on a RC MRF Building with URM Infills**
*[Sandeep S. Rajpathak; June 1998; Supervised by C. V. R. Murty]*

Ambient and low-level forced vibration tests are performed on a reinforced concrete (RC) moment resisting frame (MRF) building with unreinforced masonry (URM) infill walls to determine its dynamic properties namely, the fundamental translational and torsional natural periods, the corresponding mode shapes and the structural damping. This three-storey building lies in the seismic zone III of India as per the current code. An electrodynamics shaker, generating a maximum force of 133N, is used to apply a harmonic force at desired frequencies.

This building is analytically modeled using the FEM package, STARDYNE. Four types of models are considered. The dynamic properties of the building as derived using these models, are compared with the experimentally obtained ones. The material properties used in the modelling, i.e., modulus of elasticity of brick masonry and reinforced concrete are determined by an in-situ experiment. It is found that the analytical model with a slit between the top of the infill wall and the suffix of the beam gave very good results for the vibrations in the transverse direction, whereas, all the analytical models of the building are found to be stiffer than the actual building in the longitudinal direction.
It is observed that the vibrations produced by the electrodynamics shaker are very low and are easily influenced by an external source of disturbance. The use of this low force amplitude shaker may only be restricted to determine the fundamental natural frequencies and mode shapes but not to obtain the absolute responses.

**Cyclic Response of RC MRFs with Brick Masonry Infills**
*[Rakesh Kumar Saxena; June 1998; Supervised by C. V. R. Murty and Sudhir Kumar Jain]*

In the past few decades current EQ resistant design practice of RC framed structures effect of brick infills is neglected and infills are considered as non structural member. Performance of structures in past earthquakes and significant research expended in studying the behaviour of masonry infilled RC frames show that the infills enhance the in-plane lateral stiffness and strength of the reinforced concrete frames. In literature, most of the experimental work on infilled frames is focused on monotonic loading. And, in most of the work reported on behaviour of infilled frames under cyclic loading, attention is drawn primarily to the effect of various strengthening techniques and types of infills on lateral strength and lateral stiffness of the frame. In particular, very little work has been reported on the behaviour of infilled frames in India under reversed cyclic loading. So, in this study, cyclic testing of infilled frames is carried out to help the process of development of design guidelines for RC frames in India, which requires extensive experimental data.

In the present investigation, two single-storey one-bay reinforced concrete frames, one with reinforced brick masonry infill is tested under pseudo-static reversed cyclic lateral loading and the other without any infill is tested under monotonic loading. The lateral load is applied at the beam level; no vertical or out-of-plane loads are applied on the frames. The strength and stiffness of the reinforced infilled and the bare frame are estimated using analytical models available in literature, and compared with experimental quantities. Also, stiffness degradation, strength deterioration, strain in reinforcement bars, overall frame ductility and energy dissipation of the reinforced infilled frame is compared with the unreinforced infilled frame and ultimate load capacity, strain in reinforcement bars, and overall frame ductility of bare frame under monotonic loading is compared with the bare frame under cyclic loading tested last year.

**On Scaling of Strength Reduction Factors for Horizontal Earthquake Ground Motions**

*[Arun Kumar Tiwari; June 1998; Supervised by Vinay K. Gupta]*

The conventional approach of obtaining the inelastic response spectra for the aseismic design of structures involves the reduction of elastic spectra with the help of strength reduction factors (SRFs). SRF is considered to primarily depend on the initial time period of the single-degree-of-freedom (SDOF) oscillator and the ductility demand for the ground motion. This study proposes a preliminary scaling model for estimating the SRFs of horizontal ground motions in terms of earthquake magnitude, strong motion duration and predominant period of the ground motion, geological site conditions, and ductility ratio, with a given level of confidence. The earlier models have not considered the simultaneous dependence of the SRFs on various governing parameters. Since the ductility

demand is not a complete measure of the cumulative damage in the structure during the earthquake-induced vibrations and since the information on available ductility in the system is presently ignored, the existing definition of the SRF is sought to be modified with the introduction of damaged-based SRF (in place of ductility-based SRF). A parallel scaling model has also been proposed for estimating the damaged-based SRFS. This scaling model considers damage and ductility (supply) ratio as parameters instead of ductility (demand) ratio. Through a parametric study, it has been shown by using the proposed model for ductility-based SRFs that the hitherto assumed insensitivity of earth- quake magnitude and strong motion duration may not be always justified and that the time period of the oscillator plays an important role in the dependence of SRF on these parameters. Further, the damage-based SRFs are found to show the same parametric dependence as observed in case of the ductility-based SRFs.

**Mode Acceleration Approach to Seismic Response of Secondary Systems**
*[V. Surya Chandra Rao; June 1998; Supervised by Vinay K. Gupta]*

Formulations have been proposed for estimating the seismic response of i) a linear single-degree-of-freedom (SDOF) secondary system, and ii) a multiply-supported linear, classically damped secondary system within the framework of a PSDF-based stochastic aproach while the primary system is linear and classically damped. Transfer functions have been formulated for the desired response quantity in terms of the fixed-base modes of the primary and secondary systems. The mode acceleration approach has been adopted for this purpose and thus, psuedo- static response has been considered for a given number of high-frequency modes in both primary and secondary systems. The proposed formulations do not involve the determination of the combined system properties, and those are applicable to the secondary systems with various mass ratios and configurations. Through a few example primary secondary systems and an example band-limited white noise excitation, it has been shown that the use of mode acceleration approach leads to significantly more accurate results in case of the multiply supported secondary system response when only a few secondary modes have to be considered. This formulation has been extended to obtain the floor response spectra for use in the decoupled response spectrum analysis of multiply supported secondary systems. These spectra account for interaction effects and are shown to lead to substantial reductions in the errors associated with the decoupled analysis in case of moderately heavy-to-heavy secondary systems.

**Secondary Effects Including Shear Deformations in Design of Frame Columns**
*[Manoj Kumar Garg; May 1998; Supervised by C. V. R. Murty and Ashwini Kumar]*

The secondary effects due to axial load in the design of frame columns are incorporated through additional moments estimated using their effective lengths. The current design methods to account for the secondary effects are based on various assumptions which may not even be realized in practice. A recent study to identify the critical parameters that are omitted, or incorrectly considered, in the current design methods has also proposed a simple yet general method for determining the effective length of frame members. In the current study, this method is improved and extended to include the effect of shear deformations. Further, simplified closed-form implicit expressions is provided which can be directly coded in a computer program. Convenient design charts are proposed for elastic-end restraints to calculate the effective length factor. Approximate explicit expressions for effective length factors are also provided. A closed-form expression for moment modification factor which also takes into account the shear deformations is provided. The effect of shear deformations on the moment modification factor is also studied. The effective length factor and modified moments of six example frames are estimated by different Codal and research methods and compared with those from the current study.

This study suggests that effective length and moment modification factors of a frame column are significantly influenced by the shear deformations in them. However, effective lengths and modified moments calculated as per the design codes do not consider the shear deformations. A strong need is felt to reconsider the associated Codal provisions in this regard.

**Incorporating Contribution of Higher Modes in Equivalent Static Lateral Force Procedure in Seismic Design**
*[Reeta Jha; May 1998; Supervised by C.V.R. Murty]*

In this study, a new set of response spectra are proposed using a series of vertical cantilever beams discredited as MDOF systems. This is in contrast to the response spectra derived based on a series of SDOF systems. Three strong ground motions having different characteristics have been analysed. The proposed spectra based on MDOF systems also incorporate the type of deformation induced in the structure, i.e., flexure-type, shear-type or combined flexure-shear type. For the ground motions studied, the ratio of the spectral displacement (and the pseudo spectral acceleration) from the MDOF spectra to that from the SDOF spectra is about 1.75 in flexure-type buildings and about 1.4 in shear-type buildings. The spectral displacements from the MDOF spectra decreases with increase in , a parameter reflecting the relative translation stiffness contributed by flexural and shear deformations, and is about 1.25 times more in case of flexural-type buildings than those in shear-type buildings. The

ratio is reasonably constant in the long period range suggesting that the PSA spectra derived using SDOF systems may only be uniformly raised upwards to account for higher modes, rather than pivoting the spectrum upwards about the corner frequency (at the junction of velocity-sensitive and acceleration-sensitive regions).

The pseudo-spectral acceleration coefficients PSAMDOF from the MDOF spectra are compared with design acceleration coefficient given by equivalent static lateral force procedure in different building codes. The unconstrained power regression analysis of the PSAMDOF data in the long period range indicates that the acceleration coefficient vary as the reciprocal of the natural period raised to an exponent of 1.4 to 1.8, depending upon the ground motion and the values of . The force distribution profiles obtained for different values of indicate that those obtained for shear buildings are radically different from those given in the building codes. The study seems to suggest that the lateral force distribution in the simplified equivalent static lateral force procedure should be a function of the height of the building, natural period and shear parameter. Further, the drift limits for shear-type buildings may be reduced in comparison to those for flexure-type buildings upto about 50%.

This study is only an exploratory effort to evaluate the possibility of using the MDOF system based spectrum. Also, only three recorded ground motions have been studied. The above work should be repeated for many more recorded ground motions. The preliminary results seem to indicate a large scope for improving upon the Equivalent Static Lateral Force procedure that is widely used in seismic design.

**Implementation of Torsional Provisions in Buildings with Rigid and Flexible Floor Diaphragm**
*[Dhiman Basu; July 1998; Supervised by Sudhir Kumar Jain]*

Buildings are seldom, if ever, perfectly symmetric. Thus building vibration frequently involves coupling of translational and torsional modes. In most of the analysis and design buildings, floor slab is assumed as rigid in its own plane because of its high iii-plane stiffness. However, for certain configurations this assumption is not valid. Part-I of this thesis deals with buildings having rigid floor diaphragms while Part-11 addresses the response of buildings flexible floor diaphragm.

In the Part-I of this thesis, a flexibility based approach is presented to locate the center rigidity, shear center and center of twist of a multistorey building. Further, a convenient anal procedure is presented to compute design response. The technique accounts for all established definitions of static eccentricity.

Floor diaphragms in some buildings may have considerable flexibility in their own plane (e.g., buildings with long and narrow plan, buildings with horizontal offset). In such buildings design seismic force for a particular floor can not be applied at one single point (say, center of mass or at an eccentricity) of that floor. The problem of static seismic analysis procedure for such buildings with torsional coupling is addressed in Part 11. Two definitions of center of rigidity proposed for buildings with flexible floor diaphragm. Besides, a convenient analysis procedure is proposed. The building plan is assumed to have a single wing only.

**Comparison of Experimental Cyclic Response of RC Frames With and Without Brick Masonry Infills**

*[Neeraj Kumar Vasandani; December 1997; Supervised by C.V. R. Murty and Sudhir Kumar Jain]*

In the past four decades, significant research effort has been expended in studying the behaviour of masonry infilled RC frames. And, it has been recognized that the infills enhance the in-plane lateral stiffness and strength of the reinforced concrete frames. In literature, most of the experimental work on infilled frames is focused on monotonic loading. And, in most of the work reported on behaviour of infilled frames under cyclic loading, attention is drawn primarily to the effect of various strengthening techniques and types of infills on lateral strength and lateral stiffness of the frame. In particular, very little work has been reported on the behaviour of infilled frames in India under reversed cyclic loading. So, in this study, cyclic testing of infilled frames is carried out to help the process of development of design guidelines for RC frames in India, which requires extensive experimental data.

In the present investigation, two single-storey one-bay reinforced concrete frames, one with complete brick masonry infill and the other without any infill, are tested under pseudo-static reversed cyclic lateral loading. The cyclic lateral load is applied at the beam level; no vertical or out-of-plane loads are applied on the frame. The strength and stiffness of the infilled and the bare frame are estimated using analytical models available in literature, and compared with experimental quantities. Also, stiffness degradation, strength deterioration, strain in reinforcement bars, overall frame ductility and energy dissipation in the two frames are compared. The experimental results indicate a beneficial influence of infills on the lateral load resistance of RC frames.

**Ambient Vibration Survey of Reinforced Concrete Moment Resisting Frames with Unreinforced Brick Masonry Infills**

*[Jaswant Narayan Arlekar; July 1997; Supervised by C. V. R. Murty]*

Ambient vibration measurements of many buildings have been recorded across the world in the past to determine their dynamic properties, in particular, to ascertain the properties of the fundamental modes of vibration. It is also recognized that the experimental data from one region may not be used in another owing to the differences in the construction methods and materials.

During this ambient vibration survey, a total of seventeen (17) buildings are tested to determine the fundamental lateral translational natural periods and the corresponding mode shapes of vibration. All of these buildings are situated in Kanpur (India), which lies in the seismic zone III as per the current seismic code. Further, the buildings are reinforced concrete moment resisting frame (RC MRF) buildings with unreinforced masonry (URM) in brick as infill walls.

The buildings tested are analytically modeled using the standard analysis software, ETABS. Three analytical models are considered. In all these models, the floor slabs are assumed to be rigid in their own plane. Regression analyses of fundamental lateral natural period data from experiments and analytical models, are performed and empirical expressions are obtained for fundamental lateral natural periods of RC MRF buildings with brick infill walls. The expressions for models considering reduced thickness of walls in the ground storey show a low value of standard error of estimate.

The expressions in the current Indian code are found unsuitable for estimating the fundamental natural period of RC MRF buildings with brick infills. These expressions grossly overestimate the natural periods. Improved expressions for natural periods of RC MRF buildings with brick infill walls are proposed. It is also observed that, to obtain better estimates of the fundamental natural periods, the area of infill walls in the ground storey may be included in the expression for natural period.

The analytical techniques using the available analysis software are found to be inadequate for determining the fundamental natural periods of buildings. Ratios of experimental and analytical natural periods are determined.

**Seismic Drift Capacity of Gravity Columns Using Nonlinear Monotonic Analysis**
*[G. G. Srinibas Achary; July 1997; Supervised by Sudhir Kumar Jain]*

In many multistory buildings with shear walls, the contribution of columns towards resisting lateral loads is small, and such columns are often designed only for the gravity loads ("gravity columns"). However, such columns may loose their gravity load carrying capacity when undergoing lateral displacements under earthquake excitations. In Northridge earthquake of 1994, failures of several buildings were attributed mainly to the collapse of gravity columns.

A computer program is developed in this thesis to study the inelastic seismic behaviour of gravity columns under imposed lateral displacements. The program uses a moment-curvature relationship which is obtained from another program (Mandal, 1993) this program is modified somewhat to include a strain hardening stress-strain relationship of steel.

A parametric study is carried out to identify the influence of different parameters on the drift capacity of ACI- and IS-designed columns. ACI-designed columns were detailed as per ACI 318-89 (Revision 1992) and for ACI 318-95, while the IS-designed columns were detailed as per IS: 456-1978 and as per IS: 1 3920-1993.

It is seen that the elastic- plastic analysis reported earlier (Agarwal, 1996) overestimated the drift capacity in the range of 15% to 60%. The drift capacity depends strongly on the percentage confinement provided by the shear reinforcement. It is recommended that the codal provisions on gravity columns should incorporate a minimum percentage confinement requirement.

**Damage-Based Life of Structures in Seismic Environment**
*[R. Pradeep Kumar; June 1997; Supervised by Vinay K. Gupta]*

The current methodology for the aseismic design of structures is largely based on the concept of ensuring Structural safety during a single earthquake event. This event is usually the most severe event, during which availability of certain minimum ductility is ensured in the structure. This design methodology does not consider the occurrence of several not-so-severe earthquakes and damage accumulation during each of these earthquakes, as may be necessary in the areas of moderate to high seismicity, and thus the actual life of the structure may sometimes be significantly less than the design life. In this study, a new approach has been proposed for the estimation of the actual design life of a single-degree- of-freedom (SDOF) structure in a given seismic environment such that at the end of this life, the structure is expected to attain a specified level of

damage. This approach is based on the estimation, of expected number of earthquakes at each source with the help of Gutenberg-Richter relation and time-dependent hazard model, and on the estimation of structural damage during each of these events. The estimation of structural damage is based on the use of scaling models for Fourier spectrum, peak ground acceleration, and strong motion duration, on finding the properties of the equivalent linear SDOF oscillator, and on using the damage model proposed by Park and Ang. The structure is assumed to be hysteretic, elasto-perfectly plastic oscillator, and the strength and stiffness of this oscillator are assumed to degrade during each damaging event. A case study has been carried out for illustrating the proposed model, and it has been shown how this may be caused to determine the design force levels for maximum allowable damage at the end of the design life.

**Effect of Joint Panel Zones on Seismic response Steel Moment Resisting Frames**

*[Kintali Sankara Narayana Gupta; April 1996; Supervised by C. V. R. Murty]*

Experiences from the post-earthquake investigations clearly demonstrate the vulnerability of beam-column joints in steel moment-resisting frames (MRFs) under strong seismic shaking. These joints have finite size, stiffness and strength. Experimental and analytical investigations showed strong dependence of the seismic performance of steel structures on joint panel design. The current design specifications for steel joints are based on strength considerations. Since the performance of a frame is evaluated based on how well it dissipates the seismic energy input to it during ground shaking, it is of interest to study the performance of different joint panel designs vis-à-vis energy dissipation characteristics.

In this thesis, the parameters that affect the energy dissipation characteristics of steel planar MRFs vis-à-vis joint panel designs are emphasized through example single-storey single-bay portal frames. The various analytical models proposed in the literature for simulating the behaviour of joint panel zones are reviewed. The seismic design codes provide specifications for design of joint panels. These specifications are derived based on studies on typical interior joints, and are also employed for design of exterior joint panel zones. However, the requirements of strength and stiffness of exterior and interior joint panels may not be same under seismic conditions. So, the impacts of exterior and interior joint panel zone designs are studied separately under pseudo-static cyclic loading through the energy dissipation characteristics of storey sub-assemblages. Based on the above analytical study, a new approach for design of exterior as well as interior joint panel zones is proposed.

The performances of these proposed designs are also studied through dynamic time history analyses of a 20-storey steel planar MRF under various ground motions.

**Stochastic Response of Multiply-Supported secondary Systems to Earthquakes**
*[Aparna Dey; April 1996; Supervised by Vinay K. Gupta]*

A stochastic approach has been proposed for the seismic analysis of linear, multiply-supported secondary systems. The transfer function for the desired response quantity has been formulated by directly using tile fixed-base modes of the primary and secondary systems. This, thus, does not involve the determination of the combined system properties. The approach is applicable to the secondary systems with various mass ratios and configurations. Through a few example primary-secondary systems, tile transfer functions obtained from the proposed formulation have been shown to be in perfect agreement with those based on all exact formulation. This formulation has been extended to the flexible-base primary-secondary systems by assuming the soil medium to be a uniformly visco-elastic half-space. Using this, a study on the effects of soil-structure interaction has been carried out, and it has been shown that, the secondary system responses may increases due to soil-structure interaction effects for medium to stiff soil conditions.

**Seismic Response of Gravity Columns in Buildings With Shear Walls**
*[Varsha Agarwal; May 1996; Supervised by Sudhir Kumar Jain]*

In some reinforced concrete buildings, structural elements such as the shear walls, are designed to resist all the seismic loads, while the main structure is designed to carry only the gravity loads. In past earthquakes, several such buildings suffered partial to complete collapse that was initiated by the failure of the columns designed for the gravity loads only, i.e., the gravity columns. Objective of the present study is to investigate the behaviour of such gravity columns when displaced laterally due to deform action in the shear walls in earthquake condition.

The seismic code provisions regarding seismic design of gravity columns and related issues, such as the force reduction factor, the displacement amplification factor, and the drift limits, have been reviewed and discussed. The lateral displacements are imposed on the gravity columns at the floor levels and simple methods are outlined to analyze the column in the elastic and inelastic ranges. A parametric study has been conducted to assess the effect of different variables on

the maximum bending moment developed in the column under elastic response. For inelastic analysis, moment curvature relationship of column sections has been obtained using an already available computer program which takes into account the effect of axial load and the concrete confinement by transverse reinforcement. A parametric study has been carried out to observe the effect of different variables on maximum interstorey drift the gravity column can undergo prior to failure. Results have been obtained for two types of.

**Improvements in the Consideration of Secondary Effects in the Design of Frame Columns**
*[Aparna Sengupta; Febuary 1995; Supervised by C. V. R. Murty]*

Currently, designers incorporate secondary effects in the design of frame columns in two ways, namely through effective length factors to account for buckling and through moment amplification factors to account for excessive bending. The design tools to estimate these factors are based on assumptions, which may not even be actually realized.

A literature search is conducted to identify the critical parameters that were omitted, or incorrectly considered, in the current methods. The effect of these parameters involved is studied through a new Column Behaviour Model. A simple method for determining the effective length factors of general frame members is presented. Convenient design charts are proposed to obtain effective length factors. When bending moments are present with axial load in a frame member, closed-form expression for the moment amplification is derived for the direct use of designers. Methods of incorporating secondary effects in the design of general frame members with partial restraints against rotation and translation at their ends, are presented.

This study suggests that all frame columns should be treated as those with partial restraint against sway. The extent of partial restraint is determined by geometry, stiffness, restraints and loading of the whole frame. Some of the current design codes tend to use estimates of certain ideal situations for all general cases, irrespective of the actual conditions of partial lateral and rotational restraints of members. There is a need to reconsider these associated codal provisions.

**Modelling Seismic Response of Unreinforced Masonry Infilled Reinforced Concrete Moment Resisting Frames**
*[Amit Nagar; January 1995; Supervised by C. V. R. Murty]*

An attempt has been made to model the hysteretic characteristics of unreinforced masonry infilled reinforced concrete moment-resisting frames for the first time. The difficulties encountered in the modelling are discussed and a new model, The Trilinear Hysteresis Model has been proposed for capturing the hysteretic response of infilled frames. This model incorporates the stiffness and strength contributions of the masonry infill to the overall response of the frame. The critical parameters influencing the behaviour of masonry infill frames are identified, and a parametric study is conducted to study the affects of the same. The inelastic response spectra, and from those the ductility reduction factor spectra, are obtained for the Uttarkashi earthquake strong motion data and some other strong ground motions widely used in seismic analysis.

Based upon the results of the study, it has been concluded that the presence of the infill significantly reduces the ductility demand on the frame members. The infill-to-bare frame stiffness ratio is observed to be the most influential parameter governing the response of infilled frames. The masonry infill continues to govern the overall response of the infilled frame through the unloading stiffness even after it has cracked. Thus, it is essential to consider the influence of the infill in the seismic response of infilled frames. A few simple examples are provided to demonstrate the same. Design spectra valid for the Himalayan region are also proposed.

**A Study of Strong Motion Accelerograms Form Himalayan Earthquakes**
*[Navin N. Chandak; January 1994; Supervised by Sudhir Kumar Jain]*

Ground motion characteristics of the Himalayan earthquakes have been studied from the 198 horizontal component records and 99 vertical component records from six earthquakes in the region that are now available. The characteristics studied are the peak parameters, duration of strong shaking, shape of elastic response spectra and ductility reduction factor. It is found that wean A/V ratio is quite high in the region and does not vary much with the distance from the shock-source. A study of shape of elastic acceleration response spectra revealed that: (1) shape varies s hat insignificantly- with the distance, (2) shape of spectra in the in the intermediate period range highly depends on earthquake magnitude, (3) there is a urgent need to revise the shape of response spectra recommended in IS:1893-1984, and (4) shape of "standard spectra suggested by AERB for rock sites is comparable with the mean-plus-me-standard-deviation shape from the data. Both, the ratios of peak parameters and elastic response spectra indicate that with distance the attenuation of waves of different frequencies is not so different as elsewhere. Based on the data, shape of ductility reduction factor spectrum to be used in design is also proposed.

**A Study on Ordered Peaks in Seismic Damage Analysis**
*[Biswajit Basu; March 1994; Supervised by Vinay K. Gupta]*

The popular response spectrum technique, in its present form, provides information only about the largest peak response of a structure. However, for the economic reasons, it is common to allow the energy dissipation through inelastic excursions, and this makes the higher order peaks (i.e. second, third, fourth etc.) also important from the seismic damage considerations. The aim of the present study is to propose the distributions of these ordered peaks in the response process by accounting for the statistical dependence between them. Two formulations have been presented, one based on the Markov theory and the other on the joint density of the peaks as obtained from the digital simulation. These formulations have been compared with the histograms obtained from synthetically generated time histories. The peak estimates based on the assumption of independence are compared with those from the proposed formulations to see how good and practical this assumption is. The application of order statistics in ductility and damage studies is illustrated through two probabilistic models. A stochastic measure of ductility is formulated in the first model with the number of inelastic excursions as a parameter, whereas the second model estimates the expected damage accumulation from these excursions for a given ductility in the structure. This study shows that the traditional concept of ductility should be modified to incorporate the effect of nonlinear excursions and the total number of peaks with adequate reference to the permissible damage.

**Assessment of Seismic Over strength in Reinforced Concrete Frames**
*[Rahul Navin; June 1993; Supervised by Sudhir Kumar Jain]*

Seismic over strength of multi-storey reinforced concrete frames has been assessed by means of non7-linear pseudo-static analysis on 4-bay, 3-, 6-, and 9-storey frames designed for seismic zones I to V as per Indian codes. In pseudo-static analysis, the lateral forces have been applied in such a way that the first mode of vibration is excited. It is seen that the over strength varies with seismic zone, number of storeys, and with design gravity load. The dependence on seismic zone is the strongest. The average over strength of frames in zones V and I is 2.84 and 12.7, respectively. The over strength increases as the number of storeys decreases; over strength of the three-storey frame is higher than the nine- storey frame by 36 % in zone V and 49 % in zone I. Further, interior frames have 17 (zone V) to 47 (zone I) percent higher over strength as compared to the exterior frames of the same building. These observations have significance for formulation of seismic design codes which, at present, do not take into account the variation in over strength.

**Curvature Ductility of RC Sections With and Without Confinement**
*[Parthasarathi Mandal; August 1993; Supervised by Sudhir Kumar Jain]*

This work presents expressions of curvature ductility of reinforced concrete rectangular sections. The material stress-strain behaviour and the definition of ductility have been reviewed from the literature. A detailed parametric study has been carried out to observe the effect of various variables m ductility and moment carrying capacity of the section. Variables selected to incorporate in the expression of curvature ductility are (i) ratio of axial load on the section to the product of gross cross sectional area, and characteristic strength of concrete, (ii) ratio of amount of tension steel to the gross cross sectional area, (iii) ratio of amount of longitudinal compression steel to tension steel, (iv) volumetric ratio of transverse reinforcements, (v) ratio of core area to gross cross sectional area, and (vi) ten times characteristic strength of concrete to the yield strength of longitudinal steel. A linear regression analysis is carried out to obtain the statistical models of various variables versus ductility. Then the effect of different variables are combined together in a single expression of ductility by mans of non-linear regression analysis. Four sets of expressions are proposed, one each for unconfined two-sided reinforced, unconfined uniformly reinforced, confined two-sided reinforced, and confined uniformly reinforced sections. Each set. contains three expressions for three different grades of steel namely Fe 250, Fe 415, and Fe 500. The proposed expressions cover most of the reinforced concrete sections used in practice. The error lie, within -+10% of the actual, which is adequate enough to be used in design.

**Dynamics of Separable Multistorey Buildings With Flexible Floor Diaphargms**
*[Chandrashekhar K. Jain; June 1993; Supervised by Sudhir Kumar Jain]*

In this study analytical method for modelling the dynamics of buildings with flexible floor diaphragms is developed. The method has been applied to a) long narrow rectangular multistorey buildings with a number of transverse frames (or walls), and b) horizontal setback buildings with arbitrary plan shape.

The floors are braced as beams with flexural deformations only or with flexural and shear deformations while including the effects of in-plane floor flexibility. The vertical elements (frames or walls) are treated as frames or beams. The mass is lumped at floor-frame intersections. The eigenvalue problem of the building is expressed with the aid of direct procedure.

For these types of buildings, the most general conditions which make a building separable have been derived. A "separable" building is one for which the natural frequencies and mode shapes can be obtained from the natural frequency and mode shapes of a typical floor and a typical frame of the building. The separable building is shown to have two types of modes a) those in which in-plane floor deformation does not take place; and b) those involving in-plane floor deformations. The main advantage of separable buildings is that the modes involving in-plane floor deformations are not excited by spatially uniform ground motion. Thus, problems caused by floor diaphragm deformations can be avoided.

**Analysis of Strong Motion Data From Uttarkashi Earthquake of October 20, 1991 and Its Implications for Indian Seismic Code**
*[Sarajit Das; May 1993; Supervised by Sudhir Kumar Jain]*

Strong motion records have been obtained at 13 stations during the Uttarkashi earthquake of October 20, 1991 (magnitude 6. 6) . A study has been conducted on these time histories to assess the codal provisions. Emphasis of the study is on evaluating relative consistency of design provisions for different seismic zones. The average response spectra from this earthquake show concentration of significantly more energy in low period range. The magnitude of seismic design force for zones I, II, and III is consistent while it is too low for zone IV; no records were obtained in area with shaking intensity corresponding to zone V. It is seen that for buildings in zones I, II, and III, the present design provisions may be lowered either by relaxing the requirement of special ductile detailing, or by reducing the design force. On the other hand, design provisions for zone IV need to be revised upwards.

**On Gust Factors for Wind-Excited Building Response**
*[K. V. S. Chandra Sekhar; April 1993; Supervised by Vinay K. Gupta]*

A state-of-the-art review of the gust factor method for the alongwind response of structure has presented. The provisions of this method as recommended by the Indian Standard Code, IS:875 (Part 3)-1987, have been critically examined. It is shown that the codal values may be too conservative as those are based on the assumption of wind energy spectra being independent of height above the ground. Also, the assumption of perfect correlation between the velocities on-the windward and leeward faces of the building is shown to give conservative estimates. It has been shown that the use of more realistic logarithmic law for the mean wind velocity profile leads to even lower gust factors. Further, the assumptions of first mode shape being linear and that of the complete

dominance of the first mode in the dynamic wind response of buildings have been justified.

**Stochastic Response of Torsionally Coupled Multistoreyed Buildings**
*[Pavan Agarwal; April 1993; Supervised by Vinay k. Gupta]*

A stochastic approach based on response spectrum superposition technique has been formulated to determine the lateral-torsional response of torsionally coupled multistoreyed buildings subjected to the earthquake excitations. The eccentricity between the centre of mass and centre of resistance has been assumed to be the main cause of the lateral and torsional response of the building. This approach is quite general as it can estimate the response peaks for all orders with the given level of confidence while accounting for the cross-correlation between various modes of vibration.

By using the above approach, single storey models have been investigated for estimating the dynamic eccentricity values at different floor levels of a multistoreyed building. From these, parametric dependence of the dynamic eccentricity versus static eccentricity relationship has been shown more clearly, and it has been found that the codal provisions for torsional moments need to be thoroughly revised for more conservatism and rationality.

**Experimental and Analytical Studies on Dynamics of 140 m Stack at Narora**
*[Arvind Shrivastava; May 1991; Supervised by Sudhir Kumar Jain]*

A full-scale ambient vibration survey has been carried out on 140 m high reinforced concrete stack at Narora Atomic Power Station, Narora. Two FBA-11 force balance accelerometers have been used to determine the dynamic characteristics in terms of natural frequencies, mode shapes and damping. For these, time history plots obtained from a strip-chart recorder and Fourier spectra obtained from a spectrum analyzer have been used.

The stack has been theoretically analyzed by idealizing it as an Euler-Bernoulli cantilever beam. Lumped mass models have been developed and analyzed by SAP80 program, for fixed and flexible-base conditions. The results obtained in terms of frequencies and mode shapes have shown good agreement between the experimental results and theoretical results for the flexible-base conditions. This has indicated that during the dynamic vibrations, stack at Narora has significant interaction with the foundation soil.

**A Study on Seismic Analysis and Design of Elevated Water Tank Stagings**
*[Sajjad Sameer U.; March 1990; Supervised by Sudhir Kumar Jain]*

This thesis investigates the seismic analysis and design aspects of R.C. frame type elevated water tank staging. Performance of such staging in past earthquakes has been reviewed. The bracing girder of such tanks are particularly vulnerable to shear failure. The Indian code provisions for a seismic design of elevated water tanks have been reviewed. The code provides for rather low seismic design force for these structures due to the absence of a suitable value of performance factor which must be in the range of 2.5 - 3.5. On the other hand the code is too conservative (in most cases) in proposing that the tank be modelle4 as a single degree of freedom system.

It is shown that the analysis that assumes the bracing girders to be infinitely rigid for staging stiffness calculation is very inaccurate. Simple approximate procedures have been proposed to estimate the lateral stiffness of tank staging. These are based on the portal frame and the moment distribution methods which have been suitably modified to account for the bracing flexibility and the three-dimensional behaviour of the structure. Results from these methods are compared with those of the exact analysis on seven example tanks. It is also seen that, the tanks being slender structures, column axial deformation may contribute 5 - 15% of the total lateral displacement. Approximate, yet accurate, procedure has been proposed to account for the axial deformation in columns.

The lateral load analysis procedures often used in text books.

**Seismic Analysis of Bhakra and Lakhwar Dams**
*[J. Rajasankar; January 1989; Supervised by Sudhir Kumar Jain]*

Seismic response of Bhakra and Lakhwar dams is studied. For this, a computer program is written following the analytical procedure developed by Fenves and Chopra (1984a). The combined response of static and dynamic loads for simultaneous action of horizontal and vertical components of Taft ground motion is obtained. The displacement response of selected points of dam with respect to time and all-time highest maximum principal stresses in the dam and a cross-section are presented for the initial 15.0 seconds of ground motion, Both the dams are found to be able to safely withstand an earthquake of this nature and size.

An approximate analysis is performed on both the dams using the simplified procedure given by Fenves and Chopra (1986). The contours of maximum principal stresses are presented and a comparison is made with those from the

refined analysis.. It is seen that, even though the peak values are reasonably accurate, the location of peak stress in Bhakra dam is not correctly predicted by the approximate analysis, this is because of an abrupt change in upstream slope of this dam at about midnight.

A brief-parametric study is conducted on Bhakra dam using the refined analytical procedure. The dynamic response of the response quantities horizontal crest displacement and maximum principal stresses are presented for various.

**Analysis of Under Water Pipelines during Installation**
*[M. V. Ramarao; December 1988; Supervised by Sudhir Kumar Jain]*

Static and dynamic behaviour of a submarine pipeline during installation has been studied. The pipeline is modelled as a beam partially resting on a n elastic foundation with a discontinuous foundation modulus and analyzed by non-linear finite element method as proposed by Schmidt. Laybarge end of the pipeline is lifted and load is applied in increments to obtain static configuration and bending moment distribution by an incremental procedure together with Newton-Raphson method. A convergence study is carried out to select optimum number of finite elements to ensure faster convergence and accuracy of results. Effects of tension applied at the laybarge, ocean depth and foundation modulus on the static configuration and bending moment distribution are studied.

Stiffness matrix as obtained from static analysis together with a lumped mass matrix has been used to deter- mine natural frequencies and mode shapes. Response of the pipeline to a sinusoidal heave excitation is obtained. Effect of heave period on the forced response is studied.

The present study indicates that application of tension is very important with respect to static configuration and bending moment distribution. As tension increases, maximum positive bending moment decreases whereas maximum negative bending moment unaltered. Also suspended length increases with the increase of tension. Natural frequencies are influenced by both tension and suspended length. Heave period the dynamic response significantly. When heave period is large, dynamic response agrees very well with quasi-static response.

**Study of Seismic response of Tall Chimneys**
*[Brijesh Kumar Gupta; September 1988; Supervised by Sudhir Kumar Jain]*

Seismic analysis of tall chimneys has been carried out by finite element analysis. The analysis includes shear deformation and rotatory inertia in addition to bending deformations. Four degrees of freedom displacement y, slope y', flexural slope f flexural curvature have been considered for each node. Ten chimneys with height ranging from 107.5 to 336.2 m have been analysed by response spectra method. IS Code recommendations for time period, base shear, base moment and ACI Code provision for time period have been compared with the results of finite element analysis. IS an ACI Codes-distribution of shear force and bending moment with height have also been compared with distribution obtained by finite element analysis.

IS Code overestimates fundamental time period by up to 13% base shear by 45 to 70% and base moments in the range of 2 to 13%. IS and ACI distribution of shear along height are satisfactory. ACI distribution of bending moment with height is better than that of IS Code. IS Code tends to be overly conservative in moment distribution near the top of a chimney.

**A Study on Provisions of Indian Standards for Aseismic Design of Buildings**
*[Anil Kumar Patnaik; December 1988; Supervised by Sudhir Kumar Jain]*

This thesis has been organized in three parts. In Part I, ductility provisions of IS codes have been thoroughly reviewed compared with those in American codes. The provisions needing revisions, inclusions or clarifications have been identified. Suggestions made include rationalization of performance fact providing of ductility detailing as per zones rather than ah, introduction of strong column - weak girder concept In deal revision of minimum reinforcement requirements, etc. A method also been suggested for determination of plastic moment capacity for R.C. beams.

In Part II, the effect of providing ordinary and ductile concrete frames on the cost of buildings has been investigated f or different zones. Three buildings with significant difference design features have been chosen and designed for ductile and non-ductile construction. The quantity of steel and cost skeletal frames have been evaluated for these buildings and premium for providing earthquake resistance calculated. The introduction of performance factor has increased cost structures not detailed for ductile construction in zones III to V. it is economical to use ductile concrete frames in zones II to V, however in zones I and II providing, ductile concrete frame is uneconomical.

In Part III, design forces obtained by seismic coefficient and response spectrum methods have been compared for the three buildings. The design' forces resulting from response spectrum method are significantly lower than those obtained by seismic coefficient method because the fundamental time periods resulting from dynamic of the buildings are much than those evaluated by the code specified approximate formula for seismic coefficient method. This formula needs to be rationalized so that the protection from earthquakes provided to the buildings will be reasonably same by both the methods.

**Dynamic Response of Setback Buildings with A Flexible Floor Diaphragm**
*[Rajiv Sharma; May 1987; Supervised by Sudhir Kumar Jain]*

This study investing the dynamic response setback building with long and narrow one storey base and symmetric slender tower, including in-plane flexibility of the floor diaphragm. A continuum model is developed to investigate the behaviour of such buildings. The building is analysed by treating setback level floor as bending beam, ground storey walls or frames as distributed shear beam system and slender tower as shear beam. The resulting equations of motion and the boundary conditions are solved to obtain dynamic properties of the structure.

A parametric study has been carried out to investigate the effect of setback parameters on the response of a setback building. The parametric study compares the effect of variation in level of setback and aspect ratio of setback level floor on natural periods, mode shapes, modal shear coefficients, maximum floor displacements and maximum inter- storey drifts of setback building using two models viz, the continuum model developed here treating the floor flexible and vertical stepped shear bean model (Jhaveri, 1967) that treats the floor as rigid.

**Dynamic Analysis of Multistorey Buildings With End Walls**
*[Vikrant Vasant Joshi; January 1987; Supervised by Sudhir Kumar Jain]*

This work investigates the dynamic behaviour of multistorey buildings with end walls. In such buildings in-Plane flexibility can be important. The two models presented here treat the end walls as Timoshanko beams and floor system as an equivalent distributed flexure beam system or an equivalent distributed Timoshonko beam system. 'The analysis is performed for the symmetric modes of vibration. The governing differential equations and boundary conditions have been solved to obtain characteristic equation, the roots of which provide frequencies. These can then be substituted into expressions

derived for the mode shapes. The Timoshenko-Timoshenko model presented here is the most generalized one and takes into account the combined effects of bending, shear and rotatory inertia. The method has been used for buildings with different heights and different spans to obtain their frequencies, mode shapes model participation factors and base shears. Depending upon the aspect ratios of walls and floors situations have been identified w7nere certain models may be important. For low aspect ratios of floors and walls shear and rotatory inertia are found to be important. Whereas, in other cases this effect is found insignificant due to the dominance of either floor or wall frequency. Dunkereley's method gives excellent estimate of the fundamental frequency. Fundamental Period (in Dunkereley' s method is obtained as square, root of sum of squares of pinned-pinned floor period and the Period of rigid floor structure.

**Static and Free Vibration Analysis of Single Piles in Lateral Direction**
*[Udaya Bhatta Halabe; August 1985; Supervised by Sudhir Kumar Jain]*

Static and free vibration analysis in lateral direction of single piles with and without compressive axial load has been carried out. The governing differential equations have been solved exactly by treating the soil as a linear homogeneous Winkler's model. The boundary conditions considered are: free head or fixed head; free tip or hinged tip (hinged tip in case of static analysis only). Piles have been treated as rigid, finite or semi-infinite (semi-infinite only for statics) depending upon their relative stiffness with respect to soil

Closed form expressions have been developed for lateral displacement, bending moment and critical buckling load for laterally loaded (static) piles with or without axial load. These expressions have been used to correlate the lateral behaviour of the pile with and without axial load in terms of amplification factors which are functions of the ratio of applied axial load to the critical buckling load. For rigid and semi-infinite piles without moral load the normalised 1ateral displacement and bending moment (normalised with respect to their respective maximum values) have been found to be functions of the normalised depth only.