SECTION 1

INTRODUCTION

1.1 Background

The study presented herein is part of a comprehensive research program sponsored by the National Center for Earthquake Engineering Research (NCEER) on the seismic damage assessment and performance evaluation of buildings in zones of low seismicity, such as in the Eastern and Central United States. Buildings in such zones are typically designed only for gravity loads (U = 1.4D + 1.7L, herein referred to as GLD) according to the non-seismic detailing provisions of the code. These building are also termed lightly reinforced concrete (LRC) structures throughout this study. Although such structures are designed without consideration of lateral loads, they still possess an inherent lateral strength which may be capable of resisting some minor and moderate earthquakes. However the deficient detailing of members can lead to inadequate structural performance during seismic activity.

Two main parts from the current study (i) a seismic performance **Evaluation** of gravity load designed R/C Frame Buildings and (ii) an evaluation of seismic **Retrofit** of R/C frame structures. The first part will be mentioned as **Evaluation** and the second as **Retrofit**.

A research program on the **Evaluation of the seismic performance of gravity load designed R/C frame buildings** was developed and carried out according to the plan outlined in Fig. 1-1.

Based on a survey of typical building construction practices in the Eastern and Central United States (Lao, 1990 and El-Attar et al., 1991a and 1991b), a one-third scale model was constructed and tested on the shaking table in the State University of New York (SUNY) at Buffalo Earthquake Simulation Laboratory. The prototype design, model construction and similitude, initial dynamic characteristics, shaking table testing program along with the simulated ground motions, and the elastic response of the model from minor base motions are presented in Part I of the Evaluation Report Series (Bracci et al 1992b). Based on this report, analytical models can be developed and used to predict the inelastic response of the model building during more severe earthquakes.

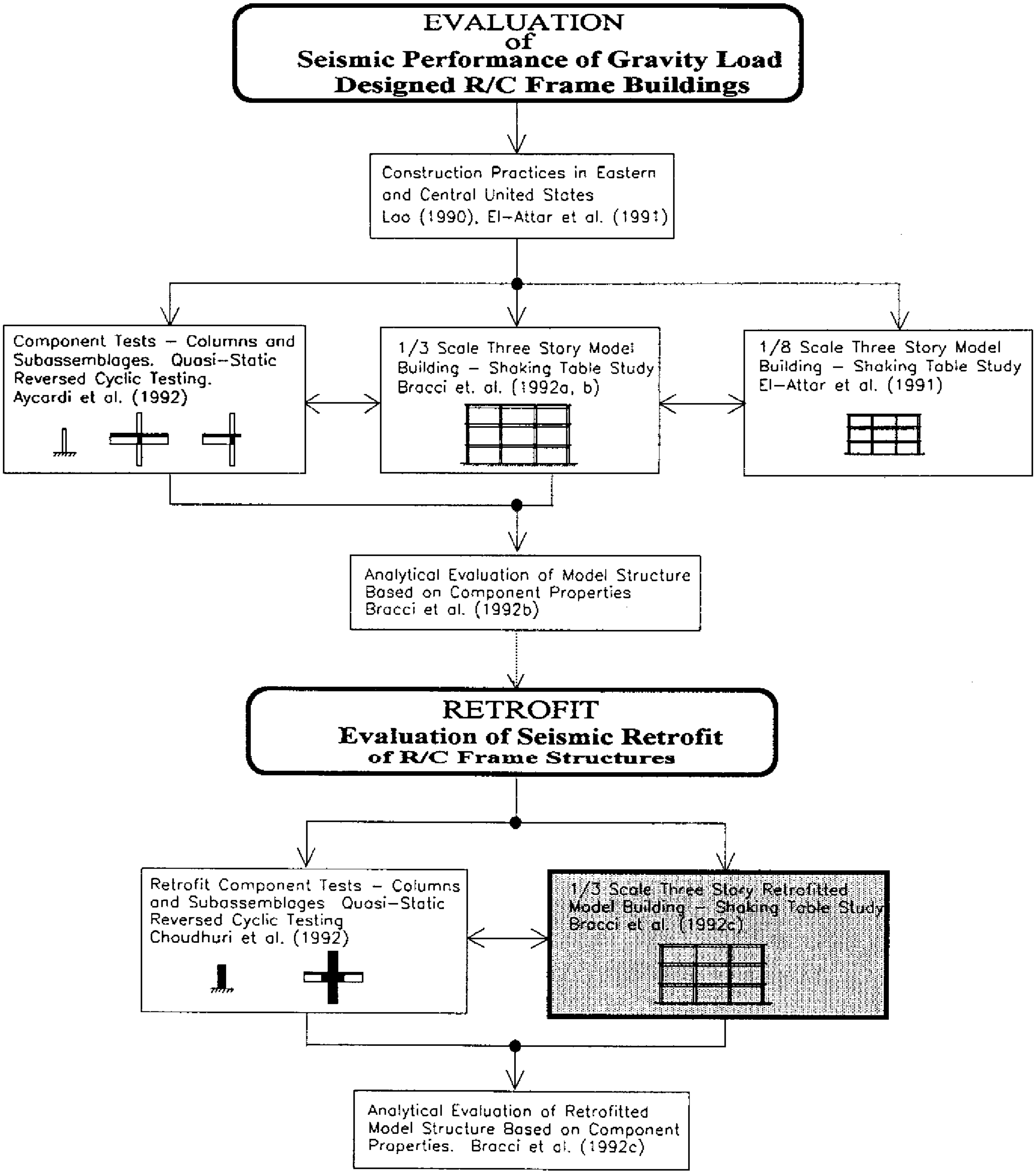

Fig 1.1 Research Context - Seismic Performance of Gravity Load Designed Reinforced Concrete Frame Buildings

Companion reduced scale slat-beam-column subassemblages were also constructed with the same materials in conjunction with the construction of the one-third scale model building are presented in Part II of the Evaluation Report Series (Aycardi et al., 1992). The components were tested under quasi-static reversed cyclic loading and conducted prior to the testing of the model building. The results of the component tests were used to identify the behavior of localized members and subassemblages of the structure and the member properties for predicting the overall response of the model building with analytical tools.

The experimental and analytical performance of the model building during moderate and severe shaking is presented in Part III of the Evaluation Report Series (Bracci et al., 1992b). The analytical predictions of the model building during these earthquakes are presented based on member behavior developed from engineering approximations and component tests. Some of the conclusions of the evaluation study are that the response of the model is governed by weak column - strong beam behavior and large story drifts develop under moderate and severe earthquakes. A one-eighth scale model of the same prototype building was also constructed and tested at Cornell University by El-Attar et al. (1991b) as part of a collaborative study with SUNY/Buffalo. A comparison of the response behavior between the two scale models is also presented.

A second part of this research program was conducted to evaluate various **seismic retrofit techniques for R/C frame structures** typically constructed in low seismicity zones (see Fig. 1-1). Based on the seismic behavior of the one-third scale model from the previous study, a series of retrofit schemes were proposed for improved seismic resistance and presented in this report which is Part II of the Retrofit Report Series.

In Part I of the Retrofit Report Series (Choudhuri et al., 1992) of this research program, a capacity analysis and redesign method for seismic retrofitting of R/C structures is developed and tested. Retrofit using an improved concrete jacketing technique was selected and first performed on companion components. The retrofitted components were then tested under quasi-static reversed cyclic loading and used to identify the behavior of the individual members. Retrofit of the components was also performed to verify the constructability of the retrofit technique for the model building.

The work done in Part I of the Retrofit Report Series is used as base to evaluate and model the member properties of the beam column components with the concrete jacketing technique and is used further for predicting the response of the overall retrofitted model building with analyses presented in this report, which is Part II of the Retrofit Report Series. Based on analytical estimates, a global seismic retrofit for the one-third scale model building was proposed and constructed. An experimental and analytical shaking table study of the retrofitted model building was then conducted and the response behavior is presented. The main conclusions from this study are that seismic retrofit of gravity load designed R/C frame buildings: (i) can be designed to successfully enforce a strong column - weak beam behavior; and (ii) is a viable economic and structural alternative as compared to demolition and reconstruction of another.

1.2 Overall Objectives of Research Program

The objectives of the overall research program are summarized below along with the corresponding NCEER publications from Table 1-1:

1. Investigate the performance and principal deficiencies of typical LRC frame buildings during earthquakes through shaking table testing of a one-third scale model under minor, moderate, and severe earthquakes. (*Seismic Resistance of R/C Frame Structures Designed only for Gravity Loads: Parts I and III*, Evaluation report series, by J.M. Bracci, A.M. Reinhorn, and J.B. Mander)

2. Identify the potential collapse mechanisms for typical LRC frame buildings. (*Seismic Resistance of R/C Frame Structures Designed only for Gravity Loads: Part III*, Evaluation report series, by J.M. Bracci, A.M. Reinhorn, and J.B. Mander)

3. Determine the behavior and material properties of individual members and subassemblages of the structure. (*Seismic Resistance of R/C Frame Structures Designed only for Gravity Loads: Part II*, Evaluation report series, by L.E. Aycardi, J.B. Mander, and A.M. Reinhorn)

4. Determine the contribution of components in the overall response of the structure near collapse. (*Seismic Resistance of R/C Frame Structures Designed only for Gravity Loads: Parts II and III*, Evaluation report series, by J.M. Bracci, L.E. Aycardi, A.M. Reinhorn, and J.B. Mander)

TABLE 1-1 NCEER Publications Summarizing Current Study

EVALUATION SERIES:
Seismic Resistance of R/C Frame Structures Designed only for Gravity Loads
Part I: Design and Properties of a One-Third Scale Model Structure (by J.M. Bracci, A.M. Reinhorn, and J.B. Mander), NCEER-92-0027
(i) Identification of deficiencies of current engineering practice. (ii) Scale modeling. (iii) Experimental identification of structural characteristics. (iv) Ground motions for structural evaluation and experimental program. Note: This report serves as bare material for evaluation of analytical tools.
Part II: Experimental Performance of Subassemblages (by L.E. Aycardi, J.B. Mander, and A.M. Reinhorn), NCEER-92-0028
(i) Identify behavior and deficiencies of various components in structures. (ii) Identify member characteristics for developing analytical models to predict the seismic response of the one-third scale model structure. Note: This report serves as evaluation of structural characteristics to be incorporated in the evaluation of the entire structural system.
Part III: Experimental Performance and Analytical Study of Structural Model (by J.M. Bracci, A.M. Reinhorn, and J.B. Mander),NCEER-92-0029
(i) Investigate the performance and principal deficiencies of typical gravity load designed frame buildings during earthquakes through shaking table testing of a one-third scale model under minor, moderate and severe earthquakes. (ii) Identify the potential collapse mechanisms for such typical frame buildings. (iii) Compare the measured response of the model building with that predicted by analytical models developed from (1) engineering approximations, (2) component tests, and (3) an experimental fit using a non-linear time history dynamic analysis. Note: This report emphasizes the structural behavior, collapse margins via damage, and efficiency of predictions using component properties evaluated from tests.

RETROFIT SERIES:
Evaluation of Seismic Retrofit of R/C Frame Structures
Part I: Experimental Performance of Retrofitted Subassemblages (by D. Choudhuri, J.B. Mander, and A.M. Reinhorn), NCEER-92-0030
(i) Presentation of retrofit techniques. (ii) Identify constructability and behavior of retrofitted components. (iii) Identify retrofitted member characteristics for developing analytical models to predict seismic response of the retrofitted model building.
Part II: Experimental Performance and Analytical Study of Retrofitted Structural Model (by J.M. Bracci, A.M. Reinhorn, and J.B. Mander), NCEER-92-0031
(i) An analytical seismic evaluation of retrofitted gravity load designed frame buildings using various local and global retrofit techniques. (ii) Shaking table testing of one of the proposed retrofit techniques on the 1/3 scale model under minor, moderate, and severe earthquakes. (iii) Verify a change in formation of the potential collapse mechanism under ultimate load from an undesirable column-sidesway/soft-story mechanism to a more desirable beam-sidesway mechanism. (iv) Compare the measured response of the retrofitted model building with that predicted by analytical models developed from engineering approximations and component tests using a non-linear time history dynamic analysis.

5. Compare the measured response of the model building with that predicted by analytical models developed from engineering approximations or from component tests using a non-linear time history dynamic analysis. (*Seismic Resistance of R/C Frame Structures Designed only for Gravity Loads: Part III*, Evaluation report series, by J.M. Bracci, A.M. Reinhorn, and J.B. Mander)

6. Investigate appropriate local and global retrofit techniques for improving the seismic performance of LRC buildings. (*Evaluation of Seismic Retrofit of R/C Frame Structures: Part II*, Retrofit report series, by J.M. Bracci, A.M. Reinhorn, and J.B. Mander)

7. Investigate the seismic performance of the retrofitted model building and compare the measured response with the response of the original (unretrofitted) model from the same earthquakes. (*Evaluation of Seismic Retrofit of R/C Frame Structures: Part II*, Retrofit report series, by J.M. Bracci, A.M. Reinhorn, and J.B. Mander)

8. Determine the behavior and material properties of the retrofitted members and subassemblages of the structure. (*Evaluation of Seismic Retrofit of R/C Frame Structures: Part I*, Retrofit report series, by D. Choudhuri, J.B. Mander, and A.M. Reinhorn)

9. Determine the contribution of retrofitted and unretrofitted components in the overall response of the structure near collapse. (*Evaluation of Seismic Retrofit of R/C Frame Structures: Part I*, Retrofit report series, by D. Choudhuri, J.B. Mander, and A.M. Reinhorn)

10. Compare the measured response of the retrofitted model building with that predicted by analytical models developed from engineering approximations or from component tests using a non-linear time history dynamic analysis. (*Evaluation of Seismic Retrofit of R/C Frame Structures: Part II*, Retrofit report series, by J.M. Bracci, A.M. Reinhorn, and J.B. Mander)

1.3 Background to Present Study

The ensuing sub-sections provide a brief summary of some of the previously tested retrofit techniques for R/C structures.

1.3.1 Epoxy Injection Repairs

A form of repair for R/C members damaged by minor to moderate earthquakes is the epoxy repair technique. Two suitable techniques for repairing cracks are (i) the epoxy impregnation and (ii) pressure injection methods. Wolfgram-French et al. (1990) showed that both methods can restore member stiffnesses to about 85% of the original stiffness and the member strengths can be fully restored to the original strength capacity. It was also shown that both methods can restore the energy dissipation capacity and rebar bond strength of the damaged member specimens.

Although both of these methods can locally restore the stiffness and strength to members of the structure, the overall structural response still remains the same in event of future strong ground motions, similar to the one that caused the existing damage. Therefore, an upgrade (retrofit) for seismic protection of the structure can not be accomplished by using the epoxy injection techniques to the damaged R/C members.

1.3.2 Steel Jacketing

Circular and rectangular steel jacketing can be used to increase the flexural strength, ductility, and shear capacity of existing vulnerable columns. Chai et al. (1991) performed experimental cyclic tests on 0.4 scale models of circular bridge columns retrofitted by encasing the critical hinge regions with a steel jacket and bonded with concrete grout. Experimental verification of the increased flexural strength, ductility, and energy dissipation was achieved by the additional confinement from the jacket.

Beres et al. (1992) performed experimental cyclic testing using a steel jacketing retrofit of full scale interior and exterior joints with discontinuous bottom beam reinforcement and without a slab. The retrofit of the interior joints was directed at preventing pull-out of the bottom beam reinforcement. The resulting damage was transferred from the embedment zone to elsewhere in the joint panel. Whereas the retrofit of the exterior joint was directed at preventing splice failure in the column, spalling of the concrete cover of the joint, and pull-out of the bottom beam reinforcement. The resulting plastic hinge formed in the joint panel zone near the top of the beam. The steel jacketing schemes were proposed for zones of moderate seismicity.

1.3.3 Concrete Jacketing

Concrete jacketing has been widely used in repairing, strengthening, and improving the ductility capacity of damaged reinforced concrete columns: Bett et al. (1985); Iglesias (1986); Stoppenhagen and Jirsa (1987); Krause and Wight (1990); and many more. An existing vulnerable column is encased in a concrete jacket with additional longitudinal and closely spaced transverse reinforcement (for shear and confinement) to satisfy the required bending moment, shear force, and ductility demands. Mander et al. (1988a and 1988b) showed that substantial enhancements of compressive strengths can be achieved in heavily loaded columns with adequate confining steel.

Bett et al. (1985) performed several forms of concrete jacketing retrofit to short columns. Their general results were similar to those described above.

Stoppenhagen and Jirsa (1987) constructed a 2/3 scale model of a moment resisting frame with deep spandrel beams and short, slender columns. The frame was insufficient for ductility capacity and for strength under seismic loads. Concrete jacketing was used to increase the lateral strength capacity and to force the hinging into the beams. Under reversed cyclic loads up to 1.6% drift: (i) a ductile failure mechanism developed with hinging in the beams and small damage to the columns; and (ii) the lateral capacity of the retrofitted frame was 5 times greater than the original.

Krause and Wight (1990) constructed a 2/3 scale model of a 2 story R/C frame with a column jacketing retrofit. Under quasi-static reversed cyclic loading, the retrofit improved the strength and ductility of the columns, ductility of the beam-column joints, and hysteretic behavior of the frame. The energy dissipation capacity was increased and the failure mode was a ductile strong column - weak beam failure mechanism.

1.4 Concluding Previous Studies on Retrofit Techniques

The previous section provides a brief summary of some of the previously tested retrofit techniques for R/C structures. The appropriate seismic retrofit techniques for low-rise gravity load designed R/C frame structures would need to upgrade the structural strength and ensure life safety during seismic events. Epoxy repair techniques can not provide the required strength capacities to properly retrofit structural systems to resist earthquakes. Steel jacketing techniques, mainly used for increasing the member shear and ductility capacities, can only provide some local strength capacity increases, which may be insufficient for such structures. Deficiencies associated with the beam-column joints would also need appropriate retrofit considerations and may generate problems using steel jacketing techniques. Concrete jacketing of columns in a structural system can be used to adequately increase the member strength capacities and effectively resist the forces generated by earthquakes. However constructability problems associated with the tightly spaced added transverse reinforcement may arise.

In this study, a global retrofit of the structural system using an improved concrete jacketing technique is applied only to selected columns. This method uses post-tensioning of the jacketed column and is accompanied by a beam-column joint strengthening.

1.5 Scope of Study in this Report

This report is Part II of a two part series on the evaluation of seismic retrofit techniques for reinforced concrete frames. In this report, several local and global retrofit techniques are proposed for repair and enhanced seismic resistance of gravity load designed reinforced concrete frame structures to ensure life safety during a future seismic event. An analytical seismic evaluation is performed for each retrofit alternative on the existing damaged model based on member properties from engineering approximations. One global retrofit alternative is selected for the structure based on the analytical seismic performance and retrofit constructibility. The retrofitted model was then tested on the shaking table under the same moderate and severe earthquakes previously performed. It is shown the retrofitted model performed adequately and was governed by a desirable strong column - weak beam behavior during the shaking.

Analytical modeling is based on integrating the identified member properties from original and retrofitted component tests and is used to interpret and predict seismic response of retrofitted model buildings. An analytical damage evaluation of the retrofitted model is also performed to assess structural integrity after the induced ground motions in terms of damage states.

The performance evaluation of the selected technique is done using the performance of individually retrofitted components studied in Part I of this report series. An analytical study was done using the information from individual components.

The following outlines the contents in each section of Part II of Retrofit Report Series (this report)·

Section 2 summarizes the assessment of seismic damage states for typical R/C frame structures, followed by a discussion of the seismic local member damage versus global failure mechanisms.

Several local and global retrofit methods for GLD frame structures are presented. An analytical evaluation of the seismic response of the model with the various global retrofit alternatives is presented.

Section 3 summarizes the selected retrofit method and shaking table testing schedule for the model according to the analytical evaluation. The initial dynamic characteristics of the retrofitted model are also presented and compared with the previously damaged state of the model before retrofit.

Section 4 details the experimental performance of the retrofitted model during moderate and severe earthquakes. A corresponding damage evaluation and identification of the ensuing dynamic characteristics is presented. Analytical modeling, with member behavior developed from the component tests (from Part I of Retrofit Report Series), is used to predict the seismic response of the retrofitted model. Comparisons with the experimentally measured response are shown. An analytical quantification of damage from the earthquakes and an elastic analysis to identify the corresponding equivalent strength ratios from inelastic response are also presented. Finally, a summary of the maximum story response and dynamic characteristic history of the retrofitted model from the earthquakes is presented along with the concluding remarks on the seismic excitation of the retrofitted model.

Section 5 provides a summary of the experimental and analytical studies and concluding remarks concerning seismic retrofit of gravity load designed R/C structures.