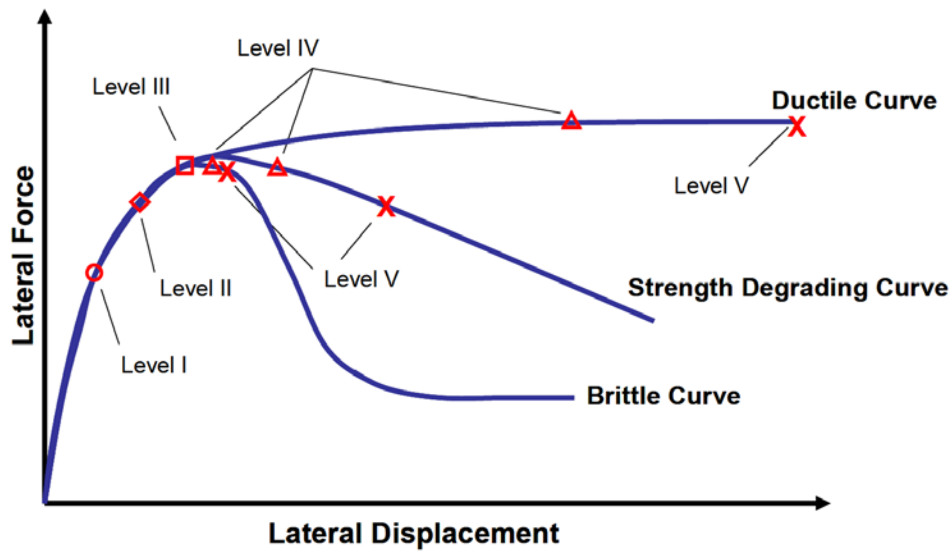
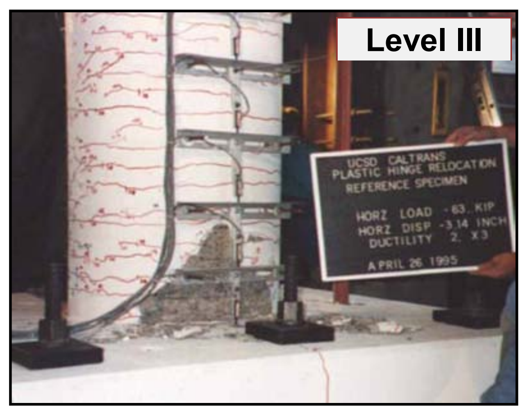
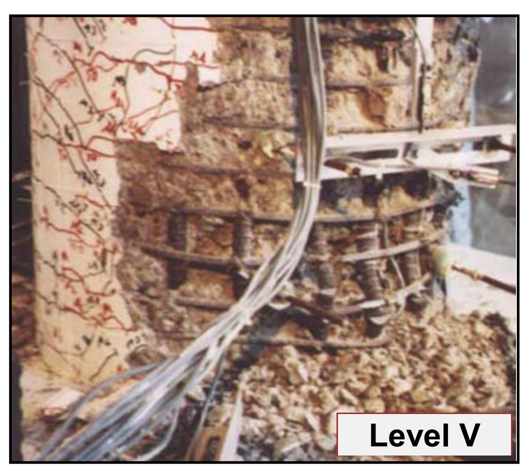
Division of Research
& Innovation

Visual Inspection & Capacity Assessment of Earthquake Damaged Reinforced Concrete Bridge Elements

Final Report







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November 2008

Visual Inspection & Capacity Assessment of Earthquake Damaged Reinforced Concrete Bridge Elements

Final Report

Report No. CA08-0284

November 2008

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15. SUPPLEMENTAL NOTES

This report captures the 'fundamental research components' developed primarily by UCSD researchers within a larger research-to-deployment effort coordinated by the Caltrans Division of Structures Maintenance and Investigations (SM&I) of the California Department of Transportation (Caltrans). The larger effort includes 'deployment products' developed jointly by UCSD researchers in collaboration with Caltrans SM&I staff consisting of a training manual for visual capacity assessment, an inspection manual with detailed procedures for post-earthquake inspection, and associated slide sets used for training of bridge engineers involved with emergency response. The deployment products and other resource materials are summarized in appendices to the report and can be obtained through direct request to Caltrans SM&I.

16. ABSTRACT

The overarching objective of this project was to produce standard procedures, and associated training materials, for the conduct of post-earthquake visual inspection and capacity assessment of damaged reinforced concrete (RC) bridges where the procedures are consistent with both Caltrans seismic design strategies and the extensive body of research laboratory testing that has been conducted in support of Caltrans seismic design.

This report presents the fundamental research concepts and experiment-based resources used in the broader development by Caltrans of standard procedures and associated training materials. It includes: 1) a summary report describing principles for classification and capacity assessment of earthquake damaged reinforced concrete bridges, and 2) an extensive visual catalog of RC bridge damage from both laboratory tests and field observations; all characterized using a consistent engineering terminology tied to bridge performance.

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Visual Inspection & Capacity Assessment of Earthquake Damaged Reinforced Concrete Bridge Elements.

Final Report

Preface:

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Visual Inspection & Capacity Assessment of Earthquake Damaged Reinforced Concrete (RC) Bridge Elements.

Final Report

Section 1: Summary Report - Post Seismic Inspection and Capacity Assessment of RC Bridges (UCSD Report SSRP-06/19)

Section 2: Visual Catalog of RC Bridge Damage

Part 1: Laboratory Test Photos and Associated Hysteresis Curves for Component Behavior

Part 2: Catalog of Bridge Damage from Historical Earthquakes 1971-2004

Part 3: Comparison of Observed Damage between Laboratory Tests and Historical Earthquakes

Part 4: Bridge Component Damage for Performance Levels IV and V

Part 5: Performance Curves for Various Bridge Components

Appendices: Summary of Related Resources Available By Request Through SM&I

A: Research Deployment Products (Developed Collaboratively by UCSD and SM&I)

B: Resources Used in Caltrans Emergency Response Training (Developed by SM&I)

Visual Inspection & Capacity Assessment of Earthquake Damaged Reinforced Concrete Bridge Elements.

Final Report

Section 1

Summary Report:

Post Seismic Inspection and Capacity Assessment

of Reinforced Concrete Bridges

(UCSD Report SSRP-06/19)

STRUCTURAL SYSTEMS

RESEARCH PROJECT

Report No.
SSRP–06/19
Final

POST SEISMIC INSPECTION AND CAPACITY ASSESSMENT OF REINFORCED CONCRETE BRIDGES

by

MARC J. VELETZOS

MARIOS PANAGIOTOU

JOSÉ I. RESTREPO

Final Report Submitted to the California Department of Transportation (Caltrans) Under Contract No. 65A0156

July 2006

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University of California, San Diego
Department of Structural Engineering
Structural Systems Research Project

Report No. SSRP–06/19

Post Seismic Inspection and Capacity Assessment of Reinforced Concrete Bridges

by

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16. Abstract

California has experienced several moderate size earthquakes in the last 30 years, yet the Office of Structures Maintenance and Investigation at the California Department of Transportation (Caltrans) does not have a standard procedure or a training program for the assessment of damage and the determination of the remaining load capacity of earthquake damage reinforced concrete (RC) bridge elements. In order to develop a standard procedure and training program, a Visual Bridge Catalog has been developed that documents damage from laboratory experiments and from historic earthquakes and classifies the performance of an array of bridge components, sub-assemblages, and systems in a consistent format. Results from the evaluation of numerous case studies using this damage/performance approach has lead to the formulation of Training and Inspection Manuals to aid in post-earthquake visual inspection of reinforced concrete bridges. In addition to these manuals and the visual catalog, an online computer based training class has been developed to easily communicate this information to Caltrans Maintenance and Inspection Engineers.

This report presents excerpts of the Visual Catalog, summarizes the Training and Inspection Manuals, and outlines the damage assessment and load capacity determination procedures for earthquake induced damage to reinforced concrete bridge columns.

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Acknowledgments

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The authors would also like to acknowledge the hard work of our undergraduate Structural Engineering interns, Jose Amador, Jose Ramirez, Justin Chung, Justin Chang, Alex Gascon, Chad Closs and our web-designer Dasha Tymoshenko. Without their efforts much of this work could not have been completed.

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California has experienced several moderate size earthquakes in the last 30 years, yet the Office of Structures Maintenance and Investigation at the California Department of Transportation (Caltrans) does not have a standard procedure or a training program for the assessment of damage and the determination of the remaining load capacity of earthquake damage reinforced concrete (RC) bridge elements. In order to develop a standard procedure and training program, a Visual Bridge Catalog has been developed that documents damage from laboratory experiments and from historic earthquakes and classifies the performance of an array of bridge components, sub-assemblages, and systems in a consistent format. Results from the evaluation of numerous case studies using this damage/performance approach has lead to the formulation of Training and Inspection Manuals to aid in post-earthquake visual inspection of reinforced concrete bridges. In addition to these manuals and the visual catalog, an online computer based training class has been developed to easily communicate this information to Caltrans Maintenance and Inspection Engineers.

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1. Introduction

California is expecting to experience several moderate size earthquakes per decade. The San Francisco Bay area alone has a 62% probability of experiencing a Magnitude 6.7 or greater earthquake by the year 2032 (Michael et. al., 2004). Seismic events of this magnitude can cause disruptions to the road network and result in important economic losses as a result of the impact. Despite this fact, the Office of Structures Maintenance and Investigation (SMI) at Caltrans does not have a standard procedure or a training program for the assessment of damage and the determination of the remaining load capacity of earthquake damage reinforced concrete (RC) bridge elements.

Following the 1989 Loma Prieta earthquake, the Mora Drive Overcrossing in Santa Clara County was closed and opened several times, because different departments had different opinions on the safety of the bridge. The lack of consensus caused public confusion and wasted the time and efforts of inspection engineers. This repeated closing and opening of the same bridge was partly caused by confusion regarding departmental responsibilities, which has since been clarified. It was also caused by discrepancies between the experience and judgment of Caltrans engineers. A common inspection and assessment protocol should prevent this from occurring in the future.

In order to develop a standard procedure and training program, Caltrans has supported a project that has developed a number of inspection and assessment tools. These tools include a first edition of a "Visual Catalog of RC Bridge Damage", a "Capacity Assessment Training Manual", and a "Post Earthquake Inspection Manual for RC Bridge

Columns". All of these documents have been transcribed into a web-based format. In addition to these manuals, an online computer based training class has been developed to assist in training Caltrans Maintenance and Inspection Engineers.

The inspection and assessment tools are based on over fifteen years of bridge seismic research. They touch upon details of seismic design practices and the historic performance of bridge components. Yet they also provide a simple step by step approach to post earthquake inspection and assessment that can be learned on the fly if necessary

2. Caltrans Current Practice

Following any emergency, SMI is officially responsible for all reports, investigations and recommendations for California bridges. They are, however, not the first responders to bridge sites. SMI has three offices in California (Sacramento, Oakland, and Los Angeles) and due to their locations, they can be many hours away from a large number of bridge in the state. The first responders are typically district construction and maintenance crews who are usually already out in the field. Engineers working in the SMI may have more experience with post seismic inspection than local construction and maintenance engineers, but there is no standard procedure for what to look for or guidelines on how to assess the remaining capacity of bridges after a significant seismic event. Thus, the decisions are ultimately based on the experience and judgment of each individual engineer, which can vary greatly.

3. Post Earthquake Inspection and Assessment Tools

3.1. Visual Catalog of RC Bridge Damage

The "Visual Catalog of RC Bridge Damage" documents damage from laboratory experiments and from historic earthquakes and classifies the performance of an array of bridge components, sub-assemblages, and systems in a consistent format. The Visual Catalog organizes photos of over one hundred test units from forty research reports dating back to 1990. The damage to each test unit has been classified into five different damage levels. The Visual Catalog also includes a force-displacement diagram of the test to document the performance of each test unit. A sample page from the Visual Catalog is shown in Figure 1. The Visual Catalog also organizes and classifies photos from fourteen historic earthquakes dating back to the 1971 San Fernando event.

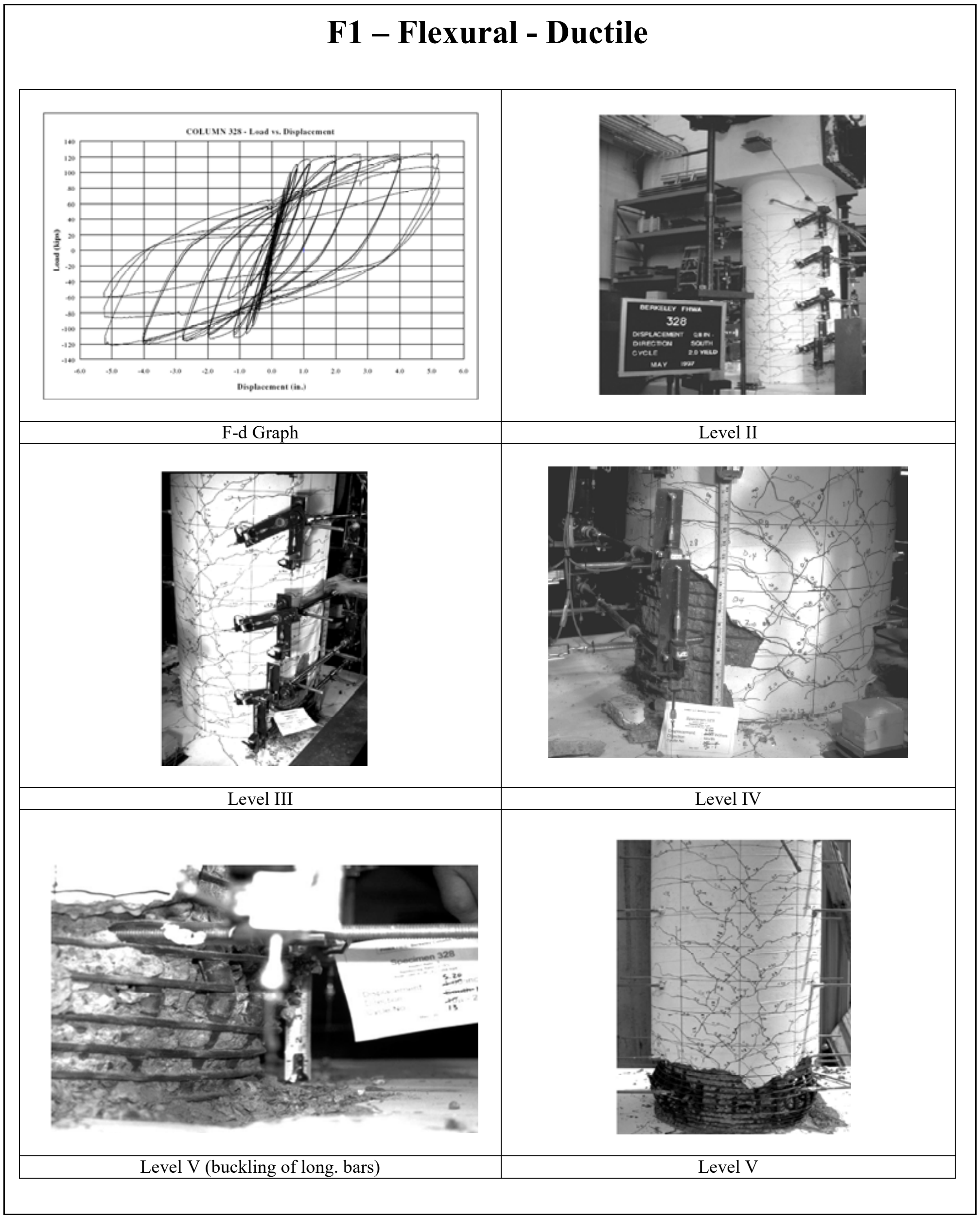

Figure 1 - Experpt from "Visual Catalog of RC Bridge Damage"

The intention is that this document will be used by inspection and maintenance engineers as a reference to confirm the type and level of damage observed after an earthquake. It will also be used as a teaching tool to train engineers in identifying the failure type and level of damage to bridge components.

3.2. Capacity Assessment Training Manual

The "Capacity Assessment Training Manual" will be a primary teaching tool for inspection and maintenance engineers. This document discusses seismic design concepts such as inelastic response, plastic hinge mechanisms, and capacity design principles. It explains the vulnerabilities of bridge from different design provision eras and reviews the past performance of RC bridge components and the seismic vulnerabilities of different construction methods. The training manual also discussed post earthquake bridge evaluation and ends with lessons learned about damage evaluation and capacity assessment. An excerpt from this manual is shown in Figure 2.

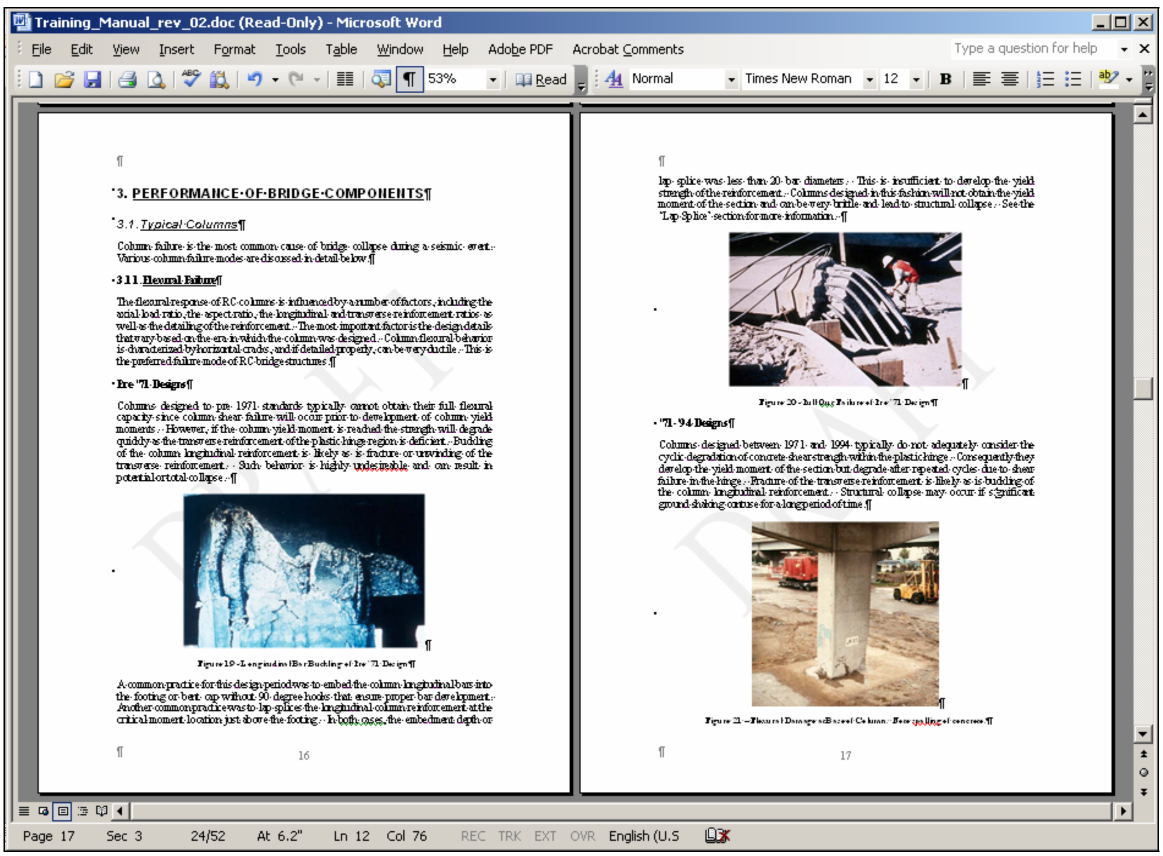

Figure 2 - Excerpt from "Capacity Assessment Training Manual"

3.3. Post-Earthquake Inspection Manual for RC Bridge Columns

The "Post Earthquake Inspection Manual for RC Bridge Columns", clearly identifies a simple step by step procedure that guides maintenance and inspection engineers in the determination of the remaining capacity of damaged reinforced concrete bridge structures. The general protocol is outlined elsewhere in this paper. Ideally, Caltrans engineers will be trained in the procedure prior to a significant seismic event. This, however, is not always practical, so the protocol has been developed to be simple enough to be followed in the field without prior training if necessary.

3.4. Web-Site and On-Line Training Course

The information in the above documents has been transformed into a web-site for easy access and information transfer. Inaccessible information is useless information, so every attempt has been made to make all these tools as available as possible. The home page of the web-site is shown in Figure 3.

Figure 3 - Excerpt from "Bridge Seismic Inspection and Capacity Assessment" Web-Site

4. Inspection and Assessment Protocol

Since the 1971 San Fernando earthquake, bridges in California have been designed with the goal of restricting all seismic damage to the columns while all other components remain essentially undamaged. Because of this fact, the focus of the inspection and assessment protocol has been limited to bridge columns. The primary goal of the post seismic inspection and assessment protocol is to keep things simple and conservative. Thus the protocol can be summed up in three phases.

Phase I - Determine the performance curve

Phase II - Identify the damage level

Phase III - Assess bridge system

4.1. Phase I – Determine Performance Curve

This phase is probably the most complicated and time intensive portion of the protocol as it requires access to all construction drawing of the bridge. Each column needs to be associated with a performance curve that best summarizes the expected seismic response. There are three performance curves to choose from: Ductile, Strength Degrading, and Brittle (see Figure 4). The engineer can determine the anticipated performance curve by following the decision making flowchart shown in Figure 5. This phase is most efficiently performed before hand in the office. The use of summary tables identifying the design detail and the performance curve for every column is recommended.

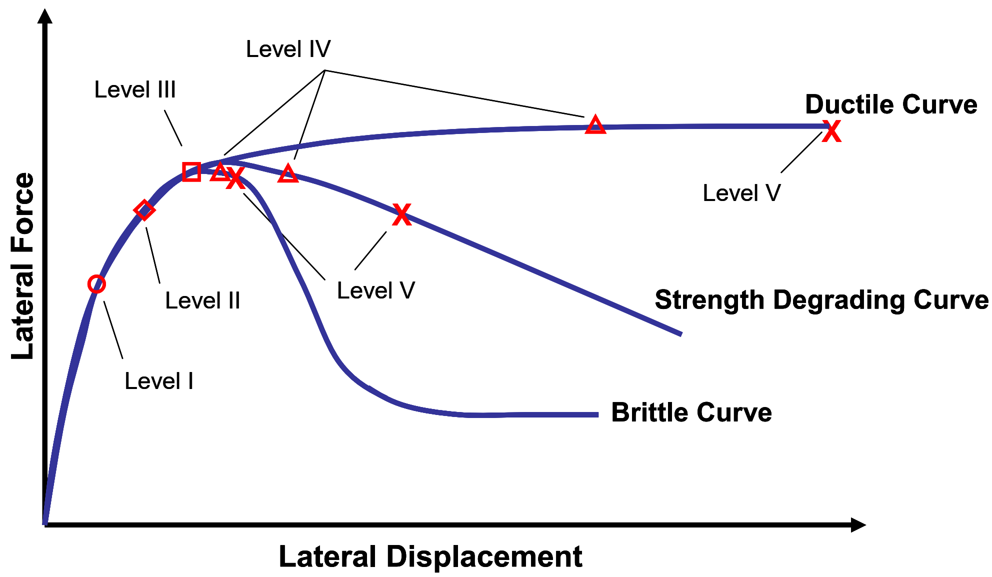

Figure 4 - Performance Curves

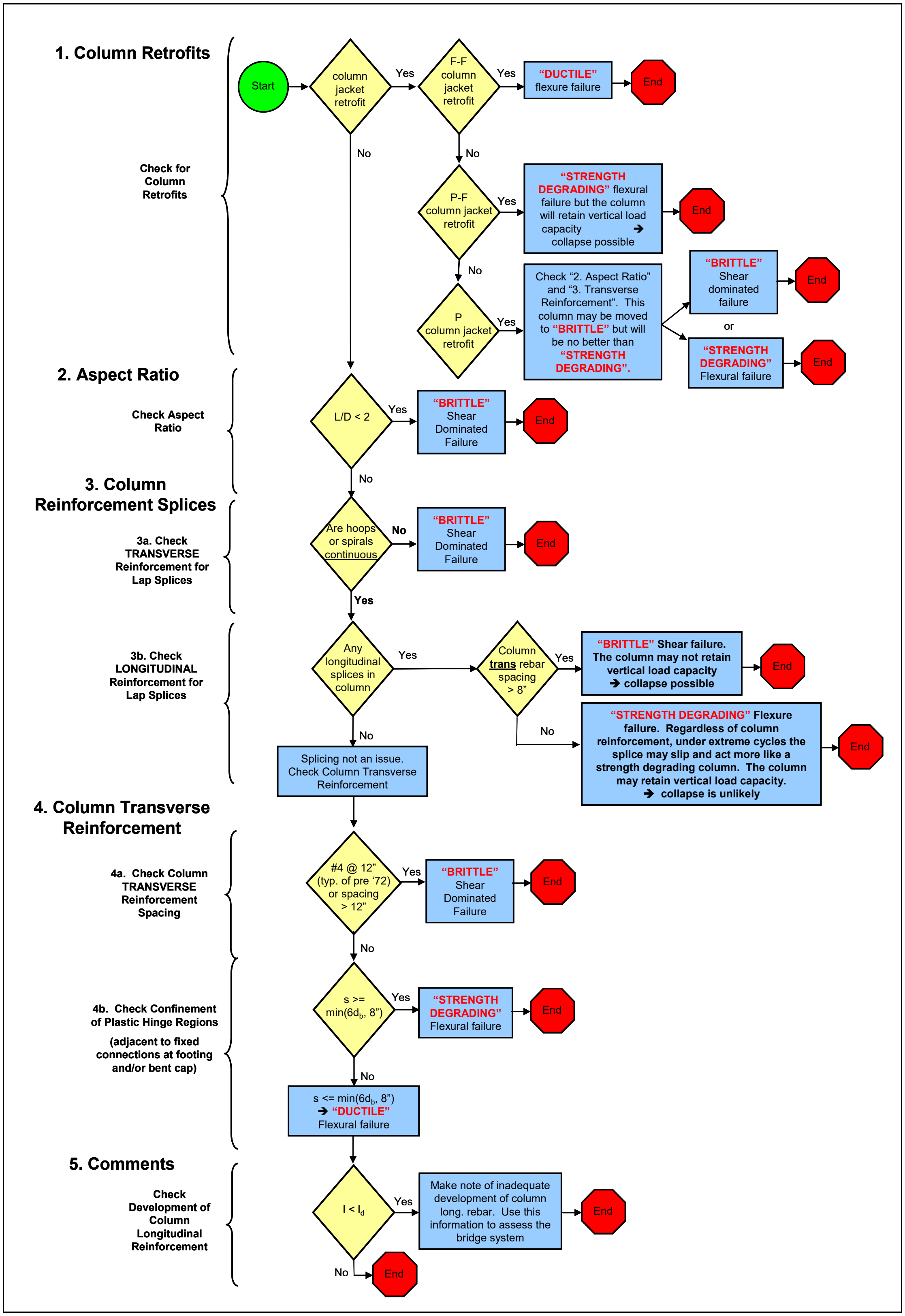

Figure 5 - Column Failure Mode and Performance Curve Decision Making Flowchart

4.2. Phase II – Identify Damage Level

This phase must be performed on the bridge site after a significant seismic event. Engineers are guided by a step-by-step procedure with the goal of determining where each column is on their respective performance curve. The steps are as follows.

Step 1 - Check for diagonal cracks.

Step 2 - Check for horizontal cracks.

Step 3 - Check for incipient concrete crushing or spalling.

Step 4 - Check for longitudinal bar buckling.

Step 5 - Check for rupture of transverse reinforcement

Step 6 - Determine the damage level based on the observations above.

The engineer is assisted by quantitative performance descriptions of each damage level (see Table 1) and a decision making matrix (see Table 2). It is recommended that the engineer refer to the "Visual Catalog of RC Bridge Damage" to confirm the level of damage they determine after following the six step procedure.

Table 1 – Performance Assessment (Hose, 2001)

Damage Level	Performance Level	Qualitative Performance Description	Quantitative Performance Description
I	Cracking	Onset of hairline cracks	Barely visible residual cracks
II	Yielding	Theoretical first yield of longitudinal reinforcement	Residual crack width ~ 0.008in
III	Initiation of Local Mechanism	Initiation of inelastic deformation. Onset of concrete spalling. Development of diagonal cracks.	Residual crack width 0.04in – 0.08in Length of spalled region > 1/10 cross-section depth.
IV	Full Development of Local Mechanism	Wide crack widths/spalling over full local mechanism region.	Residual crack width > 0.08in. Diagonal cracks extend over 2/3 cross-section depth. Length of spalled region > ½ cross-section depth.
V	Strength Degradation	Buckling of main reinforcement. Rupture of transverse reinforcement. Crushing of core concrete.	Lateral capacity below 85% of maximum. Measurable dilation > 5% of original member dimension.

Table 2 - Decision-making Matrix for Damaged Bridge Columns

Field Observations				Conclusions	
Pronounced Horizontal Cracks	Pronounced Diagonal Cracks	Incipient Concrete Crushing/ Spalling	Long. Bar Buckling	Damage Level	Possible Failure Type
No	Yes	No	No	III	Shear
Yes or No	Yes	Yes	Yes or No	IV or V	Shear
Yes	No	No	No	II or III	Flexure
Yes	No	Yes	No	IV	Flexure
Yes	No	Yes	Yes	V	Flexure

4.3. *Phase III – Assess Bridge System*

In this phase, it is recommended that engineers plot the level of damage of each column on their respective performance curve. This will assist the engineer in visualizing the remaining capacity of the structure (see Figure 6). It is important to note that bridges are complex structures and decisions about the bridge should include issues beyond column damage, such as damage to the superstructure, the abutments and expansion joints.

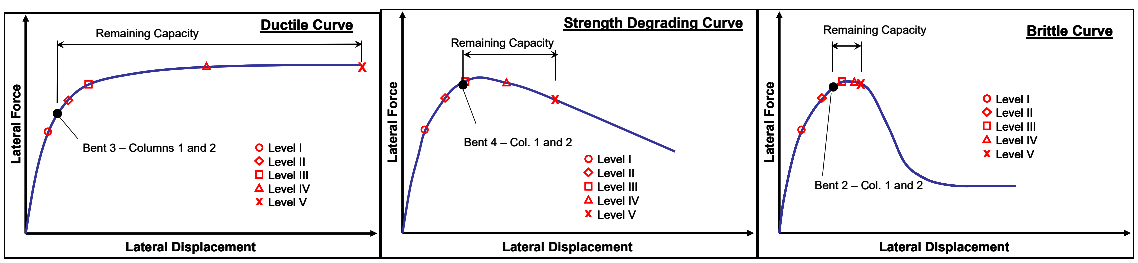

Figure 6 - Visualization of Remaining Capacity of Bridge Columns

5. Protocol Testing

The inspection and assessment protocol has been tested on undergraduate and graduate structural engineering students from the University of California at San Diego. The students have been asked to assess a number of columns that have been tested at the Charles Lee Powell Structural Laboratories and have been given no guidance other than what is in the inspection and assessment tools. The students helped the authors identify portions of the protocol that required clarification.

6. Performance Curve Pilot Study

A pilot study to identify the performance curve for every column on over two hundred bridges in California has been completed. This pilot study will allow Caltrans engineers to skip Phase I of the inspection and assessment protocol and save them valuable time and effort in the immediate hours following a major earthquake.

7. Conclusions

Post earthquake inspection and capacity assessment tools have been developed to assist Caltrans engineers after a significant seismic event. These tools include a “Visual Catalog of RC Bridge Damage”, a “Capacity Assessment Training Manual” and a “Post Earthquake Inspection Manual for RC Bridge Columns”. These tools have been transcribed into a web-based format to maximize accessibility and information transfer. Furthermore an on-line training course has been developed that will assist in training Caltrans maintenance and inspection engineers. These tools will help to standardize the inspection and assessment of bridges and improve the efficiency of Caltrans engineers during the important early hours after a large earthquake.

8. References

Hose Y.D., "Seismic Performance and Flexural Behavior of Plastic Hinge Regions in Flexural Bridge Columns", PhD Dissertation, UCSD, 2001.

Michael A.J., Ross S.L., Simpson R.W., Zoback, M.L., Schwartz D.P., Blanpeid, M.L., Understanding Earthquake Hazards in the San Francisco Bay Region, USGS Fact Sheet 039-03, September, 2004.

Visual Inspection & Capacity Assessment of Earthquake Damaged Reinforced Concrete Bridge Elements.

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Section 2

Visual Catalog of Reinforced Concrete Bridge Damage

Part 1: Laboratory Test Photos and Associated Hysteresis Curves for Component Behavior
Part 2: Catalog of Bridge Damage from Historical Earthquakes 1971-2004
Part 3: Comparison of Observed Damage Between Laboratory Tests and Historical Earthquakes
Part 4: Bridge Component Damage for Performance Levels IV and V
Part 5: Performance Curves for Various Bridge Components

California Department of Transportation
Structure Maintenance and Investigations

Visual Catalog of Reinforced Concrete Bridge Damage

Date: June 20, 2007

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California Department of Transportation Structure Maintenance and Investigation would like to acknowledge the University of California San Diego Department of Structural Engineering, Dr. Frieder Seible (Dean of Structural Engineering), for the outstanding work on the "Visual Inspection and Capacity Assessment of Earthquake Damaged RC Bridge Elements" research project. This manual/catalog is a result of that research.

Special acknowledgements go to the UCSD Project Managers, Dr. Yael "Lilli" Van Dan Einde and Dr. Jose Restrepo, and Graduate Researchers, Marios Panagiotou and Marc Veletzos. All laboratory test and earthquake field photos have been gathered by UCSD researchers from many sources including UCSD Structural Systems Research Projects, Pacific Earthquake Engineering Research Center, National Information Service for Earthquake Engineering, Earthquake Engineering Research Institute, and Caltrans Structure Maintenance and Investigations.

Other acknowledgements go to California Department of Transportation Structure Maintenance and Investigation, Structure Division of Research, Division of Earthquake Engineering, and Structure Design.

Key personnel for Structure Maintenance and Investigations were Tom Harrington, Office Chief, who initiated the Research that generated Earthquake Inspection manuals and Senior Bridge Engineer Stephen Sahs, the Research Project Manager and research contributor.

Disclaimer: The material and manuals generated from this research, "Visual Inspection and Capacity Assessment of Earthquake Damaged RC bridge Elements", should be used as a guide and training purposes only and should never replace engineering judgment in the field.

Visual Catalog of Bridge Damage
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Part II - Field Photos from Historic Earthquakes

Classification According to Earthquake

Classification According to Type of Damage

Part III - Correlation

Correlation of Field Photos with Laboratory Database

Part IV – Details

Details of Extreme Damage Levels

Part V – Performance Curves

Correlation of Damage Level with Performance Curves

Appendix

INTRODUCTION

California is expecting to experience several moderate size earthquakes per decade. These earthquakes can cause disruptions to the road network and result in important economic losses as a result of the impact. Despite this fact, the Office of Structures Maintenance and Investigation at Caltrans does not have a standard procedure or a training program for the assessment of damage and the determination of the remaining load capacity of earthquake damage reinforced concrete (RC) bridge elements.

In order to develop a standard procedure and training program, Caltrans has supported a research program that has developed a number of tools: a "Visual Catalog of RC Bridge Damage", a "Capacity Assessment Training Manual", and a "Post Earthquake Inspection Manual for Reinforced Concrete Bridge Columns". In addition to these manuals, an online computer based training class has been developed to easily communicate this information to Caltrans Maintenance and Inspection Engineers as well as to all other interested parties.

The "Visual Catalog of RC Bridge Damage" documents damage from laboratory experiments and from historic earthquakes and classifies the performance of an array of bridge components, sub-assemblages, and systems in a consistent format. The intention is that this document will be used by inspection and maintenance engineers as a reference to confirm the type and level of damage observed after an earthquake. It can also be used as a teaching tool to train engineering in identifying the type and level of damage to bridge components.

ORGANIZATION

The Caltrans Visual Bridge Catalog of Bridge Damage has been divided into five parts.

Part I is a catalog of laboratory test photos that are arranged by bridge component. The behavior of each laboratory experiment is documented with photos from various damage levels as well as a hysteresis curve of the response.

Part II is a catalog of photos from historical earthquakes dating from the 1971 San Fernando earthquake to the 2004 Mid Niigata Prefecture earthquake in Japan. For ease of referencing, the photos in this section have been arranged by earthquake as well as by type of damage.

Part III compares damage observed in laboratory experiments to damage from historical earthquakes. The intent of this section is to prove to the reader that what is observed in carefully controlled lab condition is in fact a realistic representation of in-situ behavior.

Part IV characterizes the damage at performance level IV and V for various bridge components. This section provides more detail than shown in Part I.

Part V defines performance curves for various bridge components. The performance is classified into one of three categories: ductile, strength degrading, or brittle. The damage level at various stages along the curve is indicated to clearly illustrate proximity to component failure.

DAMAGE LEVELS

This catalog utilizes a five stage damage classification system. Damage level I indicates no damage while damage level V indicates local failure or component collapse. See the table below for further descriptions.

Level	**Damage Classification**	**Damage Description**	**Repair Description**	**Socio-Economic Description**
I	None	Barely visible cracking	No Repair	Fully Operational
II	Minor	Cracking	Possible Repair	Operational
III	Moderate	Open cracks; onset of spalling	Minimum Repair	Life Safety
IV	Major	Very wide cracks; extended spalling	Repair	Near Collapse
V	Local Failure/Collapse	Visible permanent deformation	Replacement	Collapse

SEISMIC DESIGN PROVISIONS

Seismic design provisions have evolved significantly over the decades in order to fill deficiencies that became apparent after significant seismic events. Or particular importance are the 1906 San Francisco Earthquake, the 1971 San Fernando Earthquake, and the 1989 Loma Prieta Earthquake. In order to accurately assess the remaining strength in a bridge structure after a seismic event, it is imperative to understand the typical vulnerabilities of the design era. These vulnerabilities can be identified by their physical characteristics and design details.

Pre 1971 Design

In 1940, California developed the first seismic design provision for bridge in the country. This early seismic design code was simplistic and recognized that earthquakes produce forces that are proportional to the dead weight of the structure. Until 1965 the maximum lateral seismic design force was only 6% of the structural dead weight. In 1965, Caltrans incorporated the period of the structure into the design equations along with various amplification factors. The maximum lateral seismic design force increased to 13% of the weight of the structure. This was for very specific cases and was not typical of all bridge structures.

Potential Vulnerabilities (non-retrofitted bridges)

- Column shear failure
- Column longitudinal reinforcement pull-out
- Unseating of expansion hinges

Typical Design Details

- Column shear reinforcement ➔ #4 at 12” (typical, regardless of column size or size of column longitudinal bars)

- Very short seat widths at expansion joints (6-8” typ.)
- Inadequate lap splice of column long bars near footing (~20 d_b)
- Inadequate development of column long bars into footing (~20 d_b , without std. hooks)
- Lap splicing of column transverse rebar in cover (i.e. no 135 deg seismic hooks into core concrete)

<u>1971 – 1994 Design</u>

The 1971 San Fernando earthquake completely change the way California bridges are designed. Bridge engineers recognized the importance of detailing and ductility in the response of bridge structures, and the concept of capacity design was slowly incorporated into the design code. Bridges that were in the design phase when the earthquake occurred had their lateral design forces increased by a factor of 2 or 2.5 to about 0.3g, while future bridges had to account for fault proximity, site conditions, dynamic structural response and ductile details for RC construction. These provisions were incorporated into the Caltrans code in 1974 and while it was updated regularly, it remained, for all practical purposes, unchanged when the 1994 Northridge earthquake occurred. By 1980 the standard practice was to design for plastic shear of the columns. That is, the design intent was to fail the column in flexure with all other portions of the bridge remaining elastic.

The 1989 Loma Prieta earthquake prompted Caltrans to solicit the Applied Technology Council to review and revise the Caltrans design standards, performance criteria, specifications and practices. Work began in 1991, but their findings were not complete when the 1994 Northridge event occurred.

Potential Vulnerabilities (non-retrofitted bridges)

- Column shear failure of plastic hinge regions
- Shear failure of flared columns
- Unseating of expansion joint hinges

Typical New Design Details

- Closer spacing and improved column shear detailing (typical spacing 4”-6”, but no confinement/anti-buckling requirement of plastic hinge region)
- Top reinforcement matt in footing and pile caps (but no shear reinforcement)
- Column longitudinal splices prohibited at maximum moment locations
- Short seat widths at expansion joint hinges (~12”)
- Poor flare detailing (no gap between top of flare and superstructure)
- No joint reinforcement

Potential Vulnerabilities (retrofitted bridges)

- Failure of expansion joint hinge restrainers and subsequent unseating of expansion hinges, particularly for bridges with large skew (>30 deg)

Typical Retrofit Design Details

- Expansion joint hinge restrainers, short (connected to concrete bolster on either side of expansion joint)

<u>Post 1994 Design</u>

The Caltrans seismic design provisions of this era incorporated essentially all of the recommendations from the Applied Technology Council as stated in ATC-32. The recommendations included a capacity design approach that will ensure a ductile flexural failure of the column while all other bridge components remain elastic. In order to achieve this goal they recommended minimizing the number of expansions joints, avoiding large skews, minimize the use of column flares, considerations for shear demands in footings, joint shear in cap/column and footing/column connections, anti-buckling reinforcement in column plastic hinges and increasing the seat width at expansion joint hinges.

The 1994 Northridge earthquake validated the knowledge gained from recent research and from the Loma Prieta earthquake. While significant damage occurred, it was primarily in not retrofitted pre 1971 designs or bridges with the early hinge restrainer retrofits. Bridges with steel jacket column retrofits performed particularly well.

Typical New Design Details

- Tight confinement reinforcement in plastic hinge regions (~4" spacing)
- Long seats widths at expansion joints (~24")
- Improved flare column details (Gap between top of flare and superstructure)
- No lap splices in plastic hinge zones
- Shear reinforcement in footings
- Cap/column and footing/column joint reinforcement

Typical Retrofit Design Details

- Steel or concrete column jackets
- Expansion joint seat width extenders (8" XX-strong pipes)
- Top mat reinforcement in footings and perhaps additional piles.
- Expansion joint hinge restrainers, long (connected from bolster at one side of hinge to the superstructure web on the other side of the hinge)

DISCUSSION OF BRIDGE COMPONENT BEHAVIOR

Column Flexural Behavior

The flexural response of columns is influenced by a number of factors, including the axial load ratio, aspect ratio, and reinforcement ratio. The most important factor of all, however, is the design details that vary based on the era in which the column was designed.

Pre '71 Designs

Columns designed to pre 1971 standards typically cannot obtain their full flexural capacity since column shear failure will occur prior to development of column yield moments. However, if the column yield moment is reached the strength will degrade quickly as the transverse reinforcement of the plastic hinge region is deficient. Fracture of the transverse reinforcement is likely as is buckling of the column longitudinal reinforcement.

A common practice for this design period was to lap splices the longitudinal column reinforcement at the critical moment location just above the footing. Another common practice was to embed the column longitudinal bars into the footing or bent cap without 90 degree hooks that ensure proper bar development. In both cases the lap splice or embedment depth was less than 20 bar diameters. This is insufficient to develop the yield strength of the reinforcement. Columns designed in this fashion will not obtain the yield moment of the section and can be very brittle and lead to structural collapse. See the 'Lap Splice' section for more information.

’71-‘94 Designs
Columns designed between 1971 and 1994 typically do not adequately consider the cyclic degradation of concrete shear strength within the plastic hinge. Consequently they develop the yield moment of the section but degrade after repeated cycles due to shear failure in the hinge. Fracture of the transverse reinforcement is likely as is buckling of the column longitudinal reinforcement.

Post ‘94 Designs
Columns designed after 1994 are characterized by heavy confinement of the plastic hinge region with transverse reinforcement spaced at less than 6 longitudinal bar diameters. This type of design is very ductile. The confinement ensures that the column longitudinal bars do not buckle and that shear failure of the column and plastic hinge does not occur.

Column Shear Behavior

The shear strength of reinforced concrete sections comes from four essentially independent mechanisms: 1) shear friction in the compression zone, 2) dowel action of the longitudinal reinforcement, 3) aggregate interlock, and 4) transverse reinforcement truss mechanism. Dowel action contributes minimally to the overall strength of the section and is unreliable, thus it is typically ignored. The relative contribution of the remaining three mechanisms, to the overall column behavior, is highly dependant on the era in which the bridge was designed.

Pre ’71 Designs
A typical pre 1971 column design has very little transverse reinforcement, typically #4’s at 12 inches regardless of column size. Thus the column must rely predominantly on shear friction and aggregate interlock. Problems arise as the concrete cracks because the aggregate interlock component of shear strength reduces quickly with increasing crack width. The lack of transverse reinforcement produces a very brittle column shear behavior, which loses all strength shortly after the column cracks appear.

’71-‘94 Designs
Columns design during this era follow the capacity design approach and typically provide sufficient column reinforcement to develop the yield strength of the column. However, concrete shear strength cyclic degradation and longitudinal column bar buckling was not completely appreciated at this time. Thus it is not uncommon for shear failure to occur within the plastic hinge.

Post ‘94 Designs
Post 1994 column shear designs are characterized by closely spaced transverse reinforcement and heavy confinement of plastic hinge regions. These designs will typically force a ductile flexural failure of the column, but if this does not occur, ductile shear failure is likely. The shear demand is transferred primarily by the transverse reinforcement in the form of a truss mechanism. Failure will occur due to yielding and subsequent fracture of the transverse reinforcement after significant cracking.

Column Lap Splice Behavior

A common practice for pre 1971 designs was to lap splices the longitudinal column reinforcement at the critical moment location just above the footing. These lap splice are typically less than 20 bar diameters long and are insufficient to develop the yield strength of the reinforcement. Columns designed in this fashion will not obtain the yield moment of the section and can be very brittle and may lead to structural collapse. Seismic response of lap splice connections can be improved with sufficient clamping pressure from transverse reinforcement.

Hollow Column

Hollow columns are used on large, long span bridges to improve the efficiency of the piers by removing unnecessary material at the center of the very large columns.

Circular column must have inner and outer circumferential hoops as well as radial ties to prevent implosion. The radial ties must go around the longitudinal and circumferential bars to be effective. Rectangular sections are not as susceptible to implosion because they have a wider effective compression zone.

Flared Columns

Flared columns are used to engage more of the superstructure and to improve aesthetics. Prior to the '94 Northridge earthquake, column flares were assumed, incorrectly, to be non-structural. Shear failure of pre '94 designed flared columns is possible since the column was designed for the shear doe to yielding of the column, but not the shear do to yielding of the column and flare.

Post 1994 designs consider the strength of the flare or they provide a gap between the flare and the superstructure to ensure that the flare is purely architectural and does not add any strength to the column.

Lightweight Columns

Earthquake induced demands are proportional to the weight of the bridge structure. It stands to reason that reducing the weight of the bridge will reduce the seismic demands and consequently the size of structural members may be reduces as well. Thus using lightweight concrete may reduce the cost of the bridge.

The shear strength of lightweight concrete is typically 75% that of normal weight concrete. To account for this reduced concrete contribution to the total shear strength of a column, additional transverse reinforcement may be necessary. If designed properly, lightweight concrete columns can exhibit a desirable ductile flexural response.

Connections/Joints

The 1989 Loma Prieta earthquake showed the deficiencies in column-cap and column-footing connections. This is particularly so for outrigger bents. Seismic design provisions did not provide sufficient guidance until 1994. Prior to 1994, it was common practice to provide no shear reinforcement in the connections. This will prohibit transfer of the column yield moment. Failure can be brittle and lead to collapse of the structure.

Superstructure

Bridge superstructures have generally performed quite well during an earthquake. Problems have arisen primarily at expansion joints where damage to bearings or local concrete spalling due to impact of adjacent spans may occur. This type of damage is not catastrophic and is reparable. Major problems have arisen due to inadequate seat length at expansion joints. Large relative displacements between adjacent spans at expansion joints have, on occasion, exceeded the capacity of the seat length, causing the supported span to collapse. This is particularly a problem in early (pre 1971) bridge designs and for bridges with large skews, for which torsional deformations add to the lateral displacement demands.

Foundations

Bridge foundations have generally performed well in earthquakes. Foundation damage that has occurred has been after column damage and is minor compared to the column damage. Early (pre 1971) bridge foundations are typically very small and have only a bottom matt of reinforcement and no shear reinforcement. Thus they cannot carry a negative moment induced by soil overburden or tension piles and flexure or shear failure of the footing or column-footing connection is possible.

Soil liquefaction or lateral spreading due to seismic motions is possible at some bridge locations. Vertical settlement or lateral movement of bridge foundations may occur causing foundation, column and potentially superstructure damage. Total structural collapse is not common unless the movement is large enough to unseat the superstructure at an expansion joint.

Abutments/Shear Keys

Abutment seismic design philosophy has generally been focused around the protection of piles below the abutment. Thus various elements of the abutment are designed to be sacrificial in order to limit the demands on the piles. Failure of shear keys due to transverse motion and punching shear failure of the back wall is likely. Neither failure will cause total structural collapse, and is typically repairable.

Liquefaction, lateral spreading or poor soil compaction at the abutment has caused vertical settlement or lateral movement in a number of earthquakes. Unless this movement is large enough to unseat the superstructure, total structural collapse is not common

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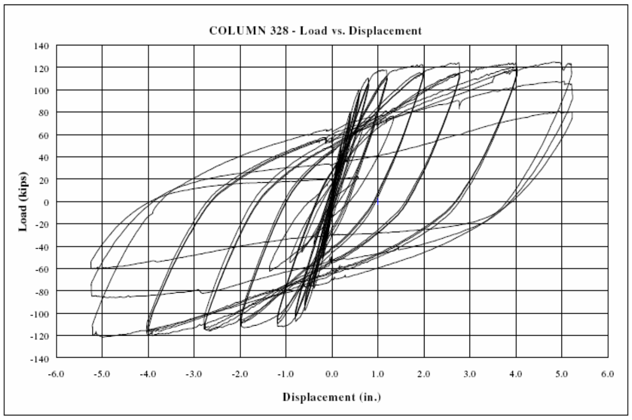
Part I

Laboratory tests photos

Ordinary Columns

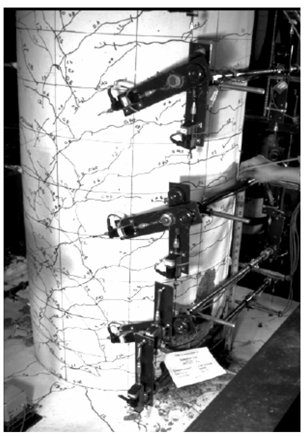
Flexural

F1 – Flexural - Ductile



F-d Graph

Level II



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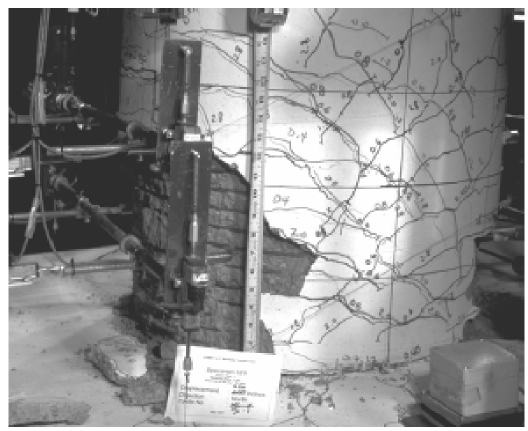
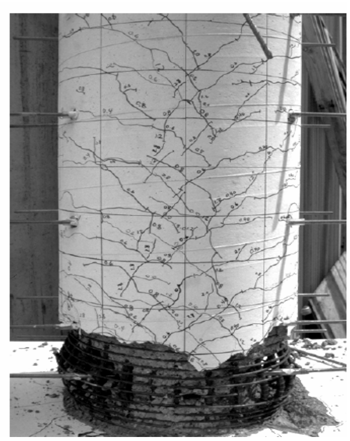


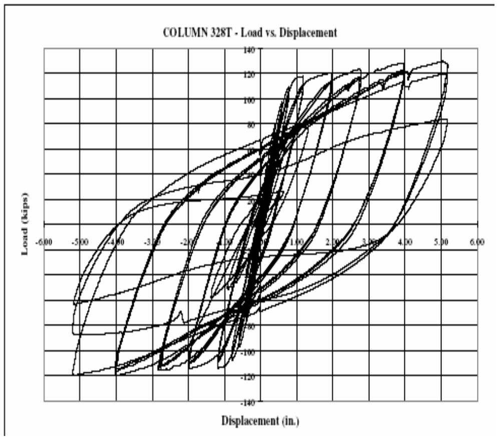
Level IV

Level V (buckling of long. bars)



Level V

F2- Flexural - Ductile



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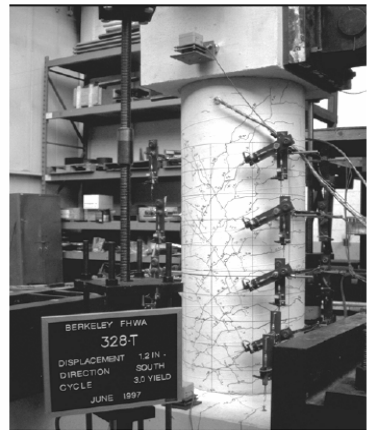
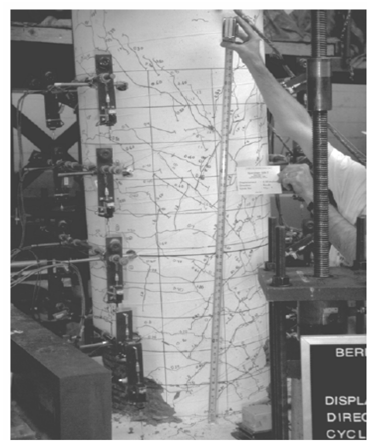


Level II

Level II



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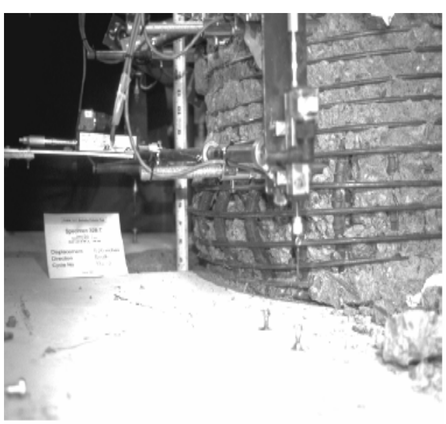
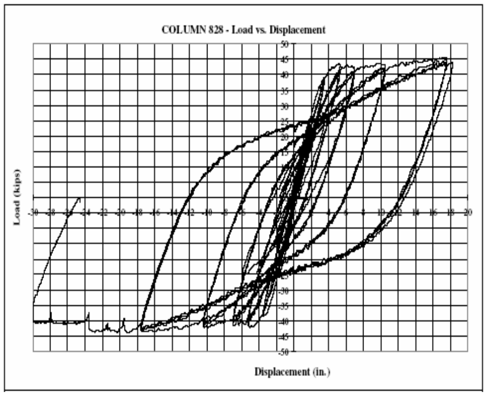
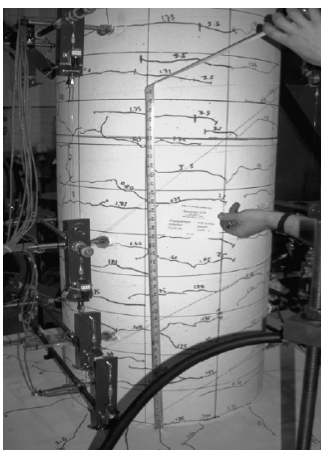


Level V cycle 1 (buckling of long. bars)

F3 – Flexural - Ductile



F-d Graph



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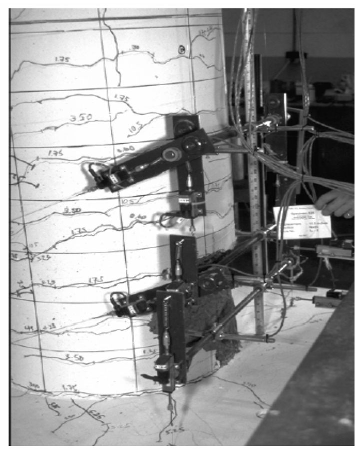

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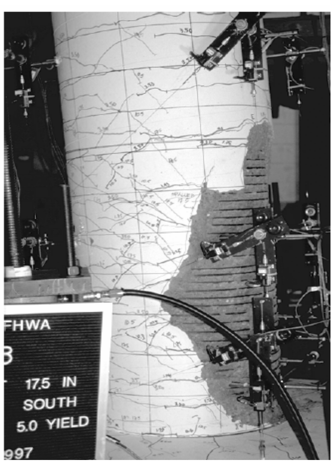

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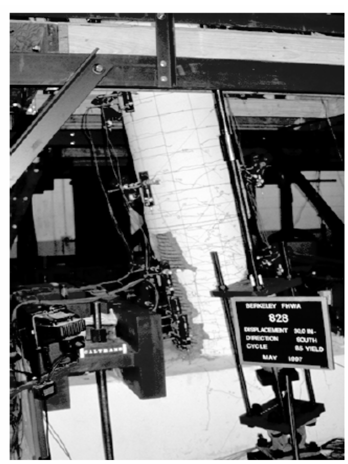
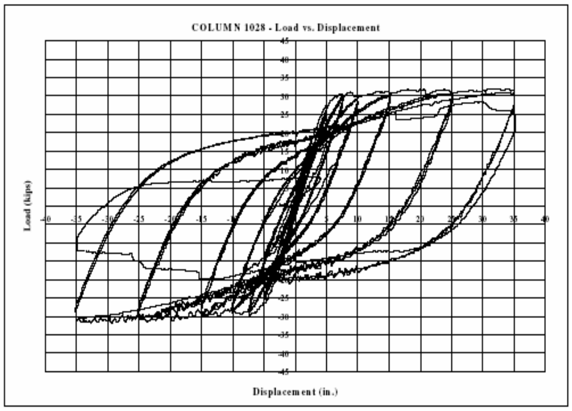
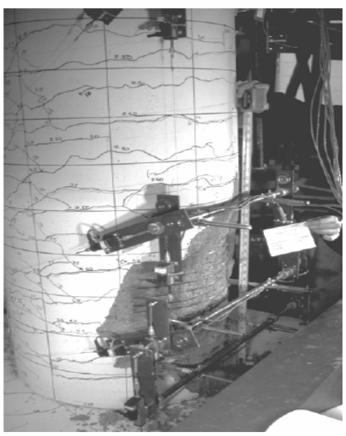
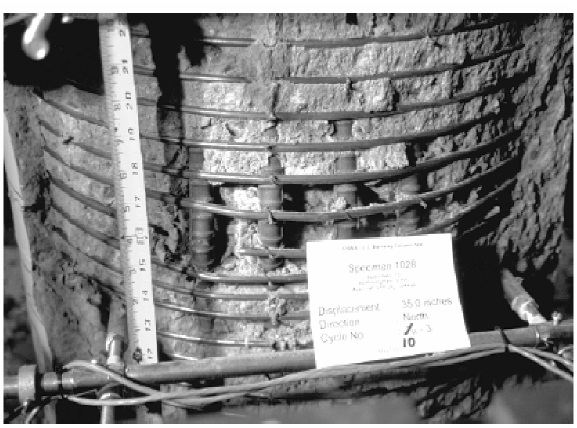
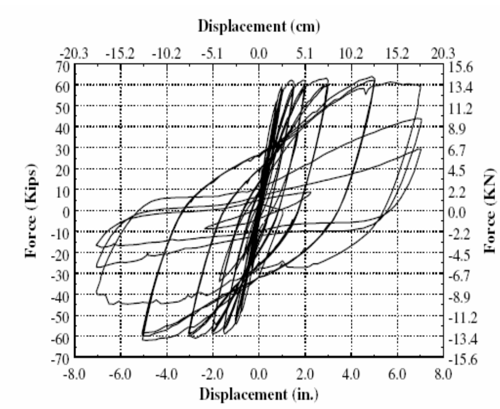


Level V (permanent deformation)

F4 – Flexural - Ductile

	
F-d Graph	
	
Level IV	Level V
	
Level V -(buckling of bars)	Level V

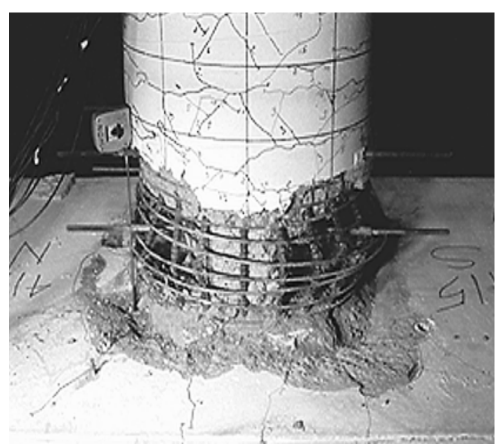
F5 – Flexural - Ductile



F-d Graph

Level II

Level IV



Level V - cycle 1 - (buckling of long. bars)

F6 – Flexural - Ductile

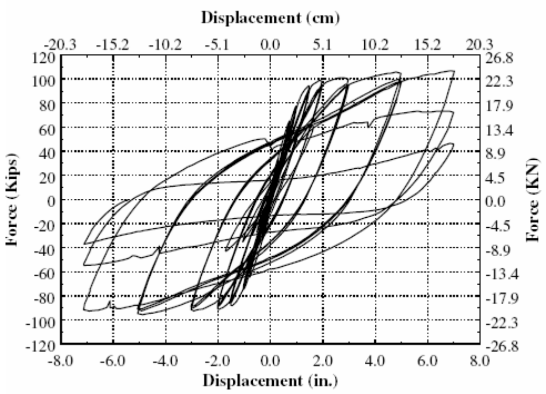
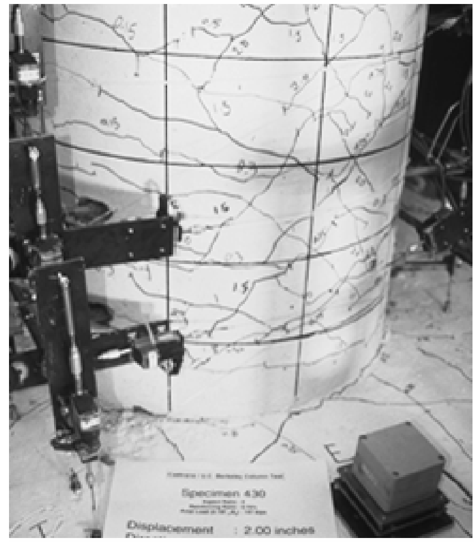
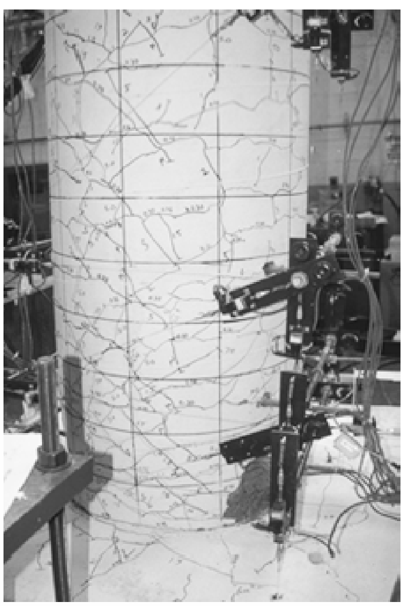


Figure 3.24: Column 430 Force-Displacement Response

F-d Graph



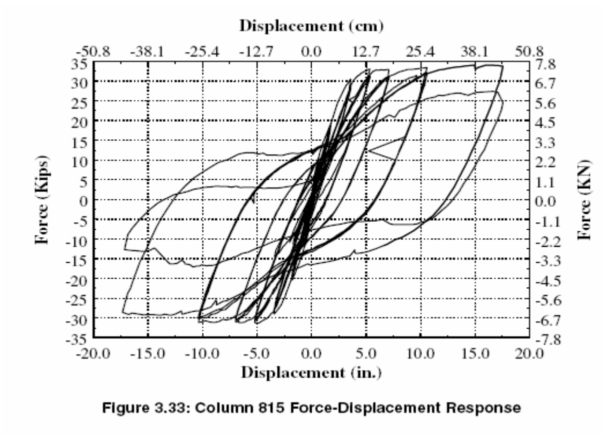
Level II



Level III

Level V - cycle 1 – (buckling of long. Bars)

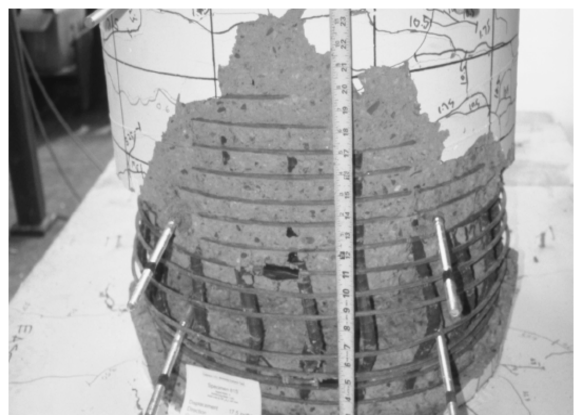
F7 – Flexural - Ductile



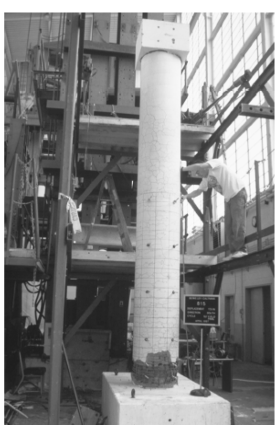
F-d Graph

Level II

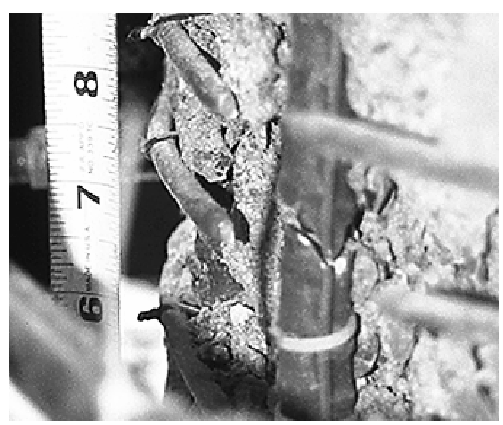
Level IV



Level V – cycle 1 – (buckling of long. Bars)



Level V



Level V cycle 2 (fracture of long. bars)

F8 – Flexural - Ductile

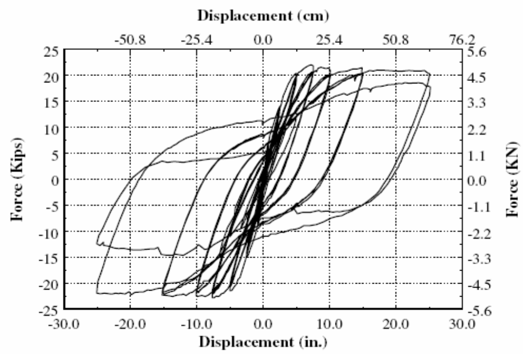
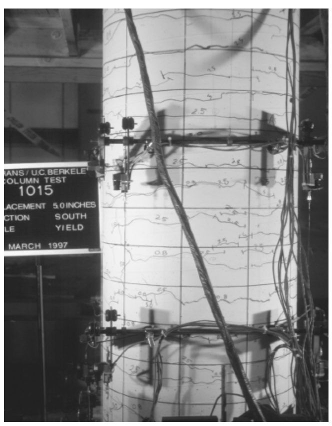
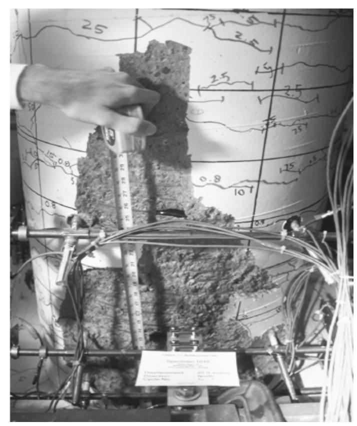


Figure 3.39: Column 1015 Force-Displacement Response

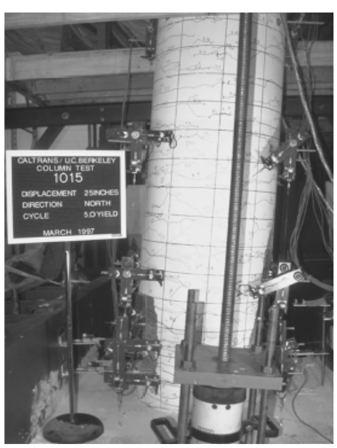
F-d Graph



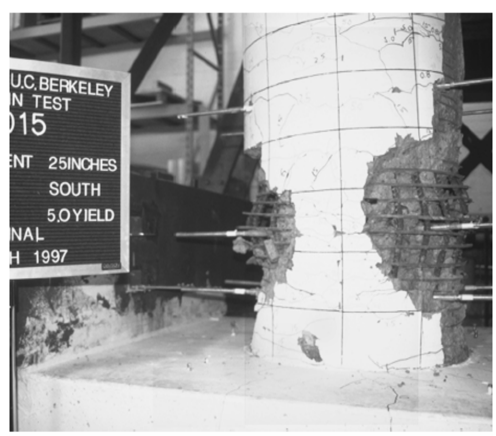
Level II



Level III

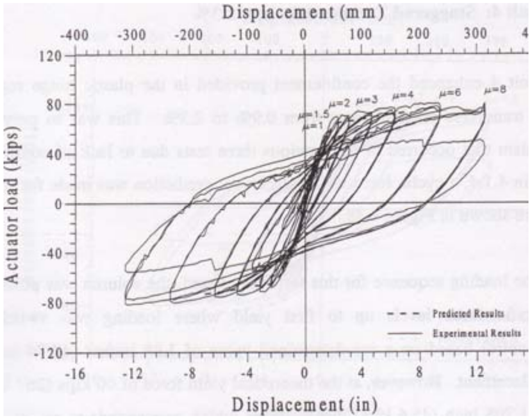


Level V (permanent deformation)

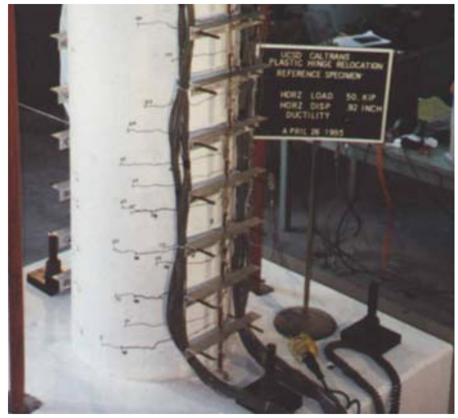


Level V (buckling of long. bars)

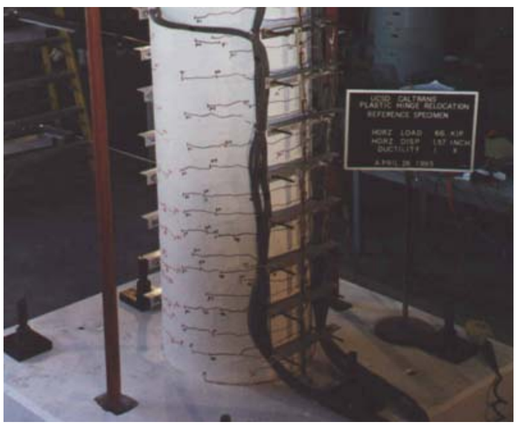
F9 – Flexural - Ductile



F-d Graph



Level I



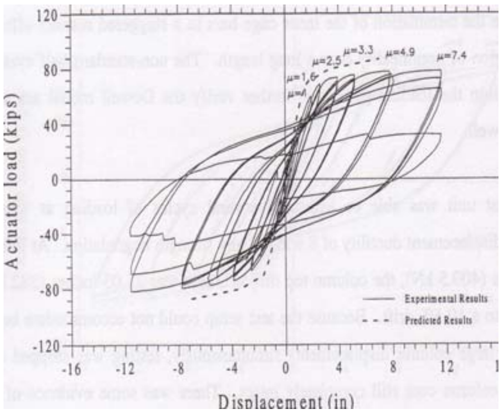
Level II

Level III

Level IV

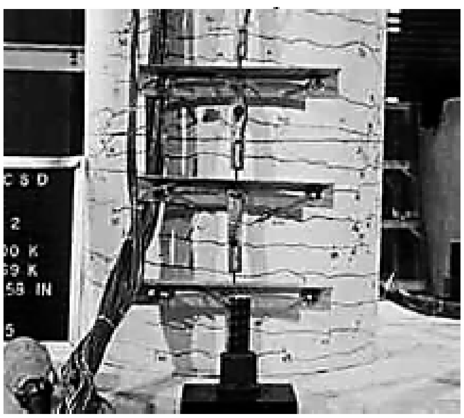
Level V (buckling of long. bars)

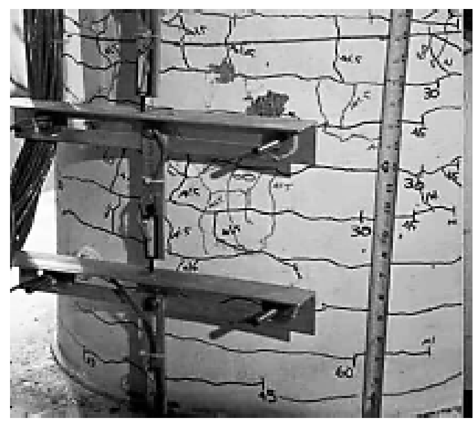
F10 – Flexural - Ductile



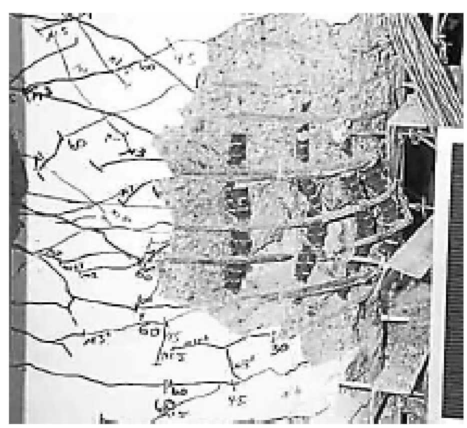
F-d Graph


Level I

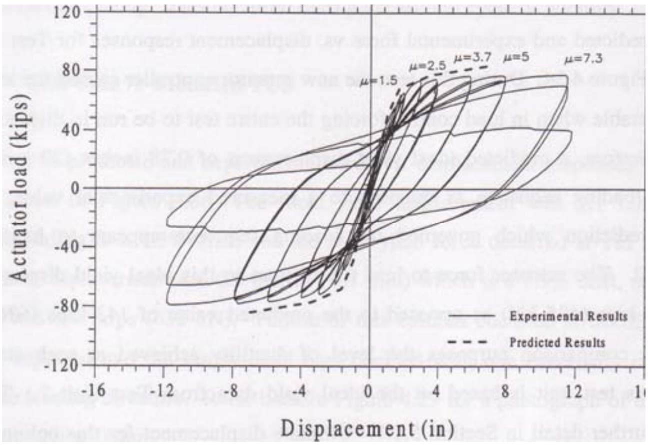
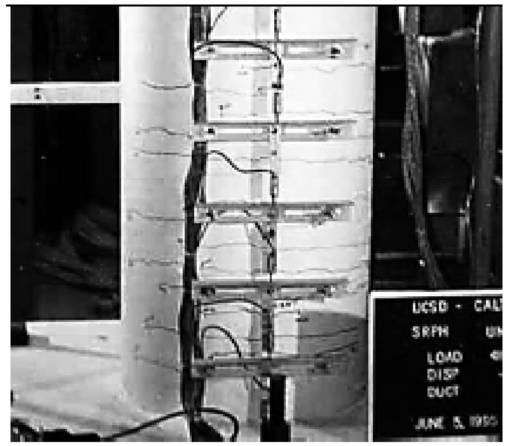
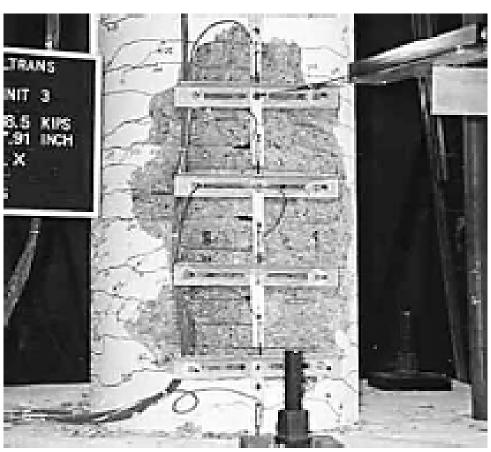

Level II


Level III

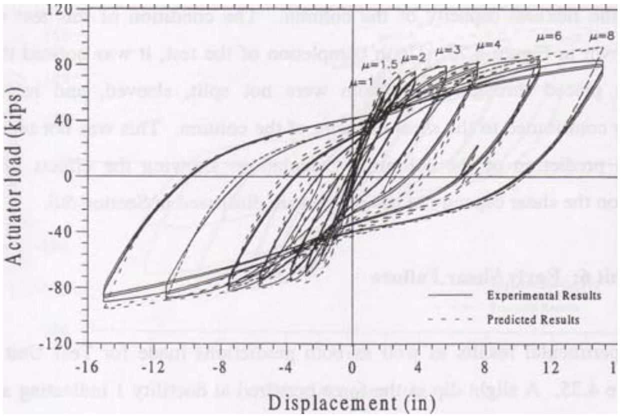

Level IV


Level V (buckling of long bars)

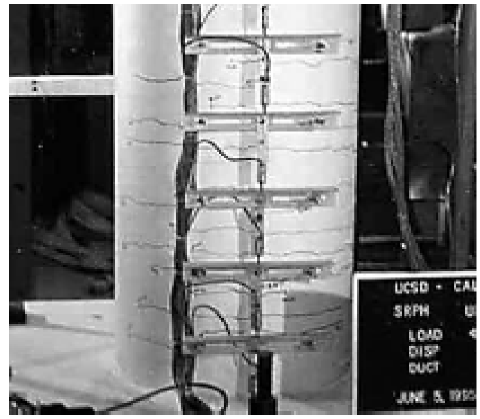
F11 – Flexural - Ductile

	
F-d Graph	Level I
	
Level II	Level III
	
Level IV	Level V (buckling of long. bars)

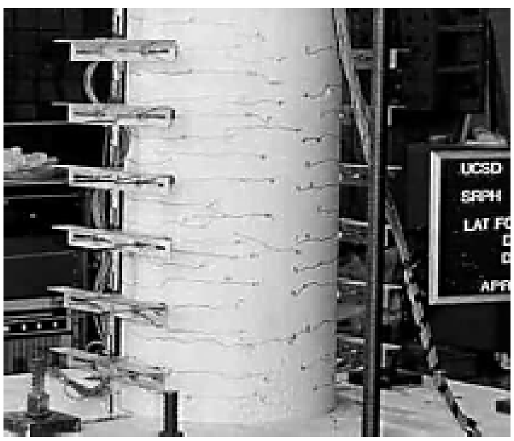
F12 – Flexural – Ductile



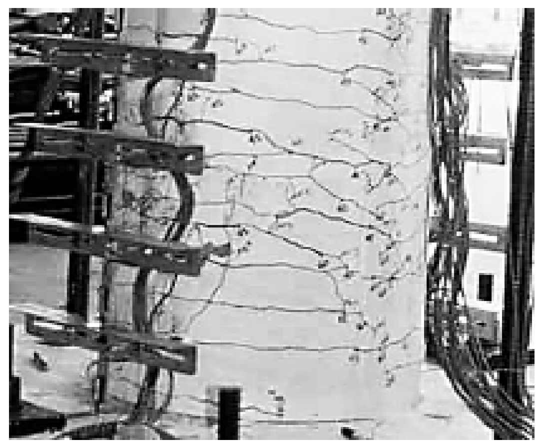
F-d Graph



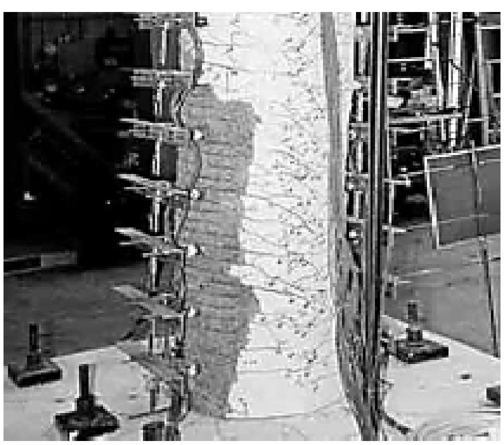
Level I



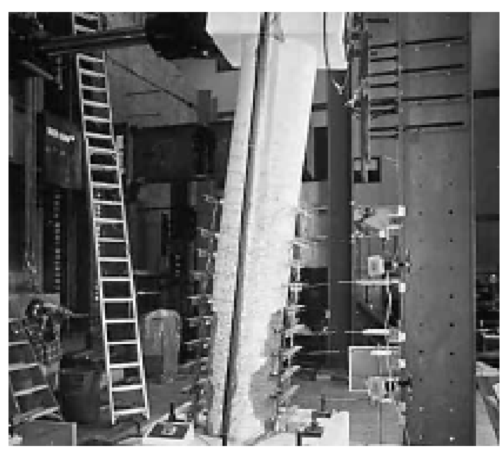
Level II



Level III

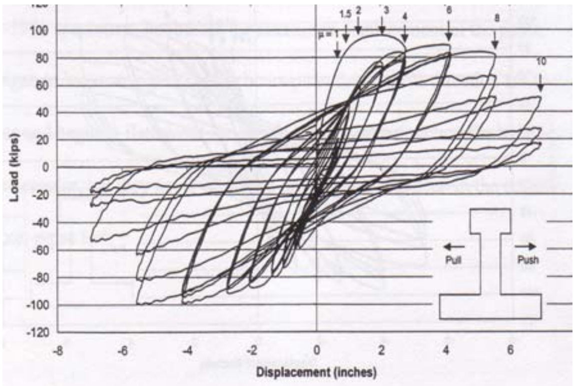


Level IV

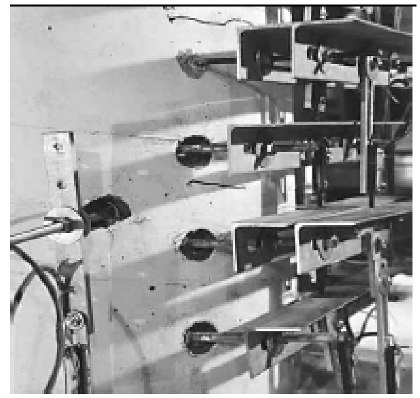


Level V (permanent deformation)

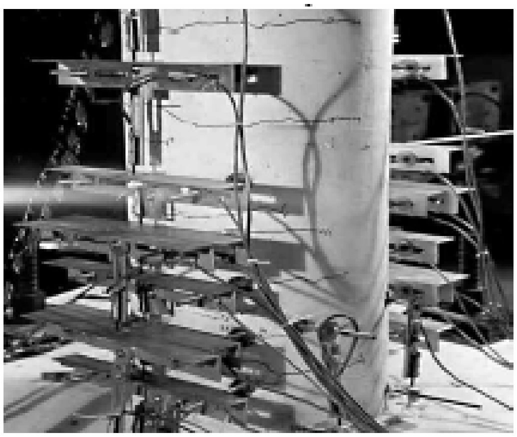
F13 – Flexural – Ductile



F-d Graph



Level I



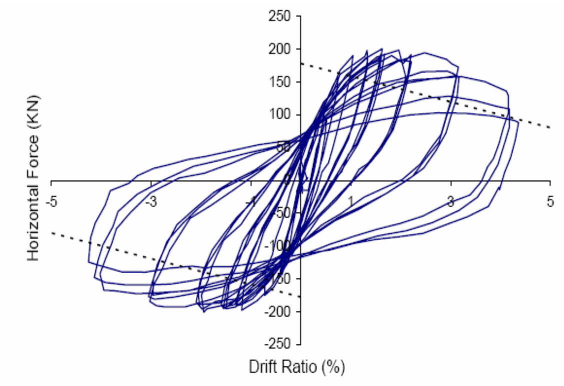
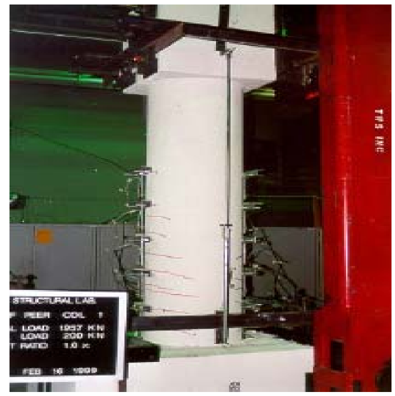
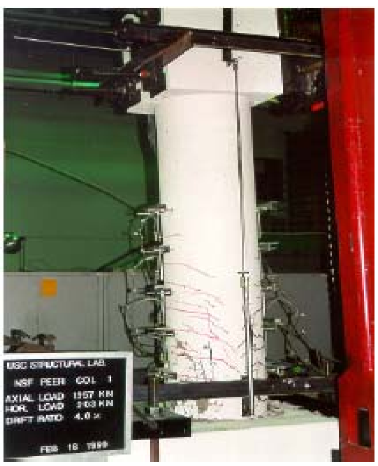
Level II

Level III

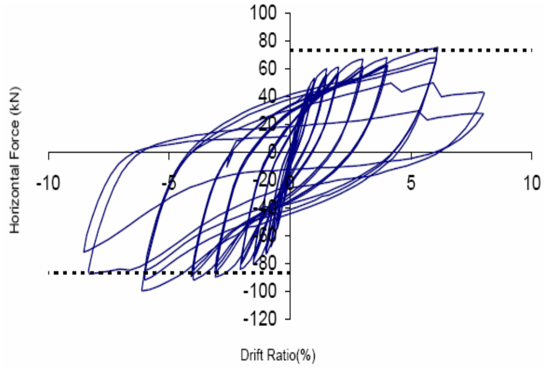
Level IV

Level V (buckling of long bars)

F14 – Flexural - Ductile

	
F-d Graph	Level II
	
Level IV	Level IV
	
Level V	Level V

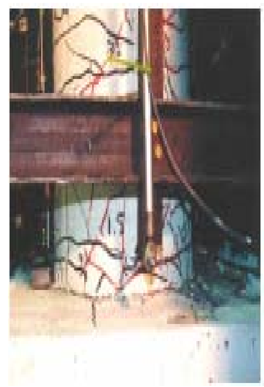
F15 – Flexural – Ductile

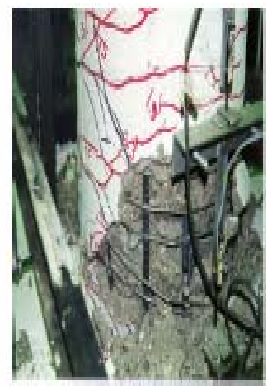


F-d Graph

Level II

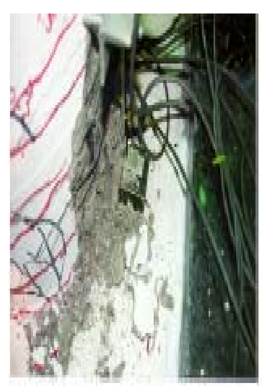
Level III

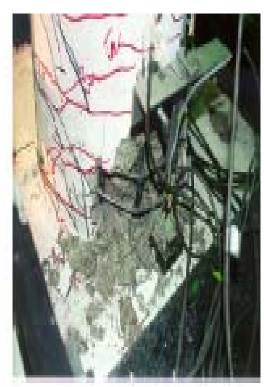




Level IV

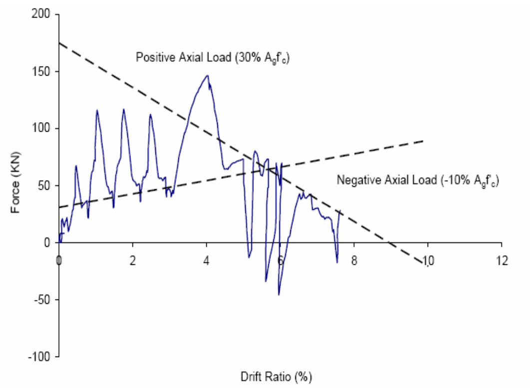
Level V



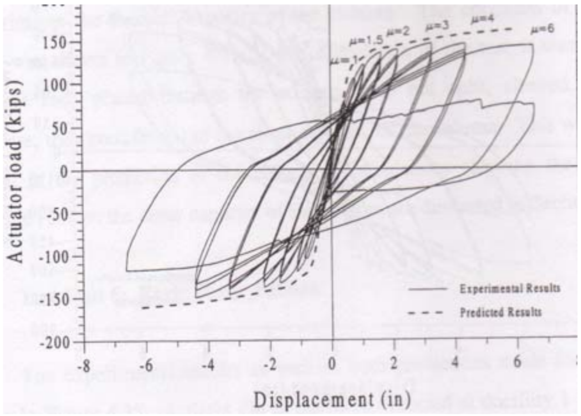


Level V

F16 – Flexural – Ductile

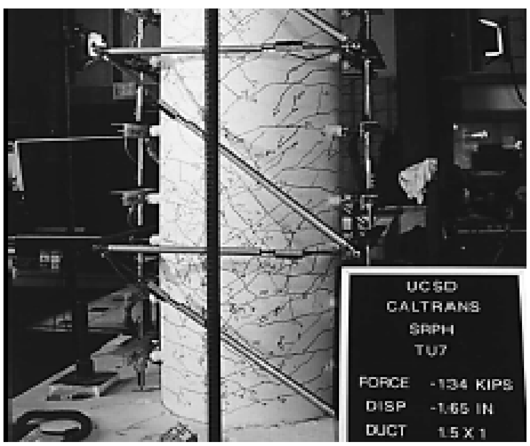
	
F-d Graph	
	
Level II	Level III
	
Level IV	Level IV

F17 – Flexural/Shear – Ductile

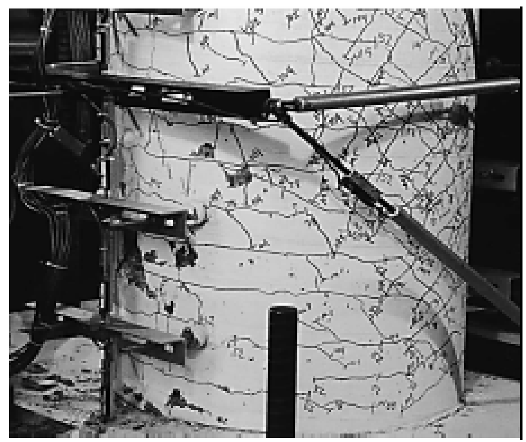


F-d Graph

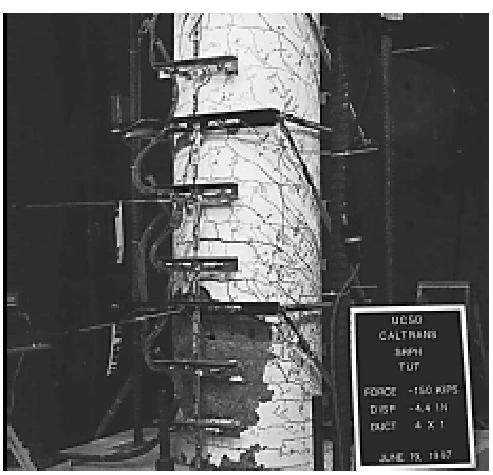
Level I



Level II



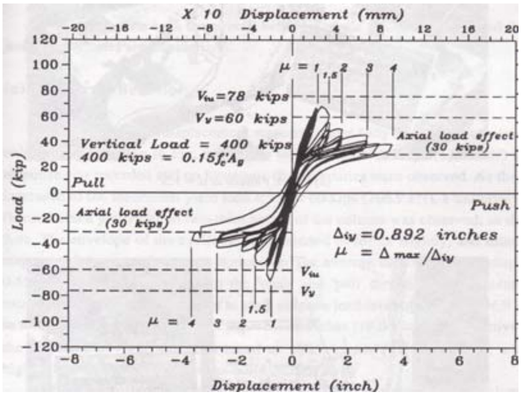
Level III



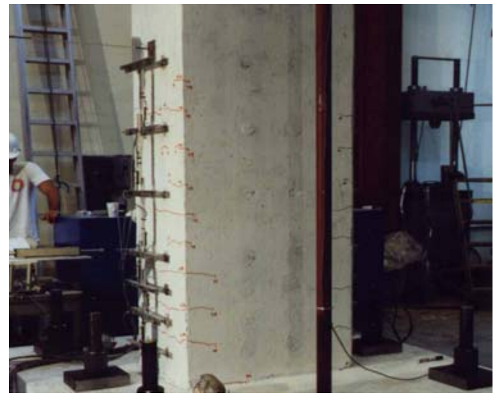
Level IV

Level V

F18 – Flexural – Brittle



F-d Graph

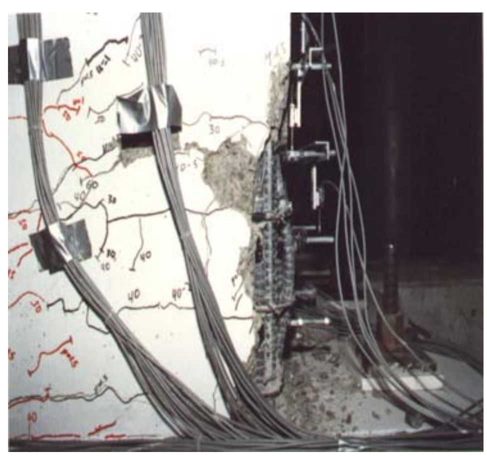


Level I

Level II

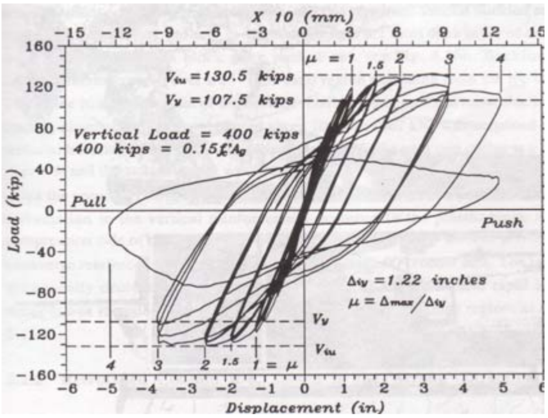
Level III

Level IV

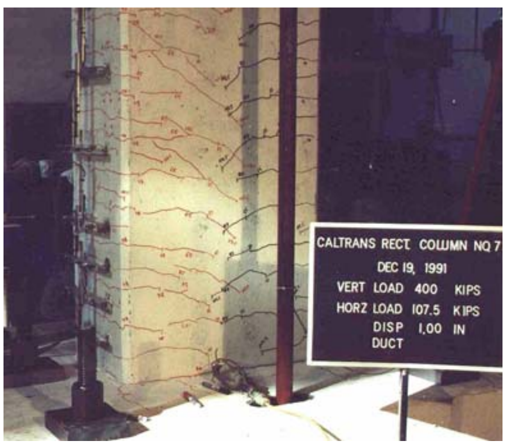


Level V - (buckling of long. bars)

F19 – Flexural – Ductile



Level I



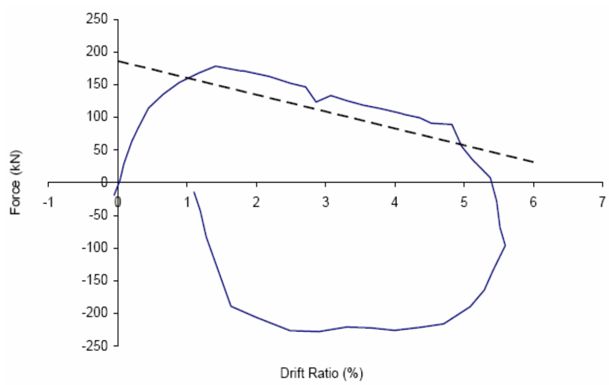
Level II

Level III

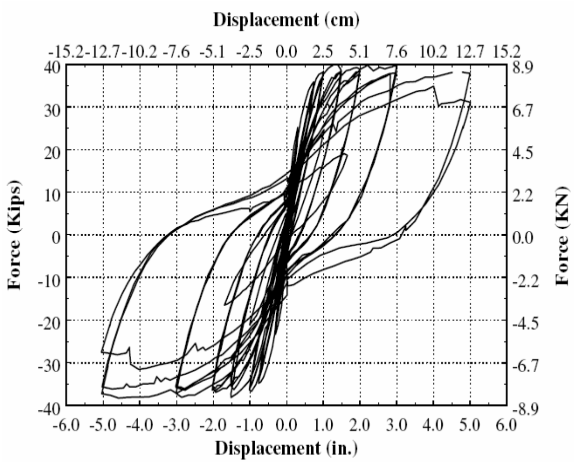
Level IV

Level V - (buckling of long. bars)

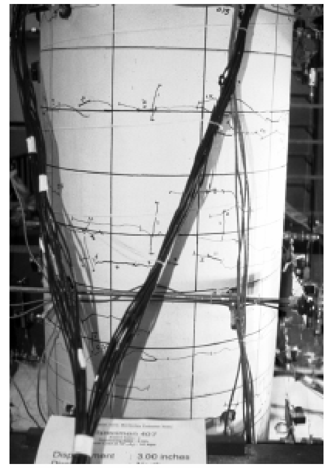
F20 – Flexural – Strength Degrading

	
F-d Graph	
	
Level III	Level V
	
Level V	Level V fracture stirrup, buckling bars

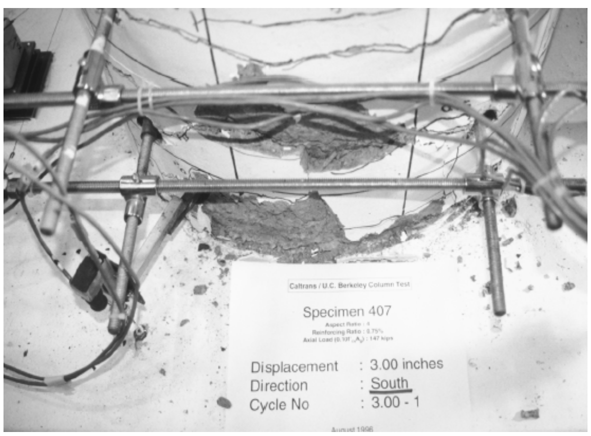
F21 – Flexural – Ductile



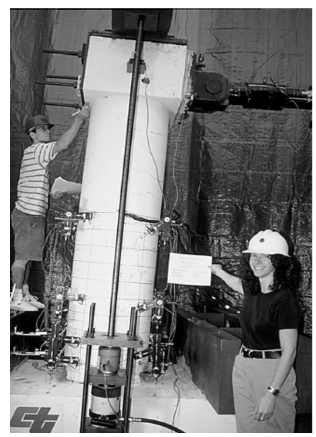
F-d Graph



Level I



Level III



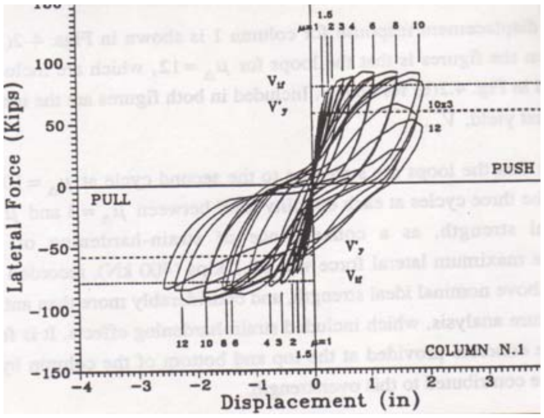
Level V (permanent deformation)

Level V cycle 1 (buckling of bars)

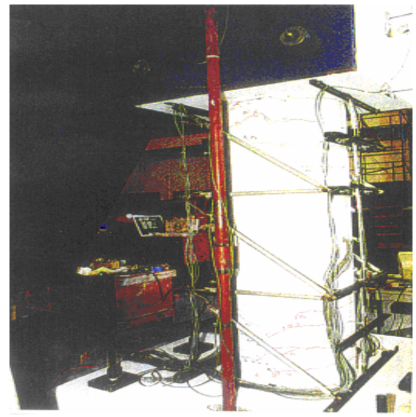
Level V cycle 2 (fracture of bars)

Shear

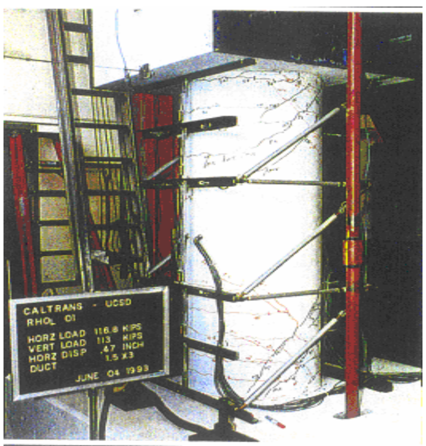
S1 – Shear – Ductile



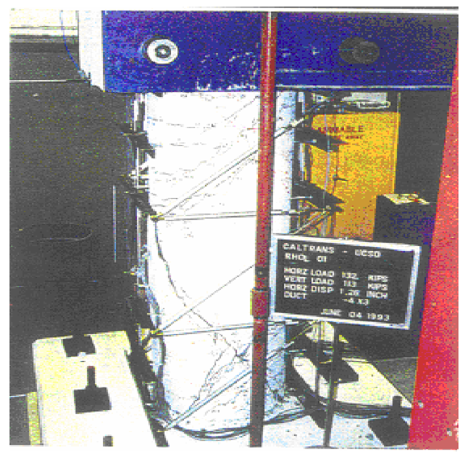
F-d Graph



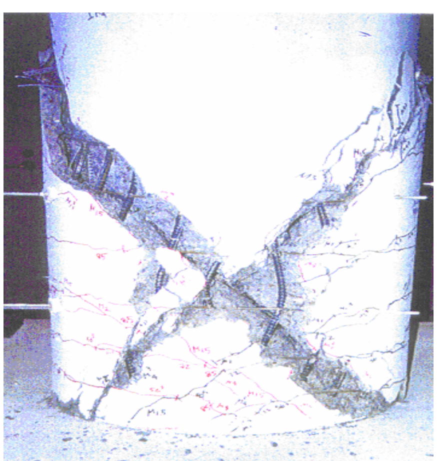
Level II



Level III

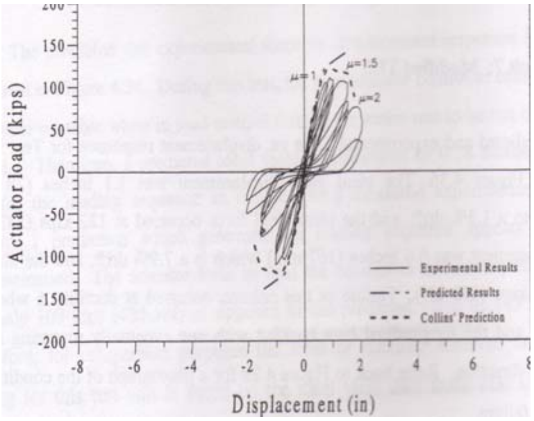
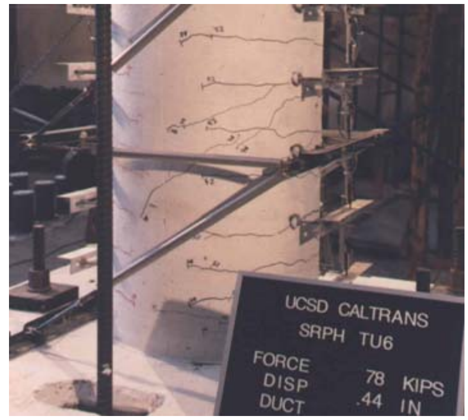
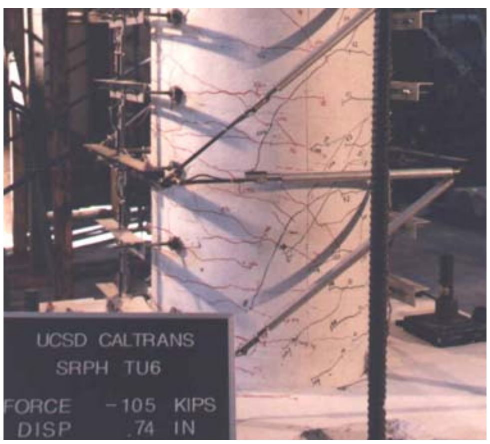
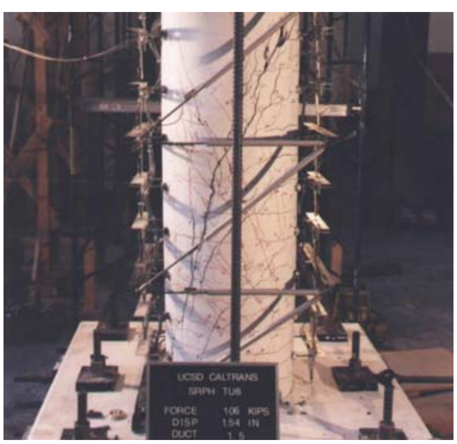


Level IV

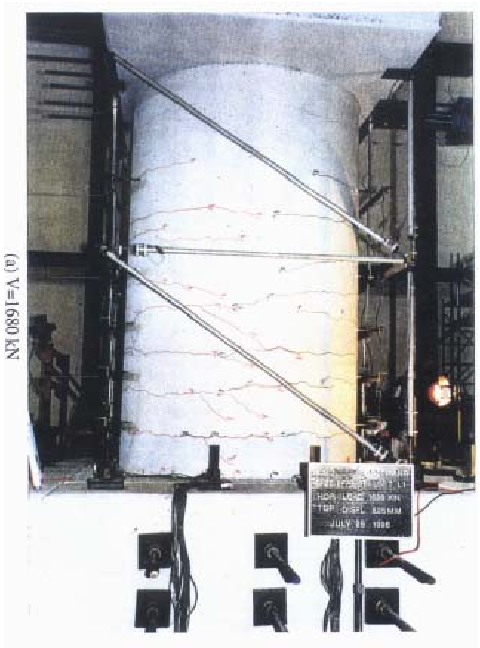
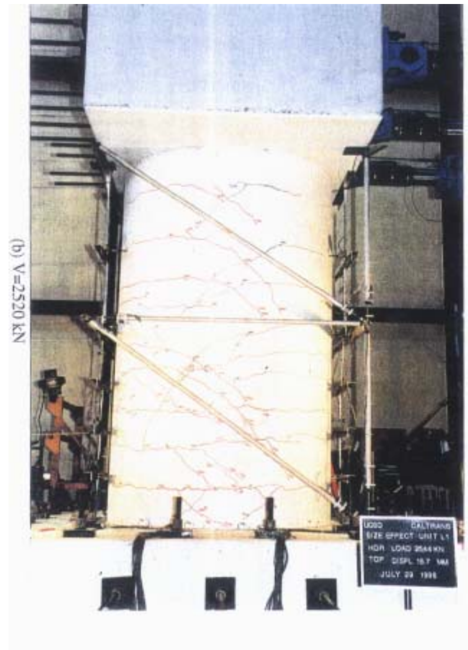
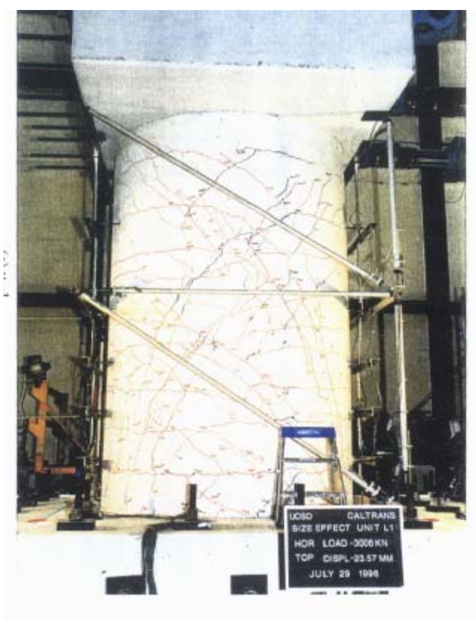
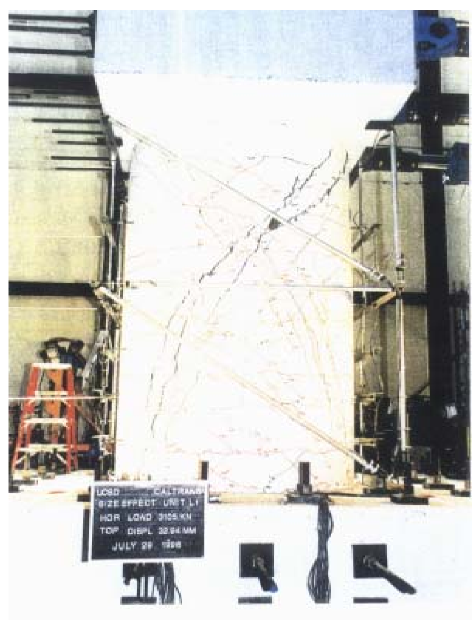


Level V

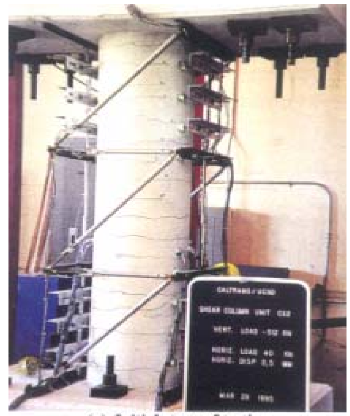
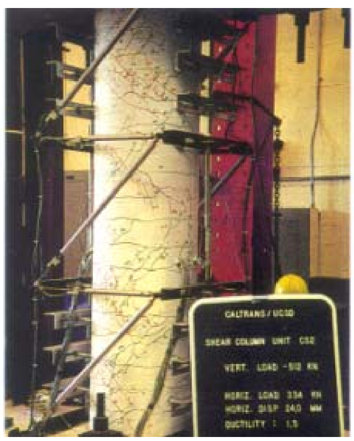
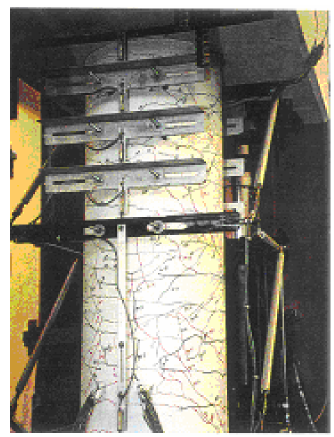
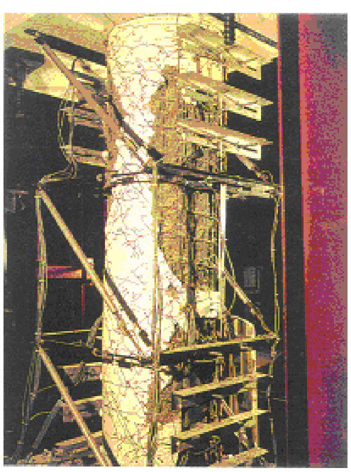
S2 – Shear – Brittle

	
F-d Graph	Level I
	
Level II	Level III
	
Level IV	Level V

S3 – Shear – Brittle

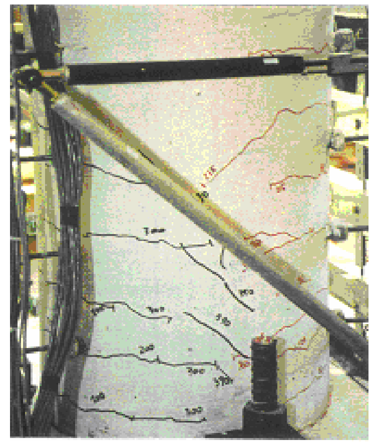
	
Level II	Level III
	
Level IV	Level V

S4 – Shear – Brittle

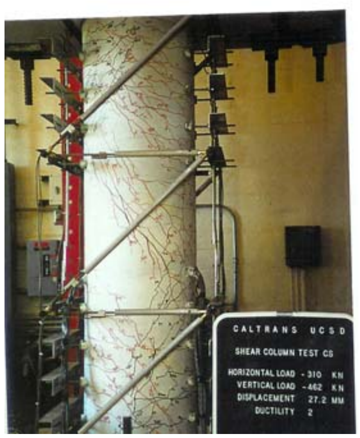
	 (a) Initial stage of testing
F-d response	Level II
	
Level III	Level IV
	
Level V	Level V

S5 – Shear – Brittle

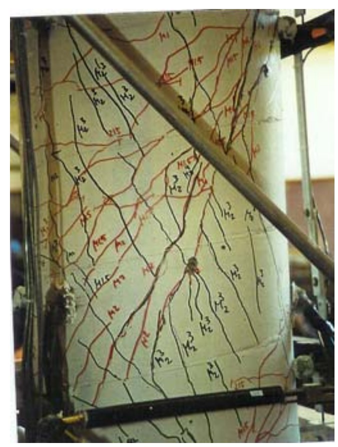
F-d Graph



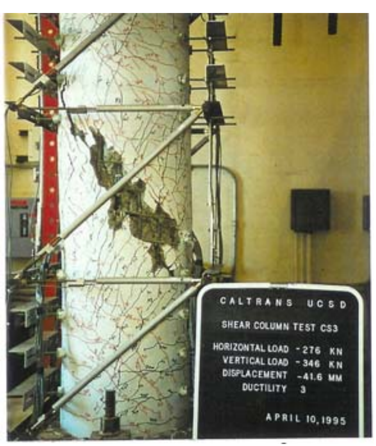
Level II



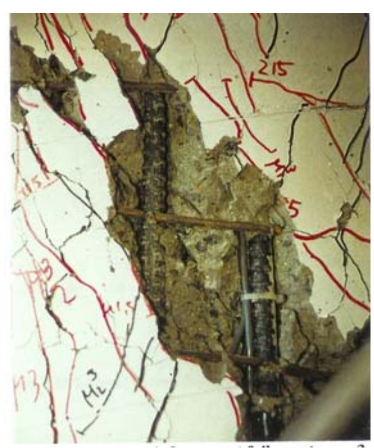
Level III



Level IV

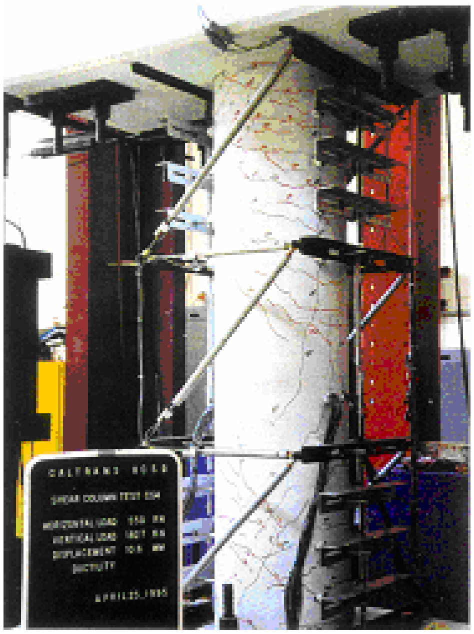


Level V



Level V

S6 – Shear – Brittle



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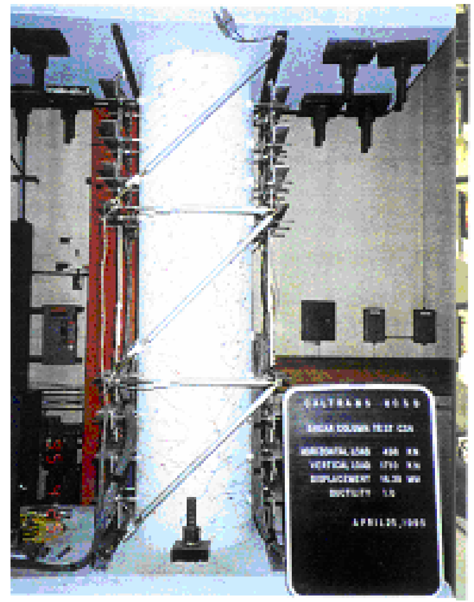
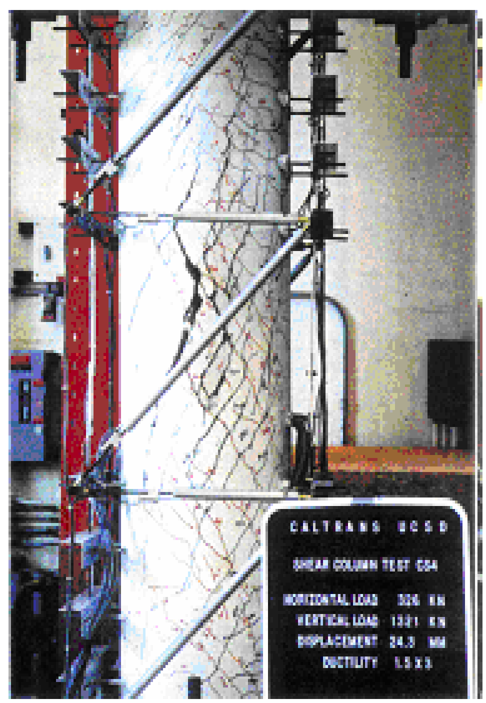


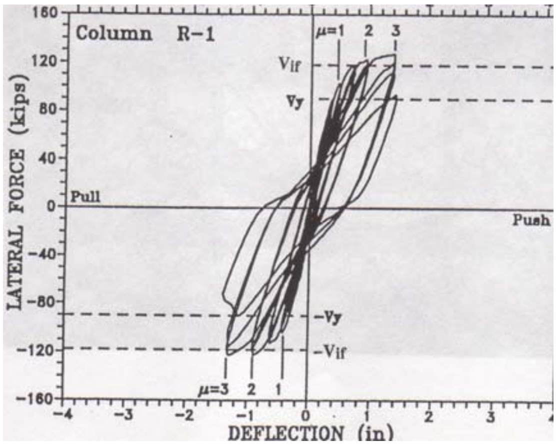
Level IV

Level V



Level V

S7 – Shear – Brittle



F-d graph

Level II

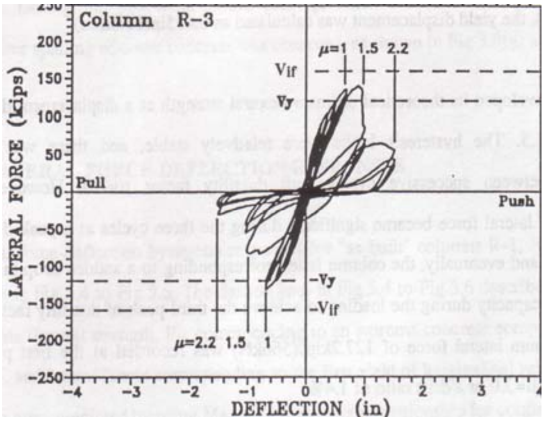
Level III

Level IV

Level V

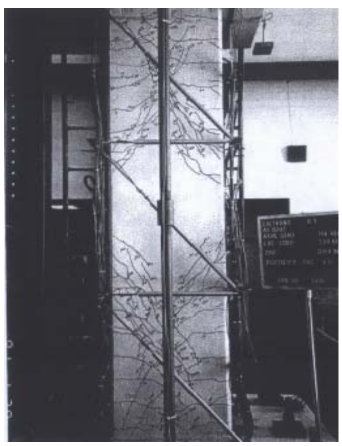
Level V

S8 – Shear – Brittle



F-d graph

Level II



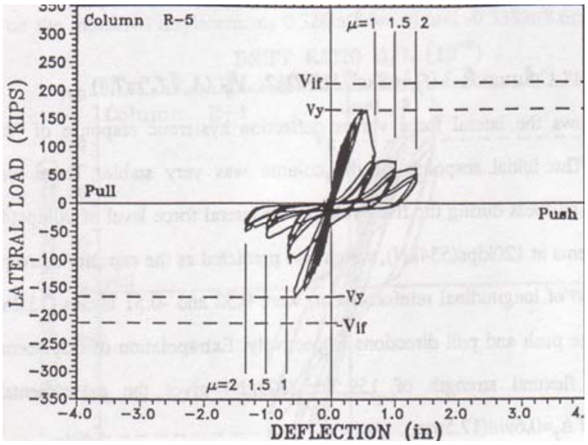
Level III

Level IV

Level V

Level V

S9 – Shear – Brittle



F-d graph

Level II

Level III

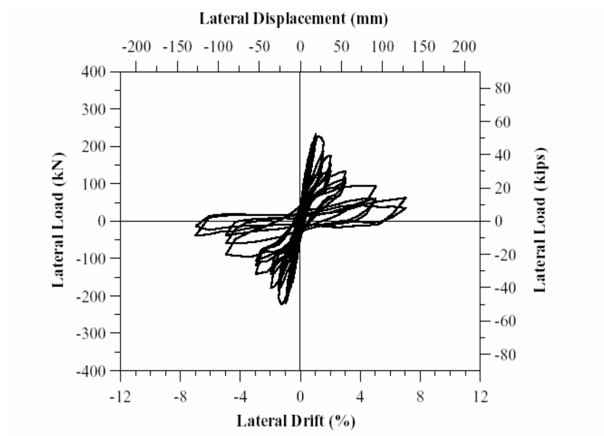
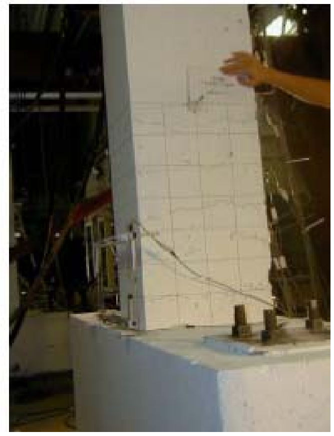
Level IV

Level V

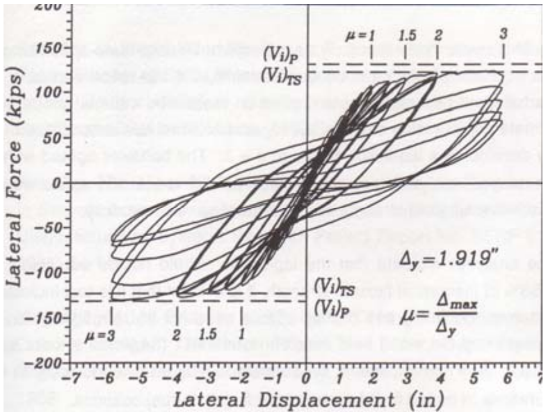
Level V

Lap Splice

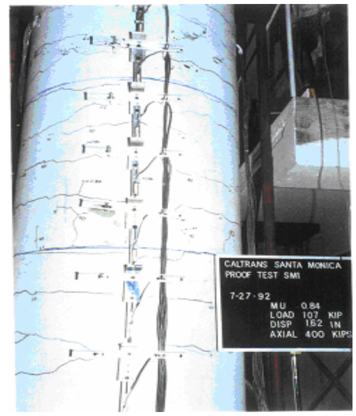
LS1 – Lap Splice – Brittle

	
F-d Graph	Level II
	
Level III	Level IV
	
Level V	Level V

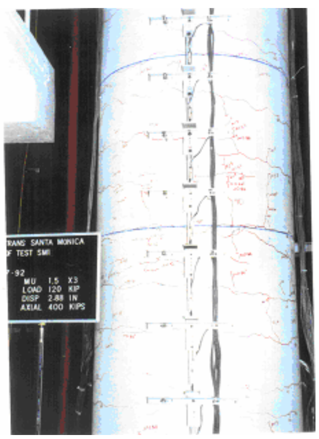
LS2 – Lap Splice - Ductile



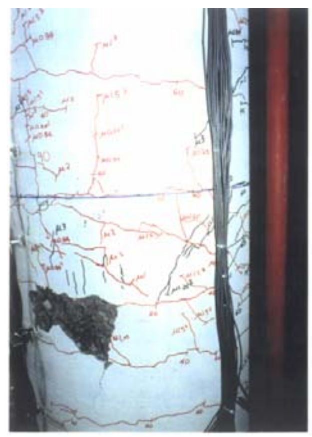
F-d Graph



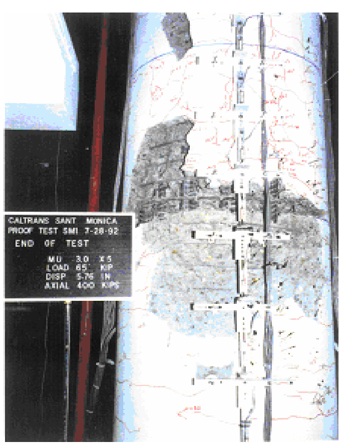
Level II



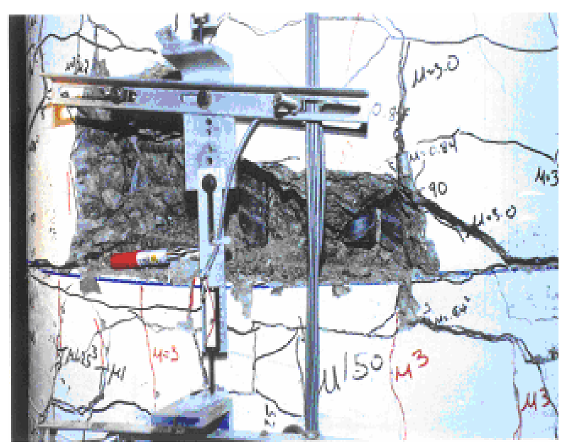
Level III



Level IV (inclination of cracks at splice)



Level V –well confined region below lap splice

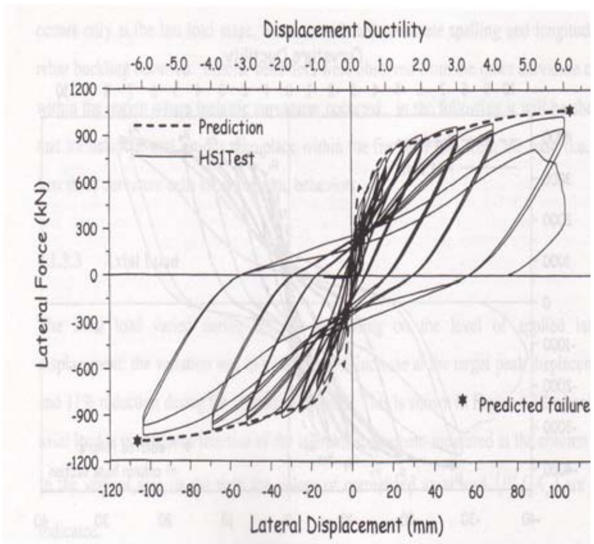


Level V - bond slip – space of bars

Special Sections

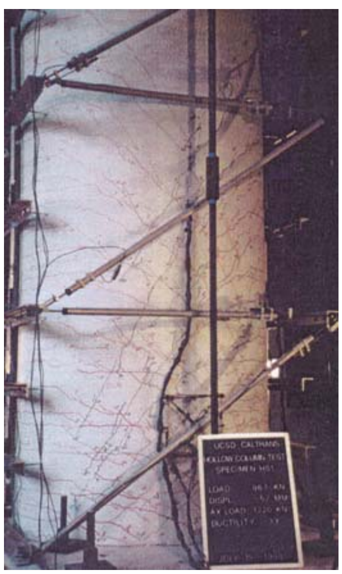
Hollow

SS1 – Flexural – Ductile



F-d Graph

Level II

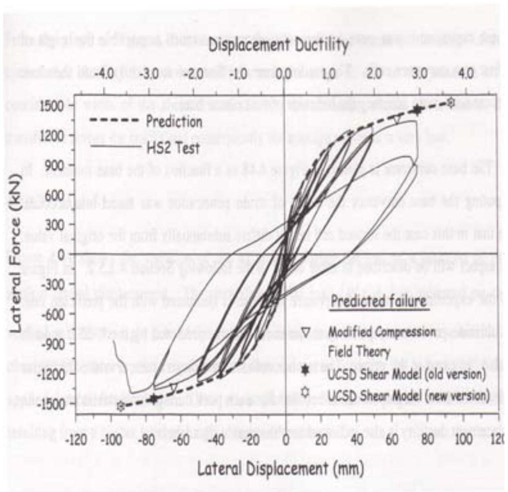


Level III

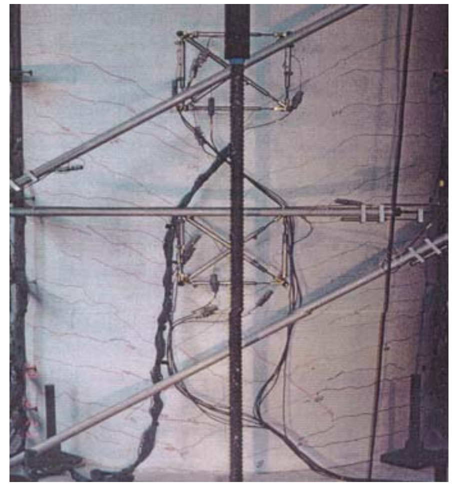
Level V

Ref: SSRP 2001/01, HS-1

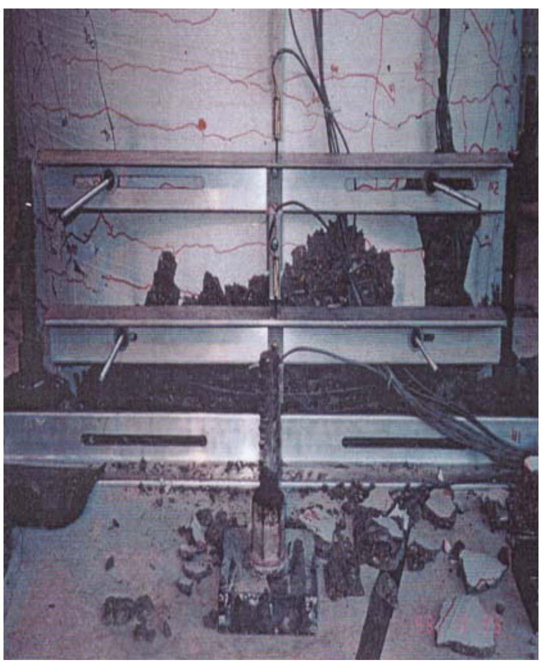
SS2 – Flexural – Ductile



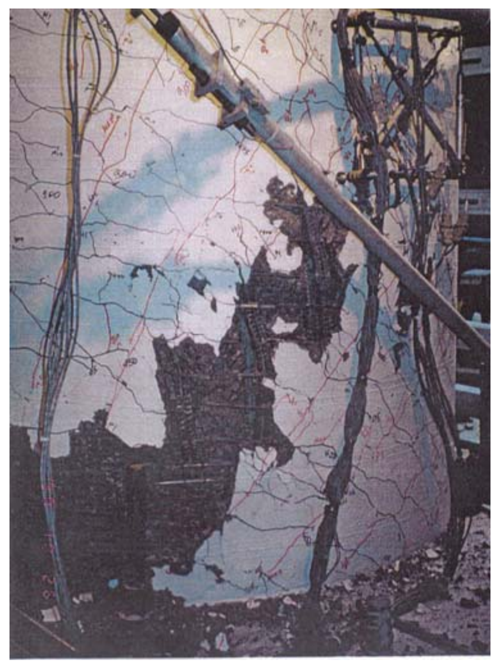
F-d Graph



Level III

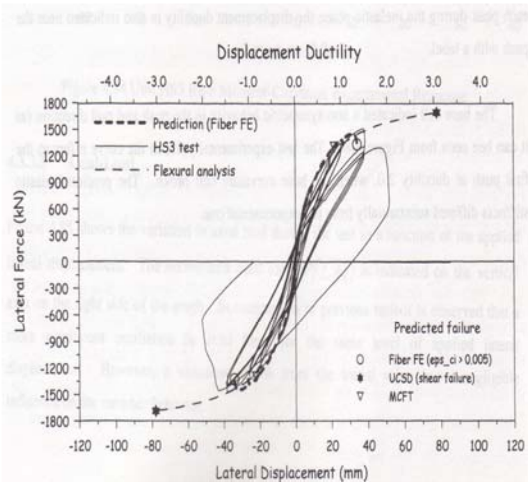
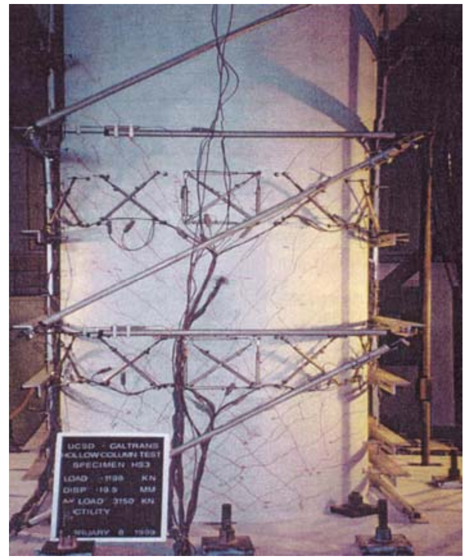


Level IV



Level V

SS3 – Shear – Brittle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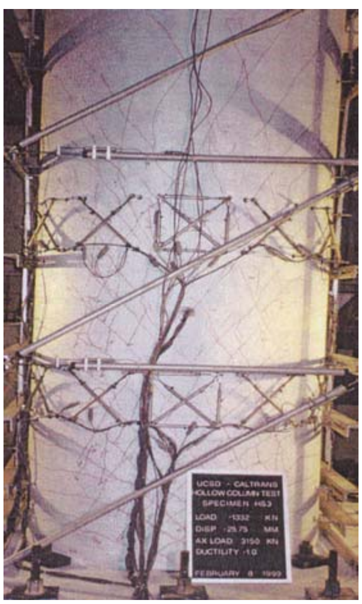
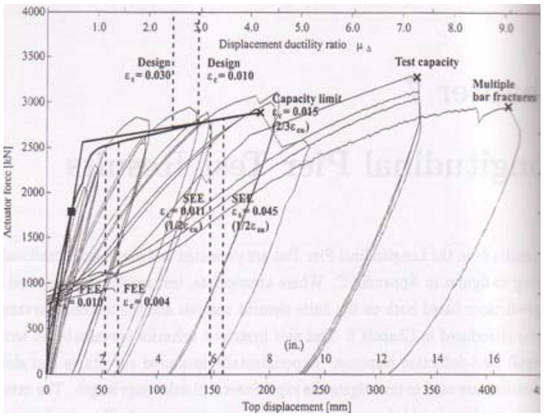
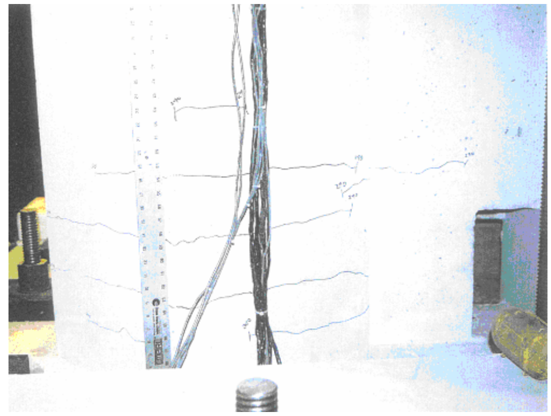
	
Level IV	Level V

Columns with Boundary Elements

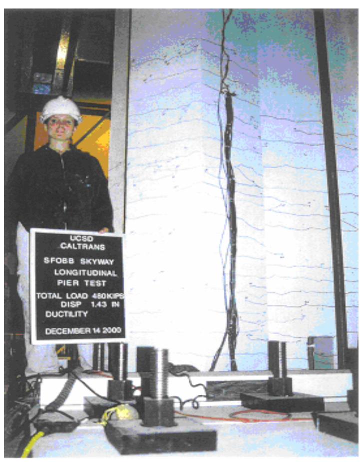
SS4 – Flexural – Ductile



F-d Graph



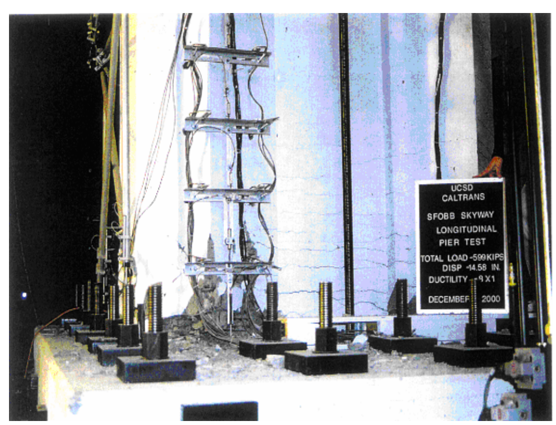
Level II



Level III

Level IV

Level III



Level V

SS5 – Flexural – Ductile

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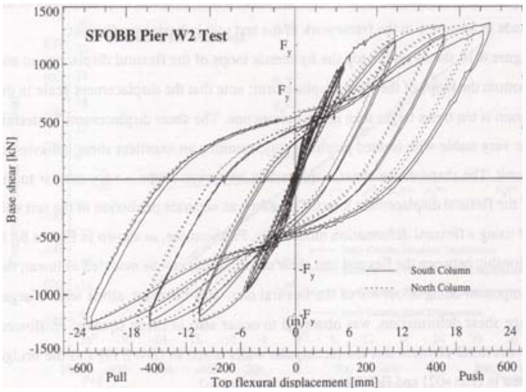
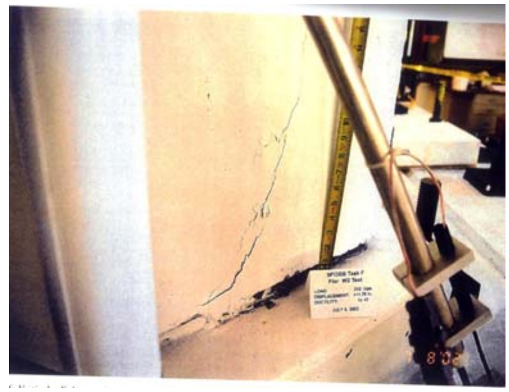
<tr><td>
</td><td></td></tr>
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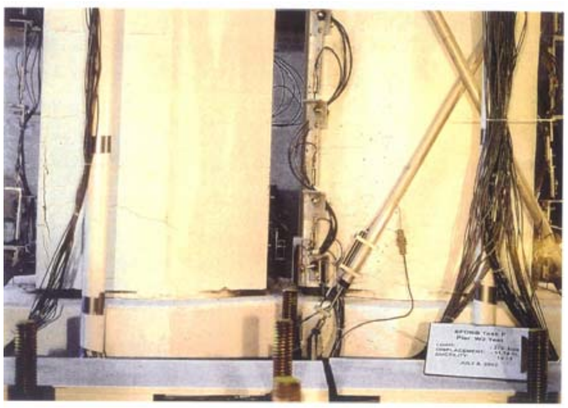
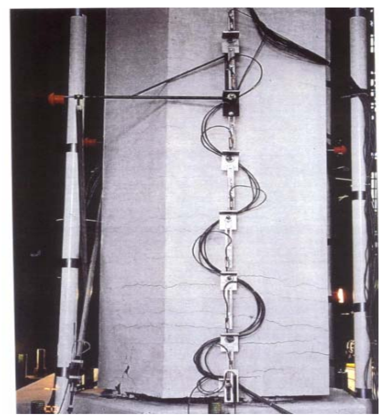
<tr><td></td><td></td></tr>
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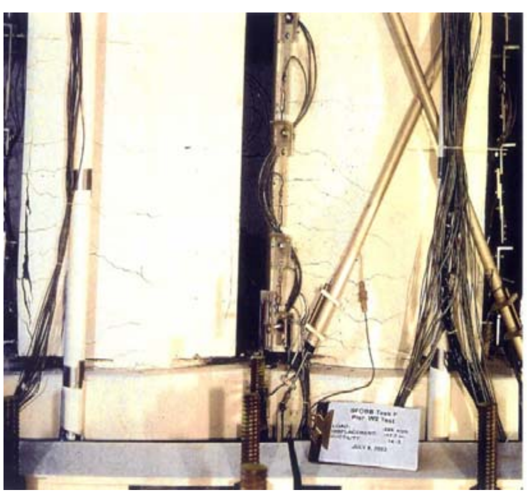
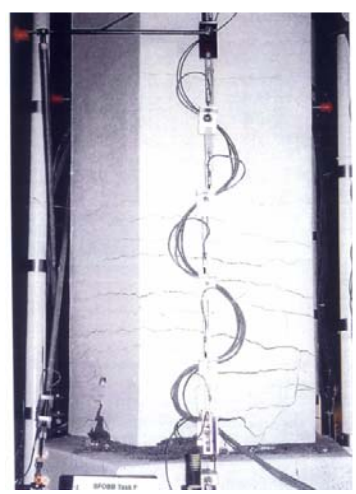
<tr><td></td><td></td></tr>
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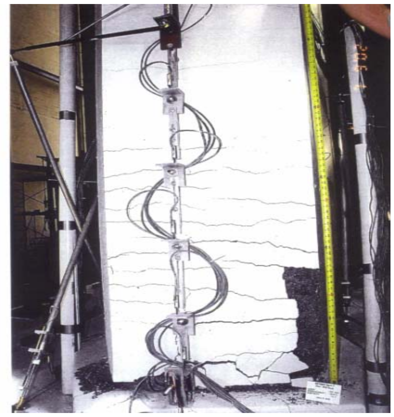
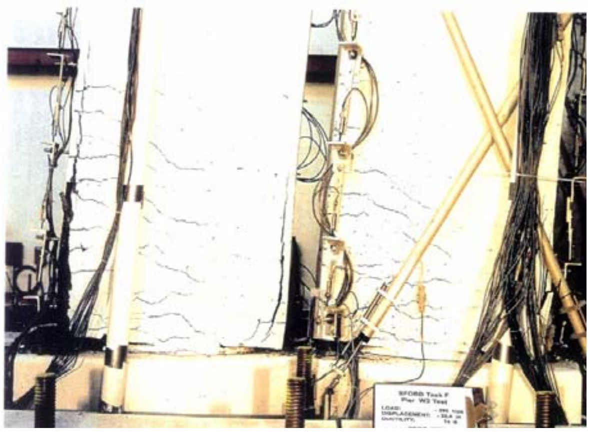
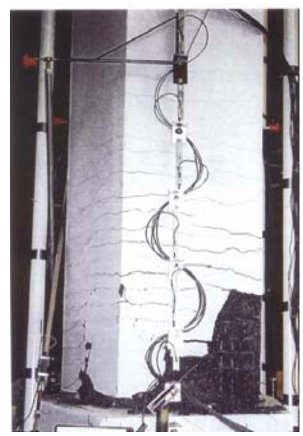
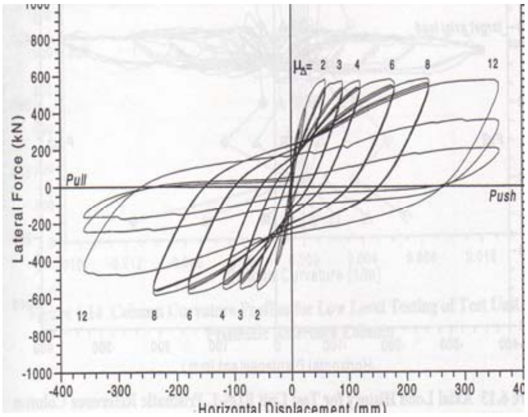
SS5 – Flexural – Ductile

	
Level IV	Level IV Tension side
	
Level V	Level V tension side
	
Level V	

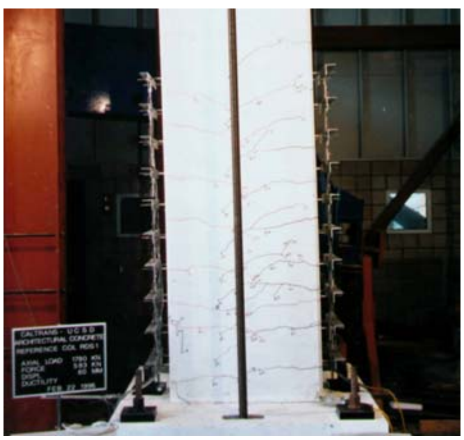
Flared

SS6 – Flexural – Ductile

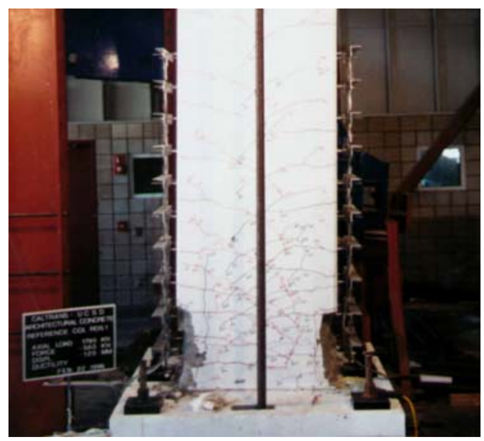


F-d Graph

Level I

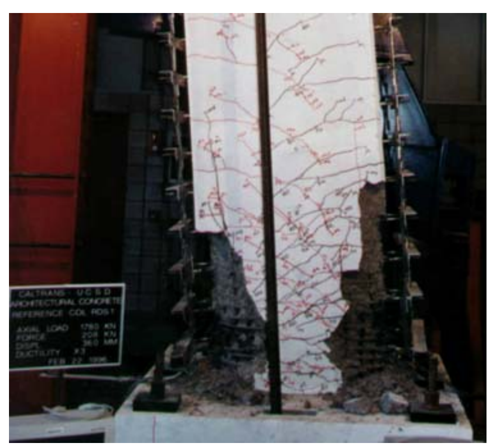


Level II



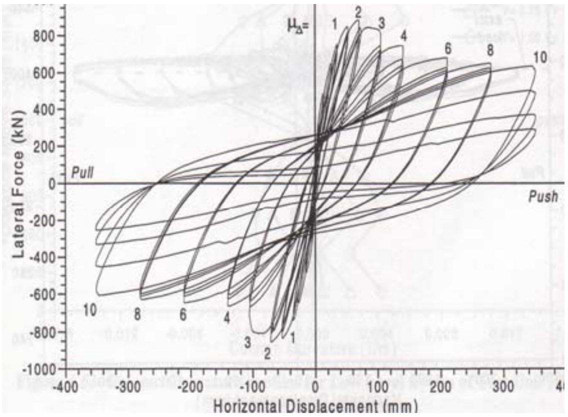
Level III

Level IV

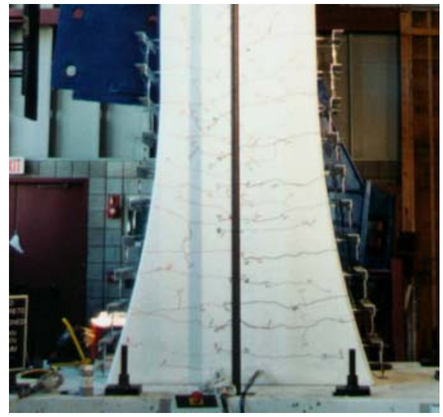


Level V

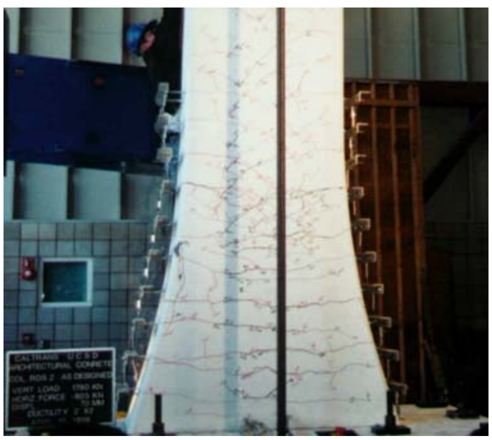
SS7 – Flexural - Ductile



F-d Graph



Level II



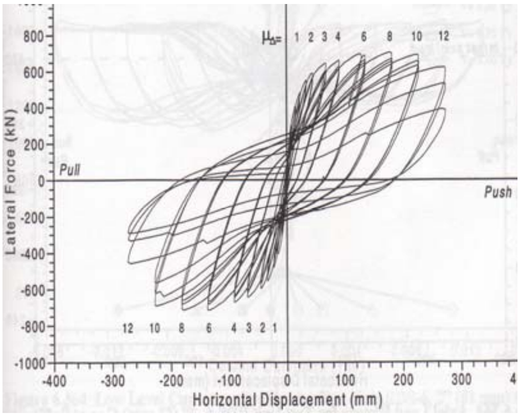
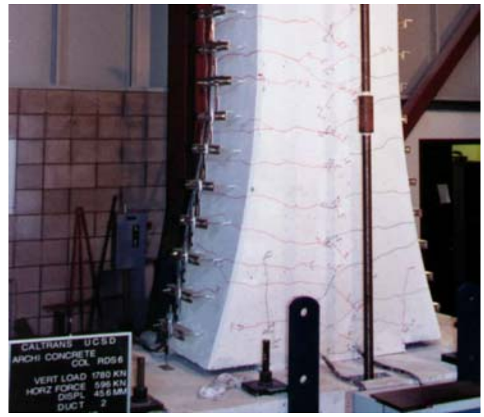
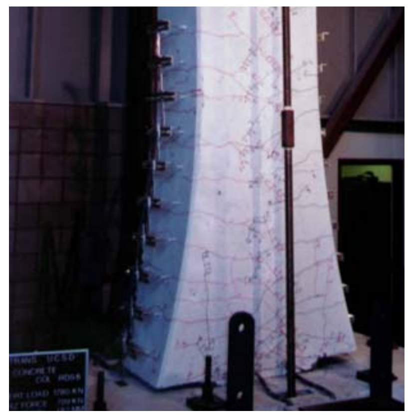
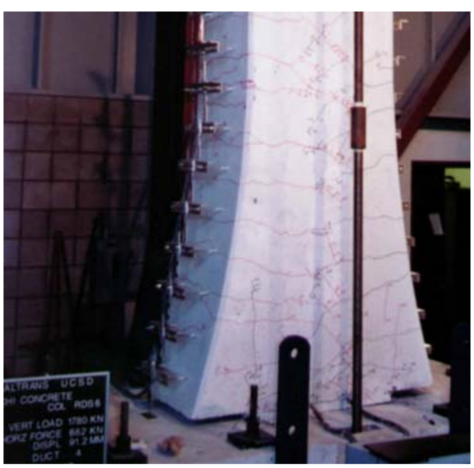
Level III

Level III

Level IV

Level V

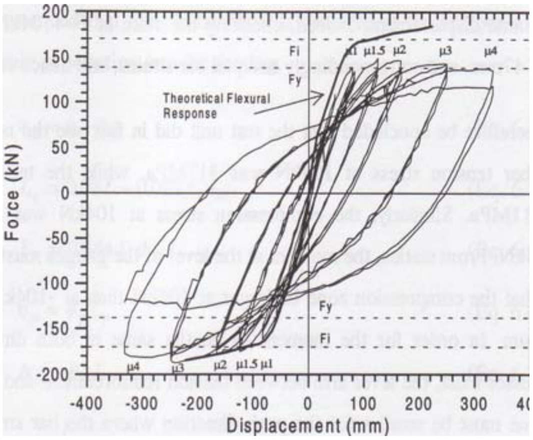
SS8 – Flexural – Ductile

	
F-d response	Level I
	
Level II	Level III
	
Level IV	Level V

Special Material

Lightweight

SM1 – Flexural – Ductile



F-d Graph

Level III

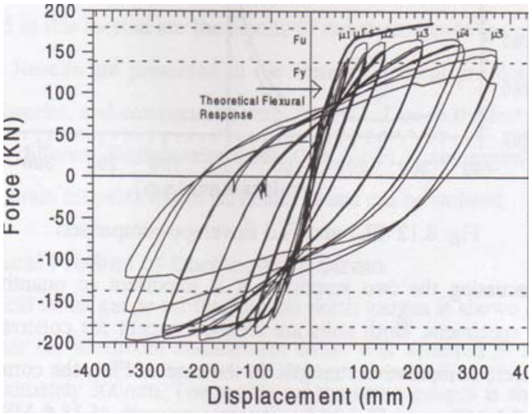
Level IV

Level IV

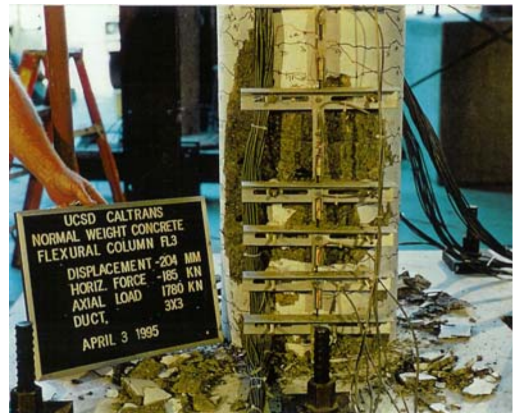
Level V

Level V

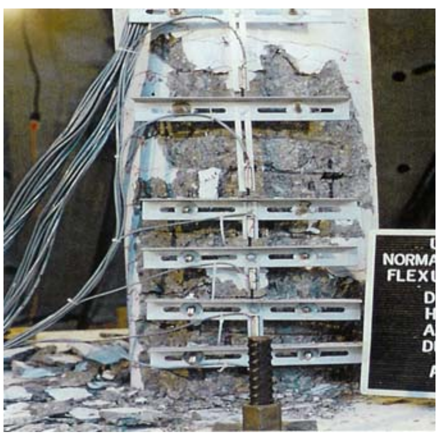
SM2 – Flexural – Ductile



F-d Graph



Level IV



Level IV

Level V – permanent deformation

Level V

SM3 – Shear –

Level III

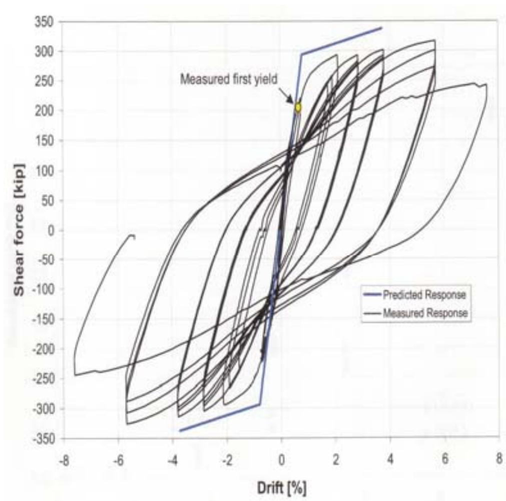
Level III

Level IV

Level V

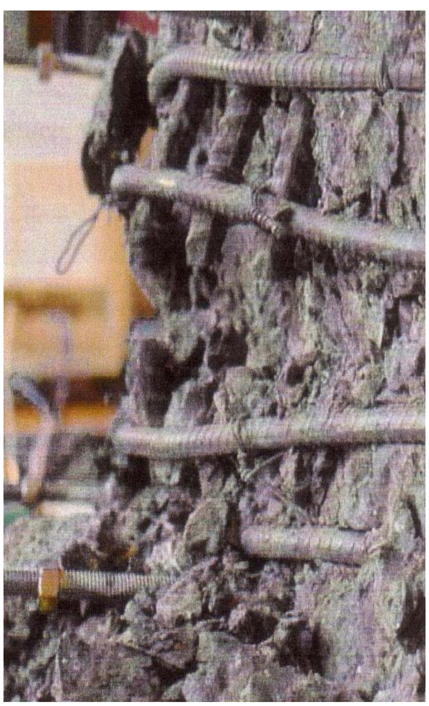
MMX Steel

SM4 – Shear - Brittle

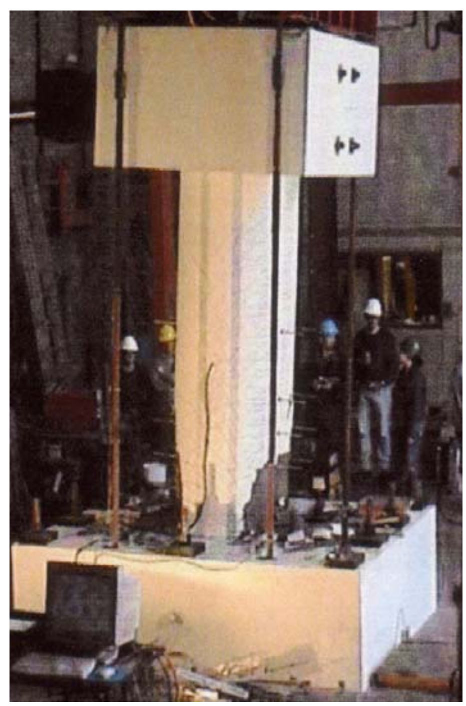


F-d Graph

Level V

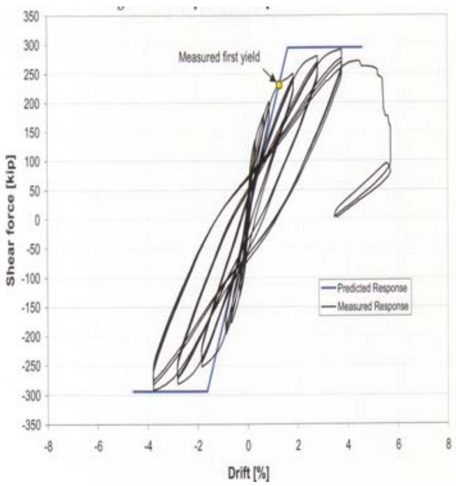


Level V



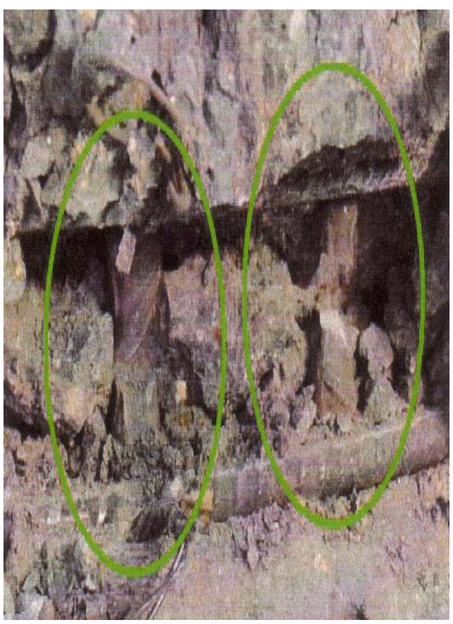
Level V

SM5 – Shear – Brittle

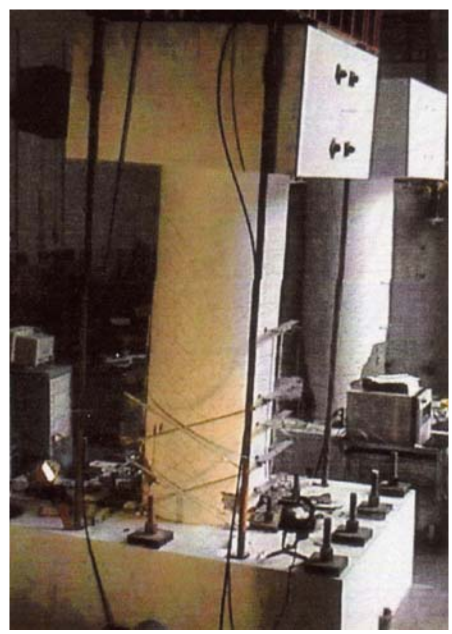


F-d Graph

Level V (Hoop fracture)



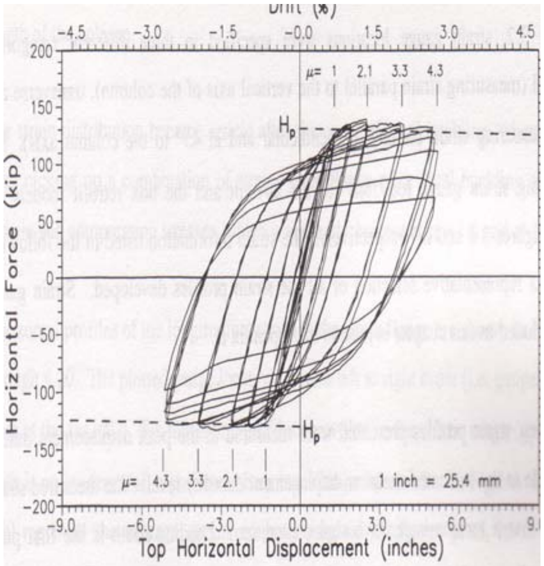
Level V longitudinal bar fracture)



Level V

Steel Columns

SM6 – Shear - Brittle



F-d Graph

Level III

Level IV

Level V

SM7 – Shear – Brittle

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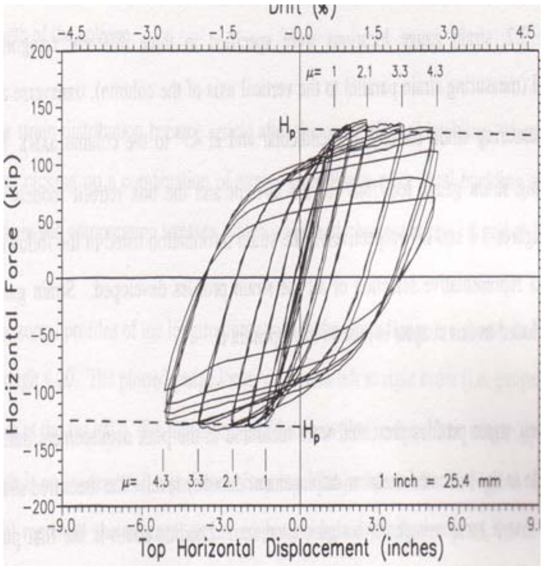
<tr><td>
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<tr><td>F-d Graph</td><td>Level III</td></tr>
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<tr><td>Level IV</td><td>Level V</td></tr>
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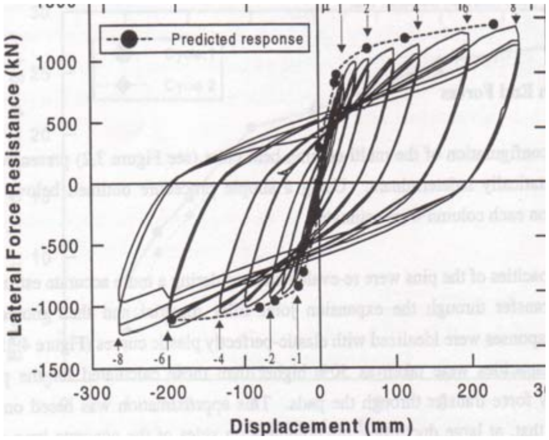
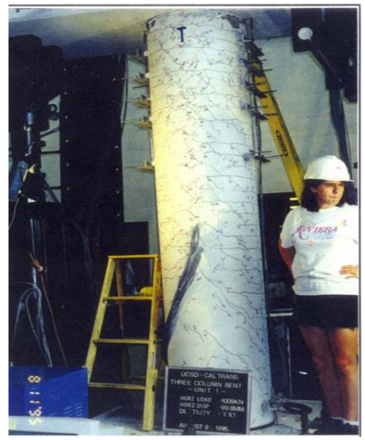
Joints

J1 – Flexural – Ductile

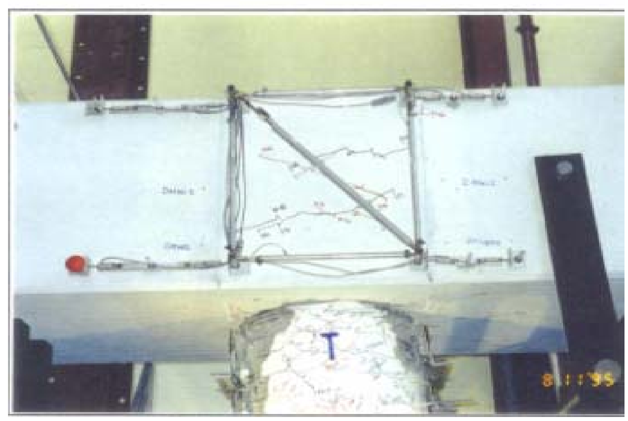


F-d Graph

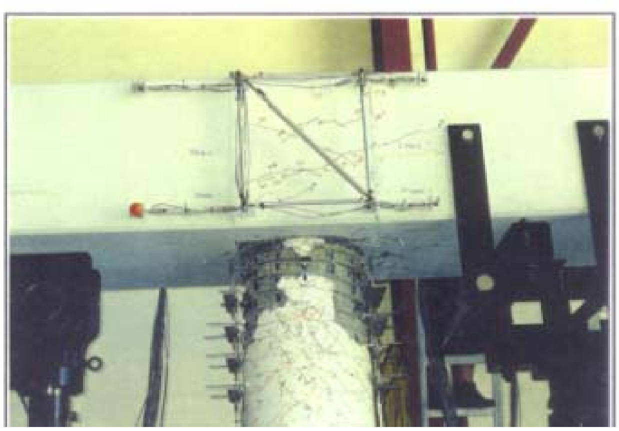


Level II

Level III



Level IV



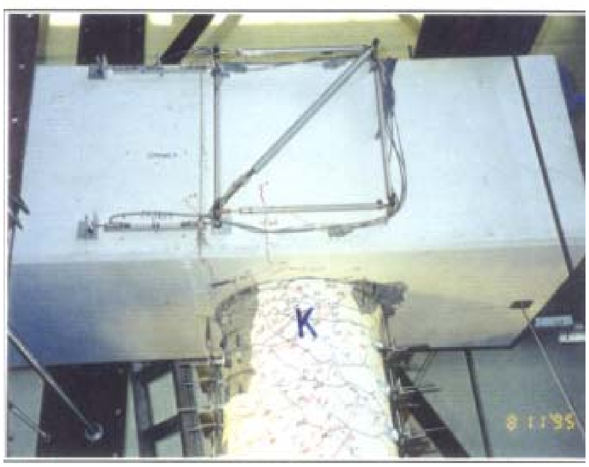
Level V

Level V

J2

Level III

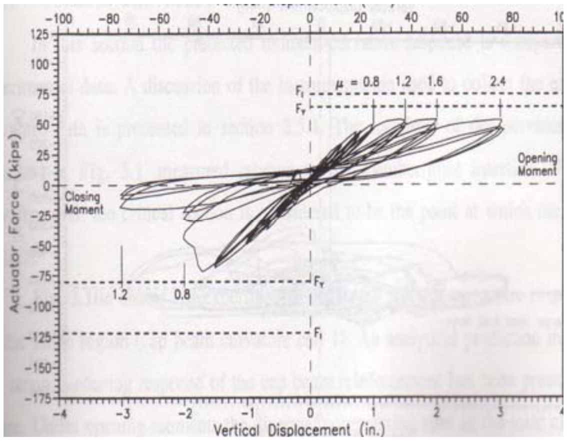
Level IV



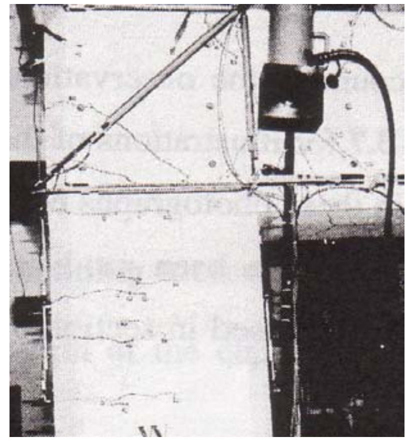
Level IV

Level V

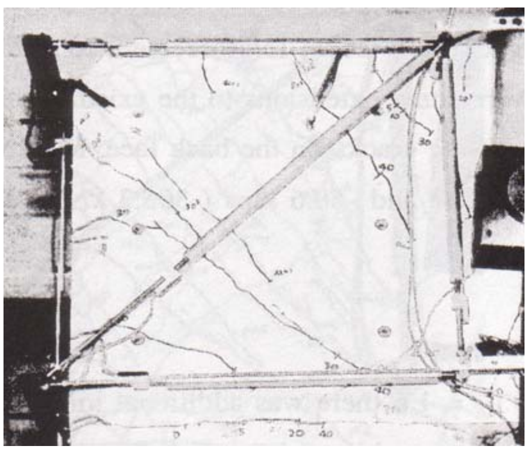
J3 – Shear - Brittle



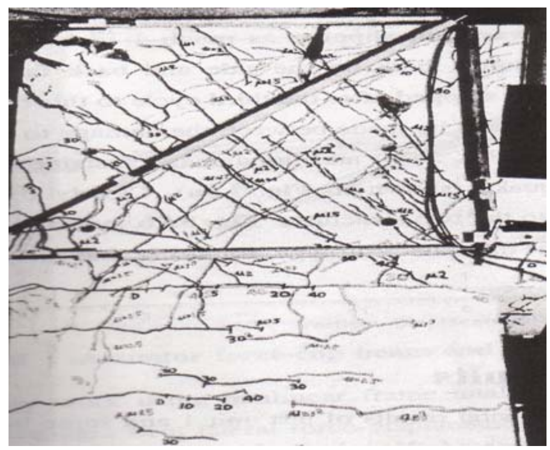
F-d Graph



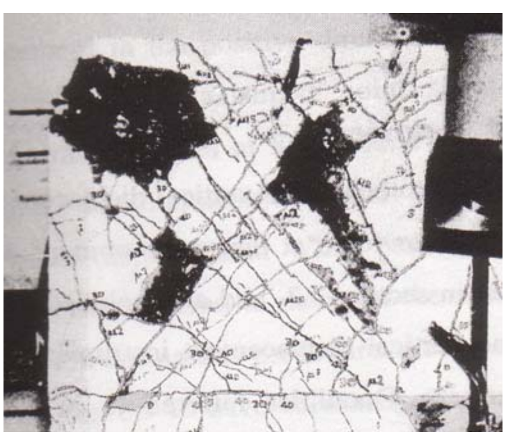
Level II



Level III

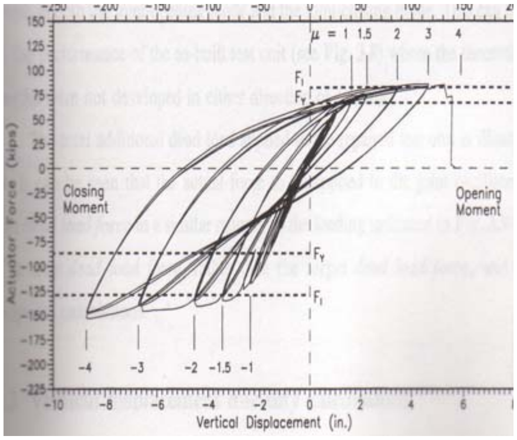


Level IV

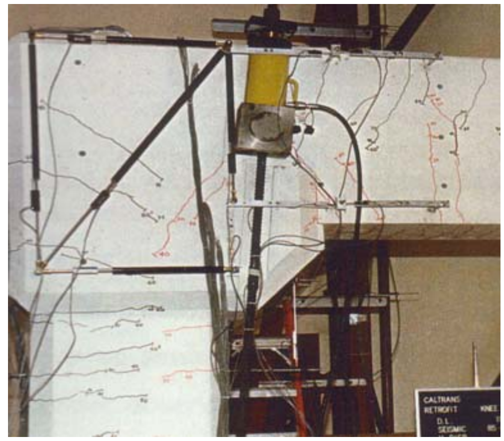


Level V

J4 – Shear - Brittle



F-d Graph



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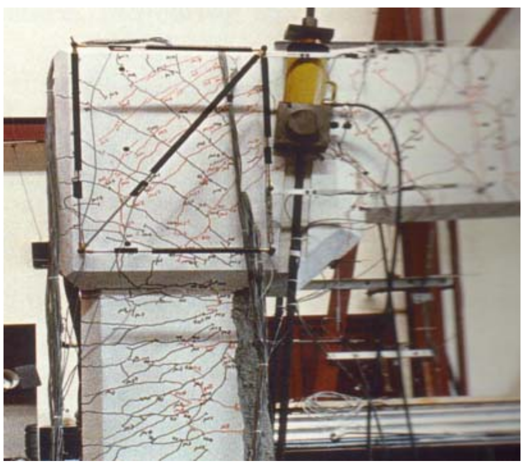
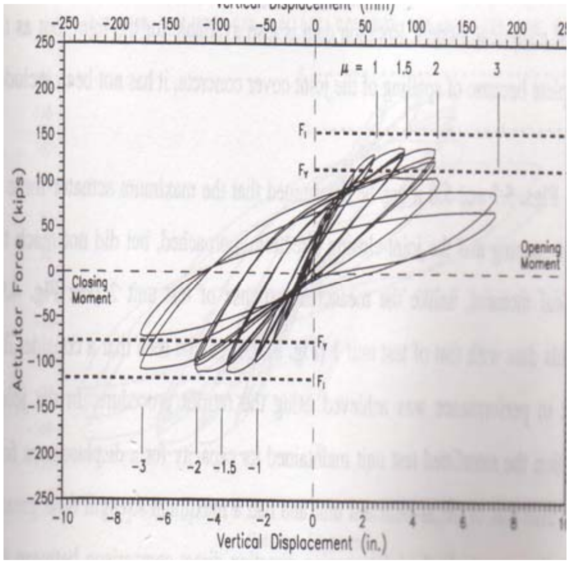


Level IV

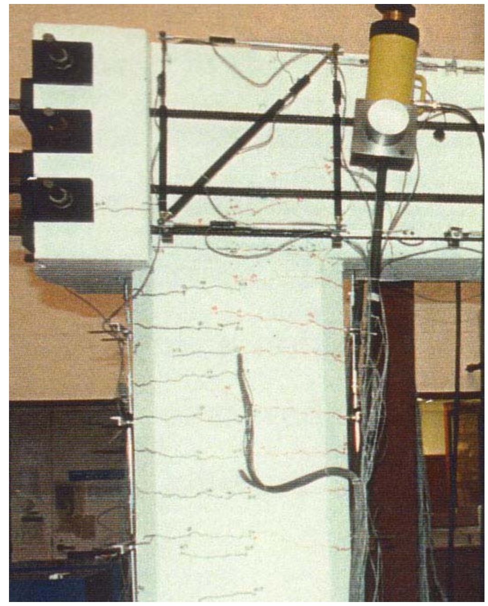
Level V

Level V

J5 – Shear - Brittle



F-d Graph



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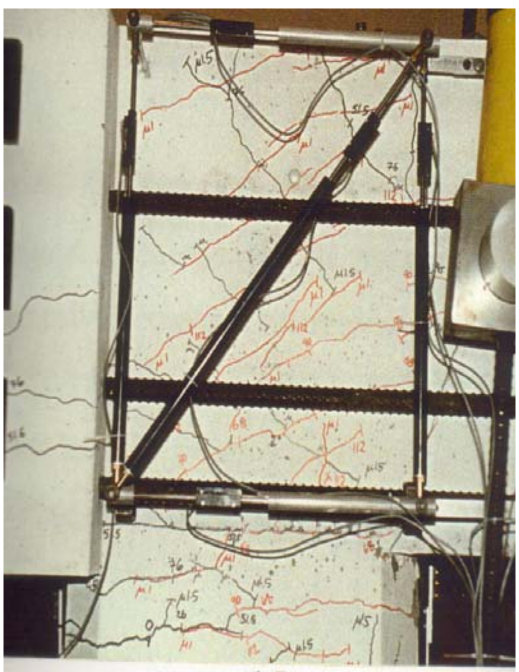

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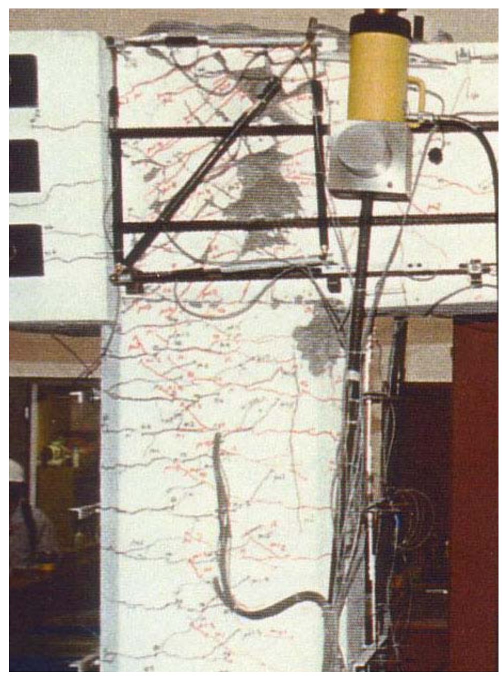
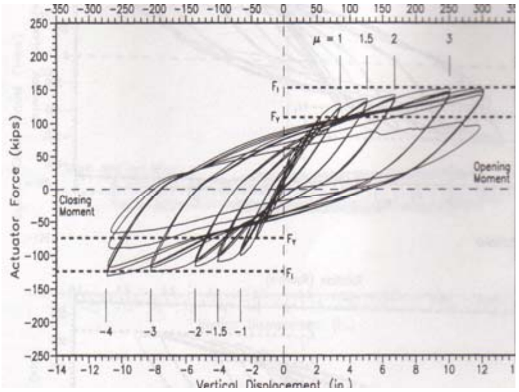
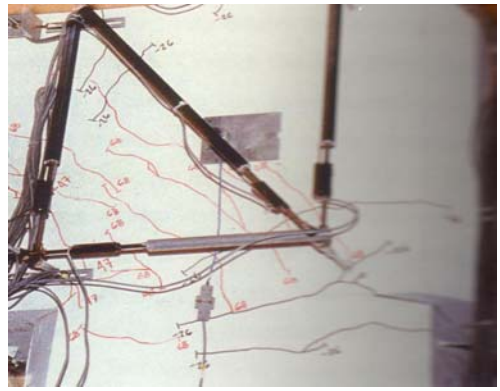


Level IV

J6 – Shear - Brittle



F-d Graph



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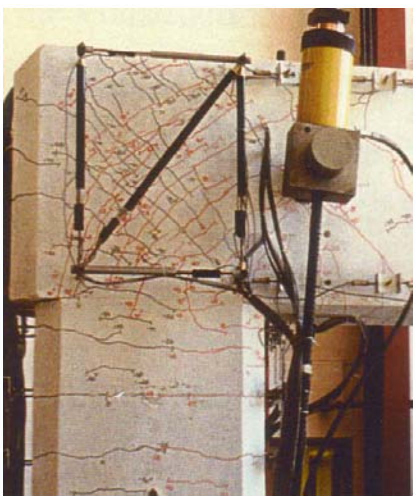

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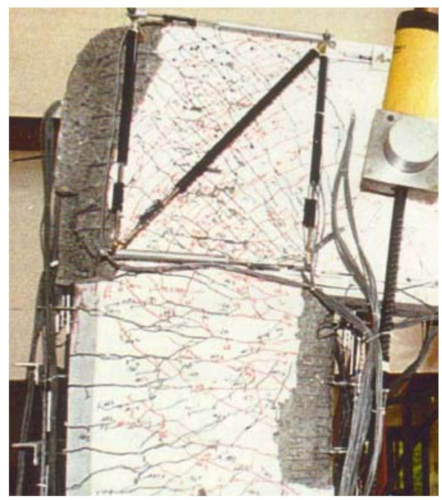

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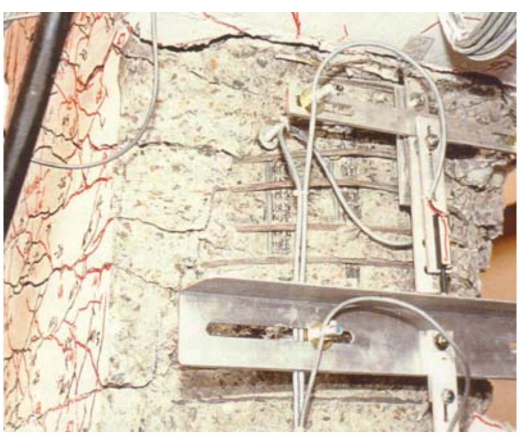
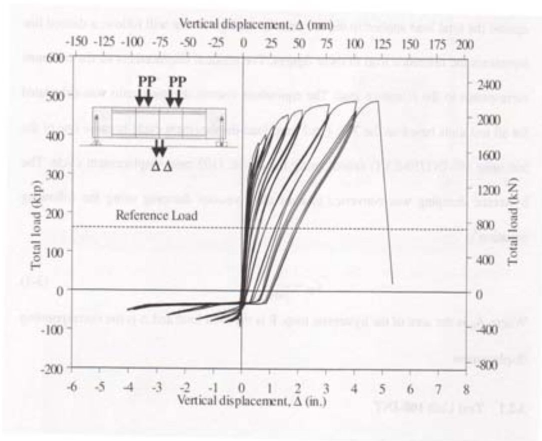


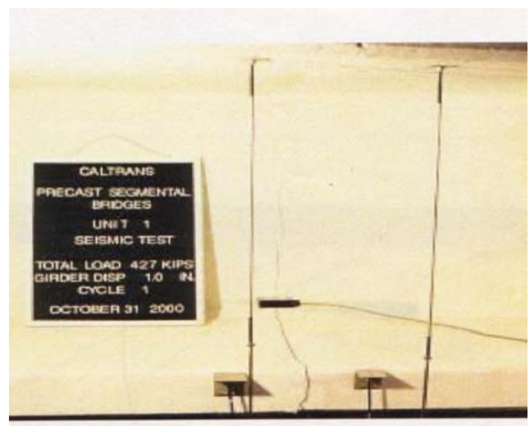
Level V

Superstructure

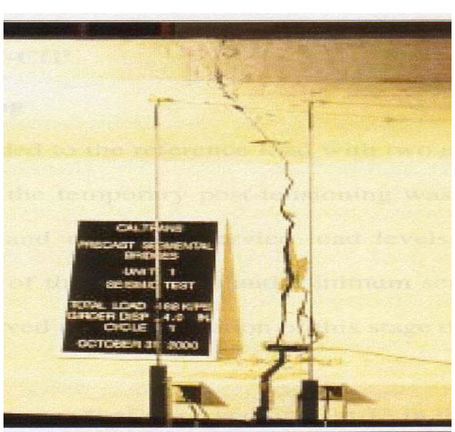
SP1 – Flexural - Brittle



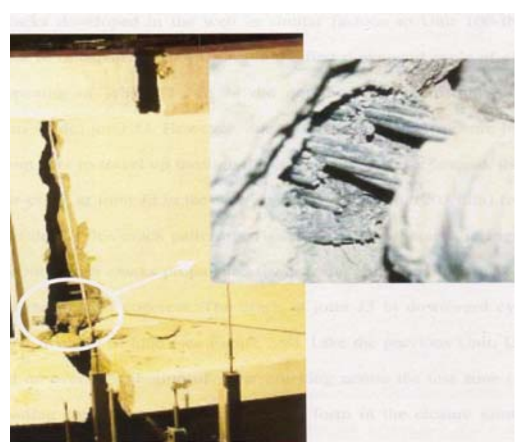
F-d Graph



Level III

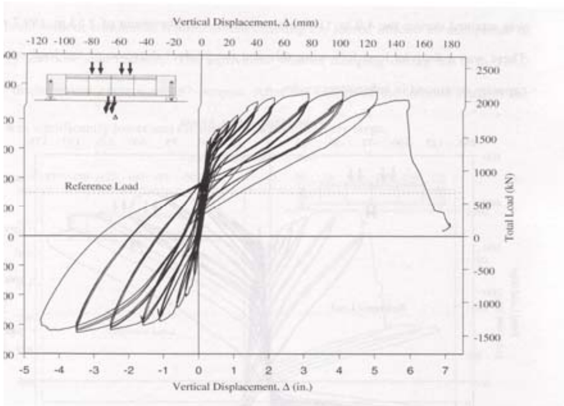


Level IV

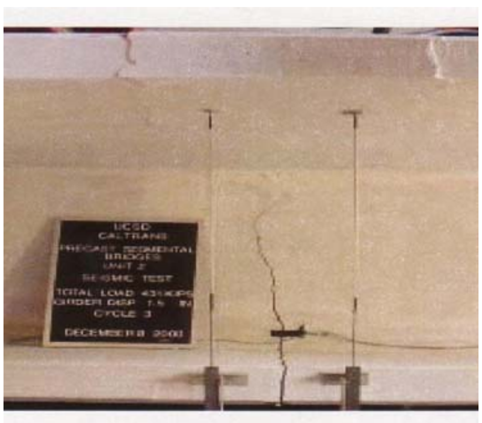


Level V

SP2 – Flexural - Ductile

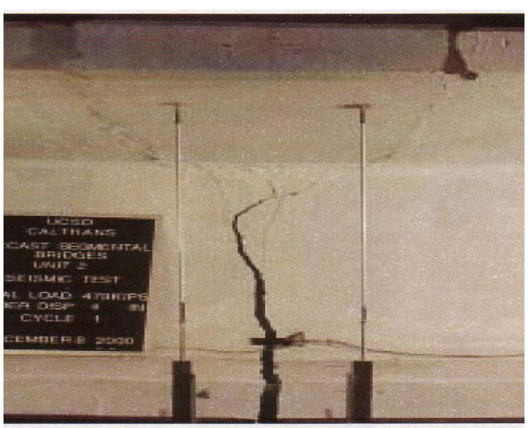


F-d Graph

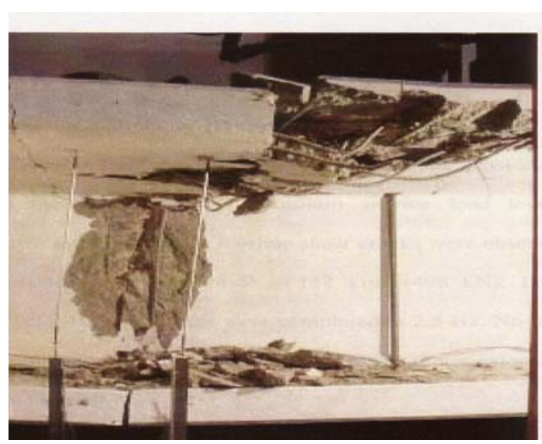


Level III

Level III

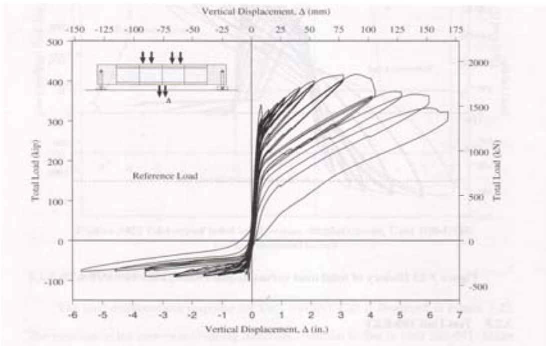
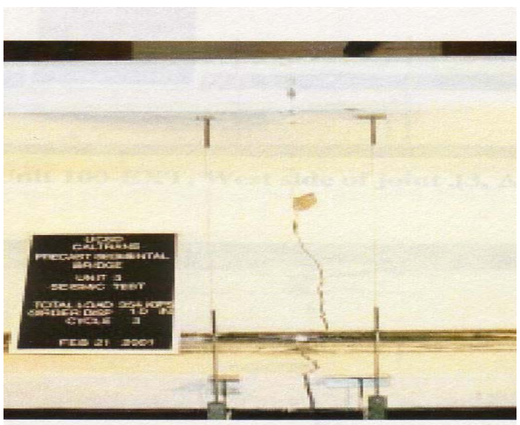
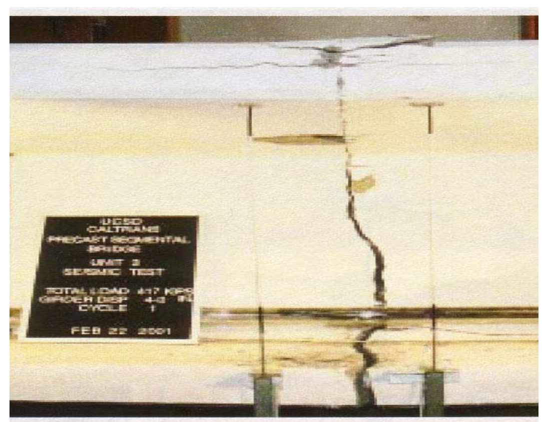
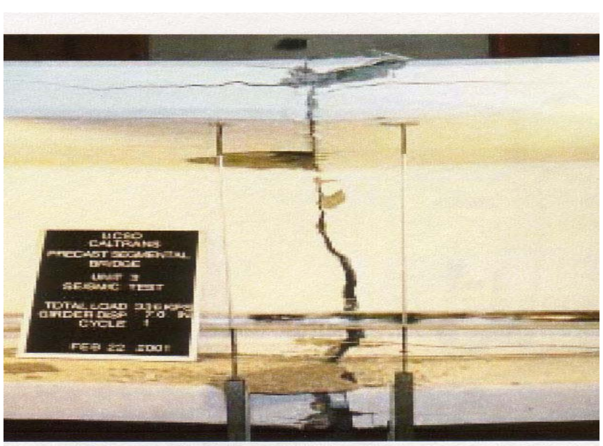
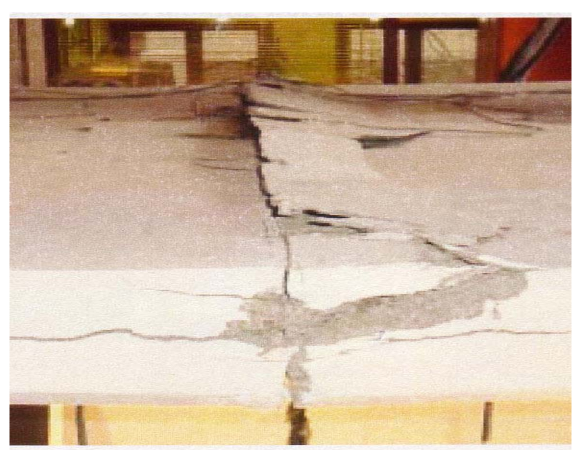


Level IV

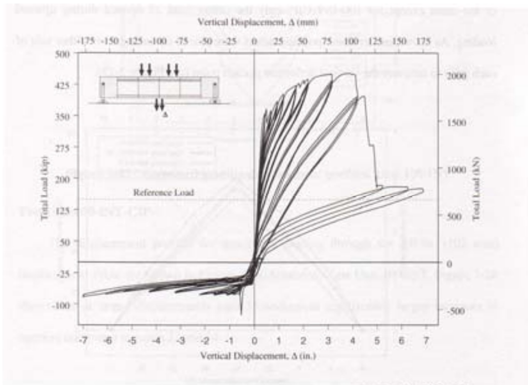


Level V

SP3 – Flexural - Ductile

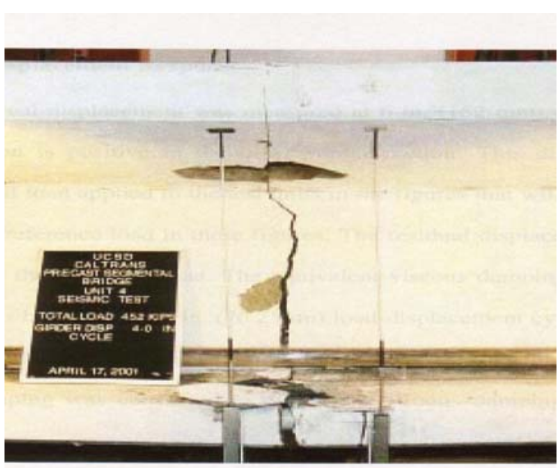
 Figure 3-24 History of total load versus displacement, Unit 100-EXT	
F-d Graph	
	
Level III	Level IV
	
Level V	Level V

SP4 – Flexural – Brittle

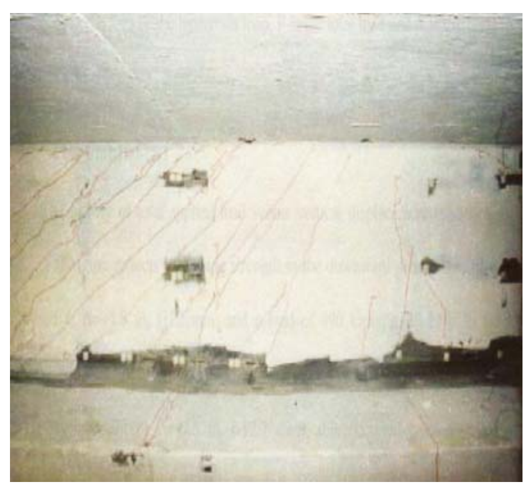


F-d Graph

Level IV

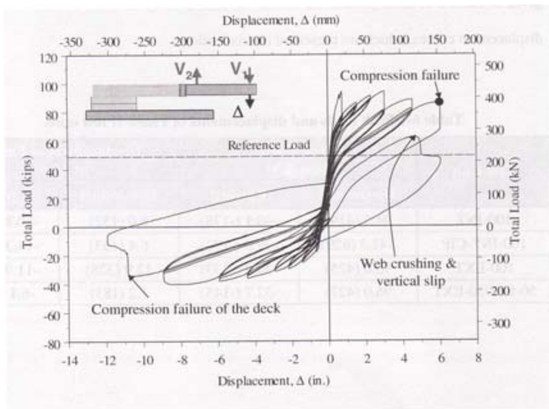
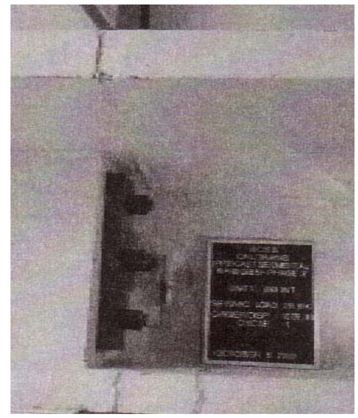
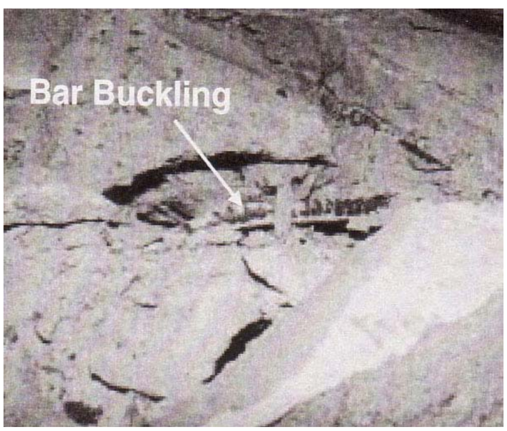
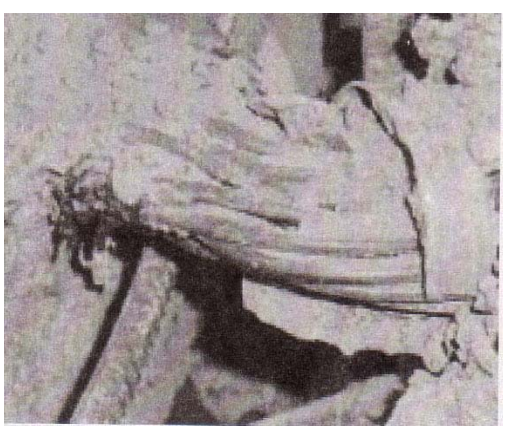
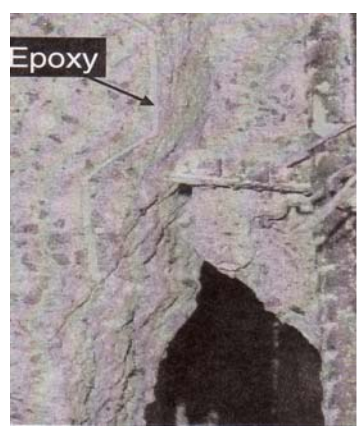


Level V

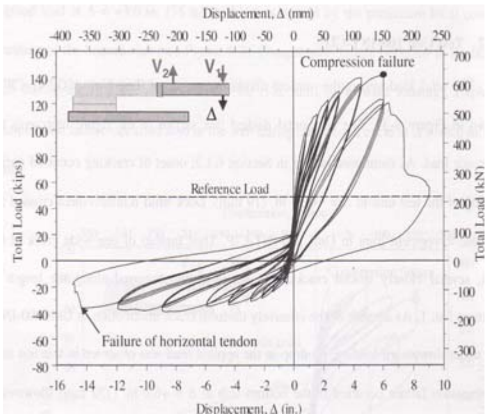


Level V

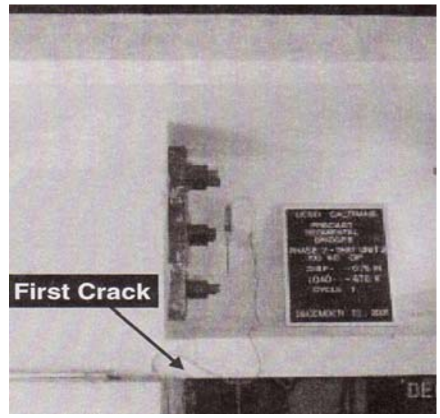
SP5 – Flexural – Brittle

	
F-d Graph	Level II
	
Level V	Level V (Compression failure)
	
Level V (prestress steel failure- lower tendon)	Level V

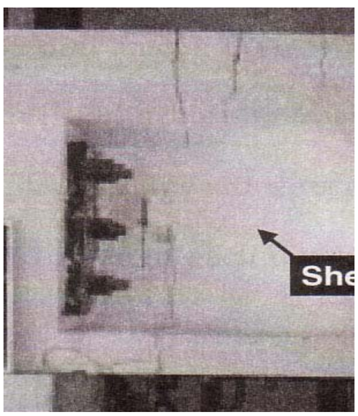
SP6 – Flexural - Brittle



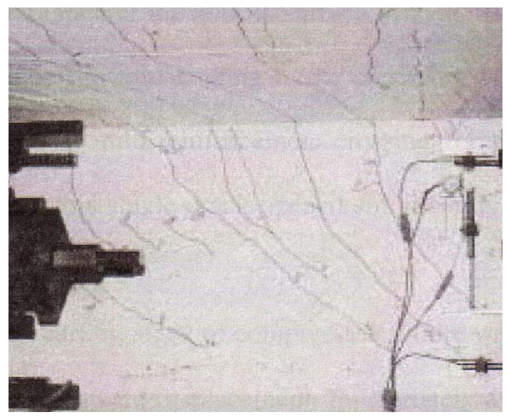
F-d Graph



Level II

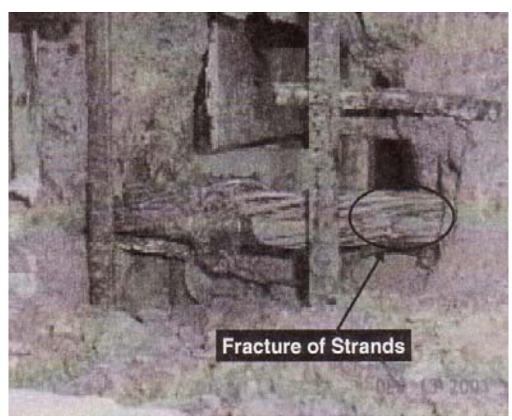


Level IV



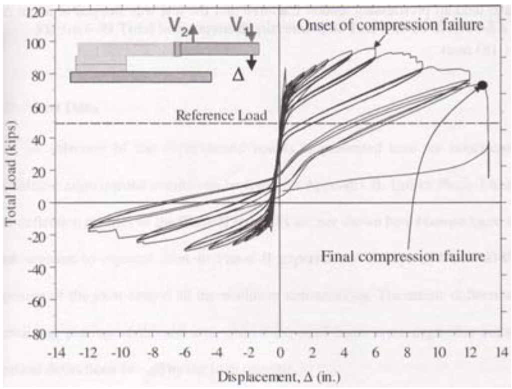
Level IV

Level V



Level V

SP7 – Flexural – Brittle

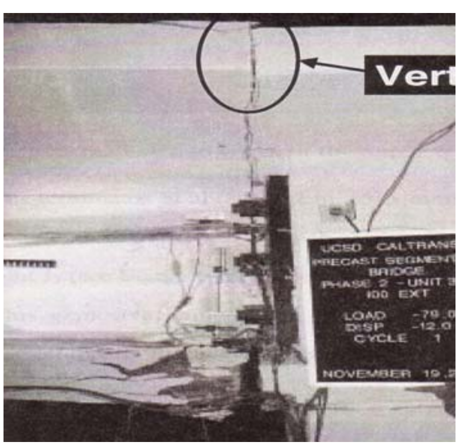


F-d Graph

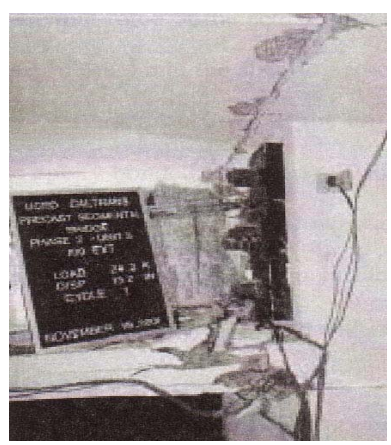
Level I

Level IV

Level V

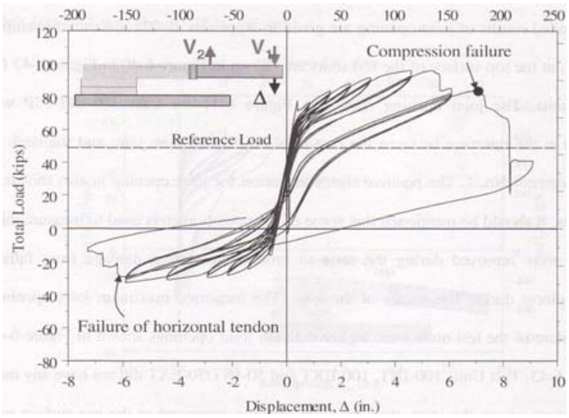


Level V



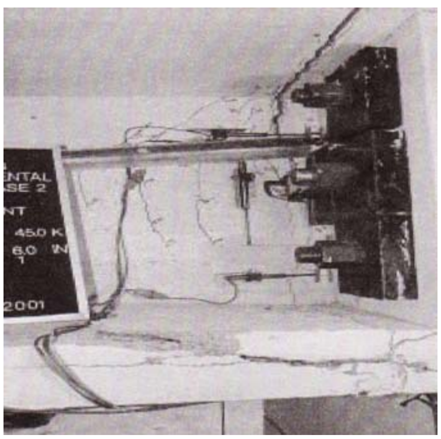
Level V

SP8 – Flexural – Ductile

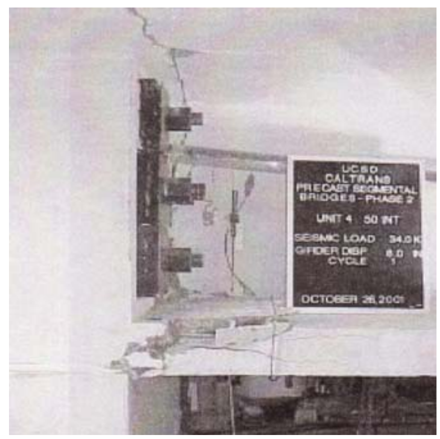


F-d Graph

Level II



Level III



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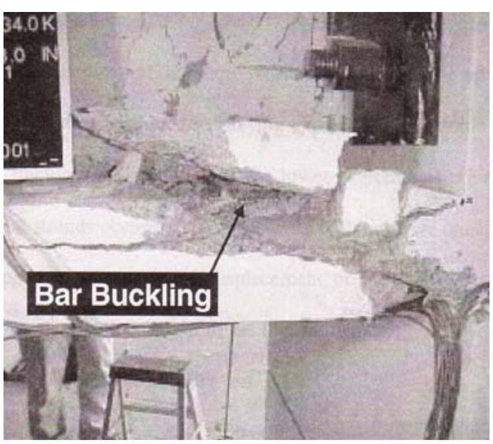
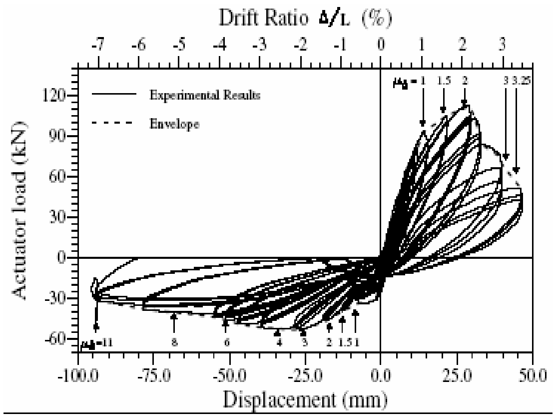


Level V

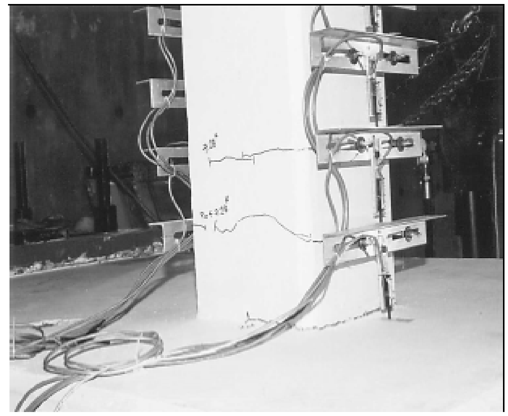
Level V

Foundations

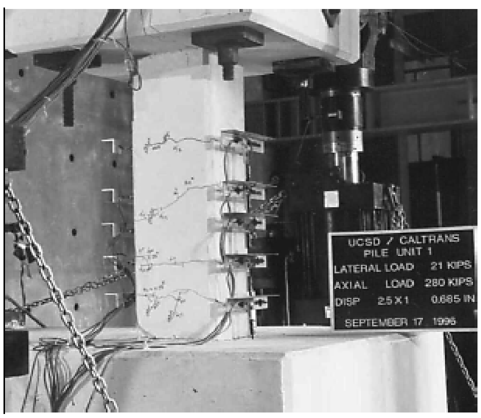
F1 – Shear – Brittle



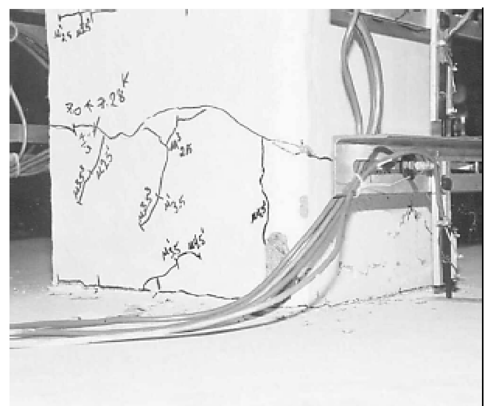
F-d Graph



Level I

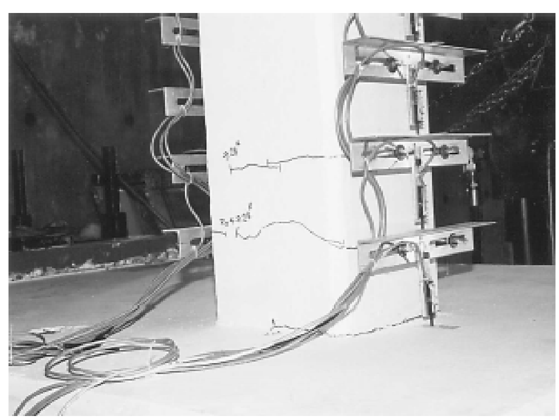


Level II



Level III

Level IV



Level V

F2 – Degrading - Ductile

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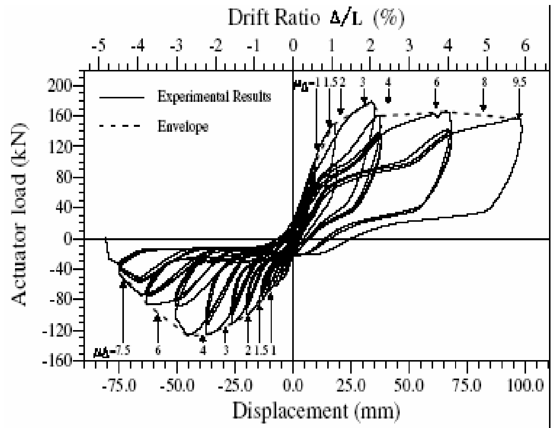
<tr><td>
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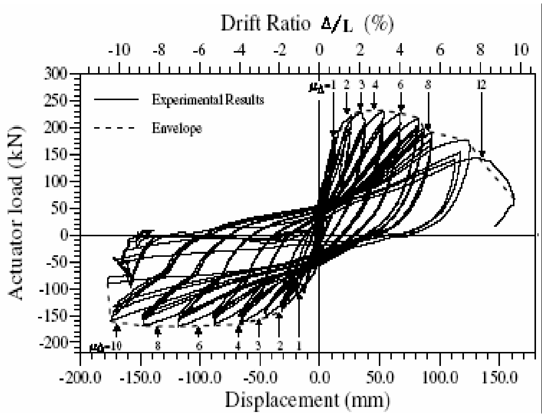
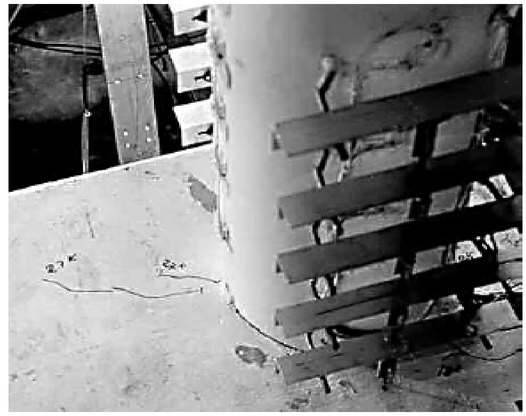
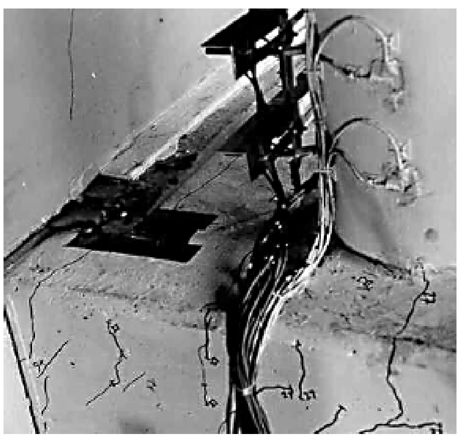
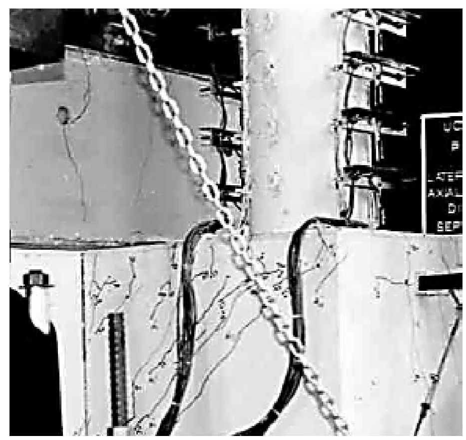
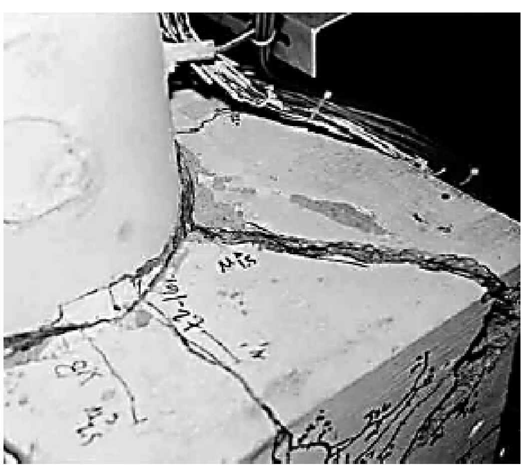
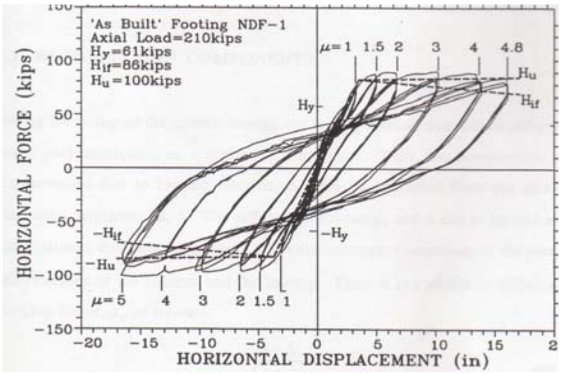
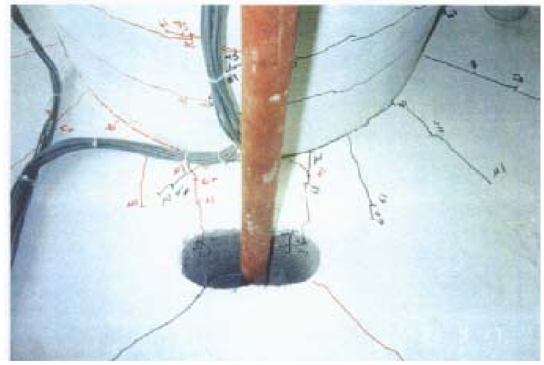
F3 – Degrading – Ductile

	
F-d Graph	Level I
	
Level II	Level III
	
Level IV	Level V

F4 – Flexural - Ductile



F-d Graph



Level I

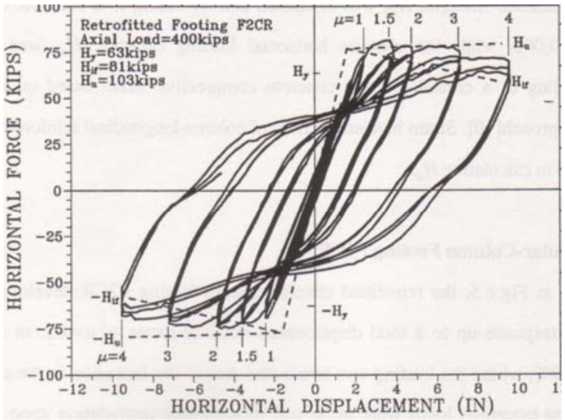
Level II

Level III penetration of footing cracks

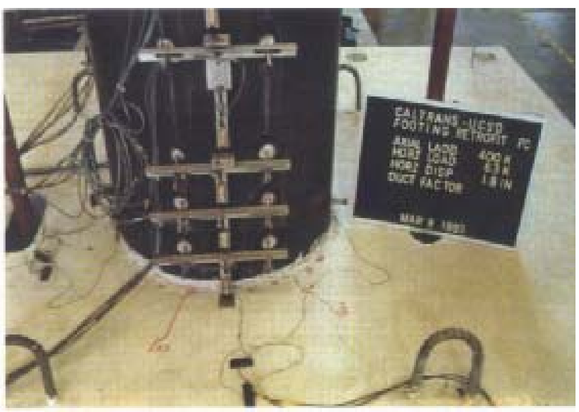
Level IV

Level V

F5 – Flexural - Ductile



Level I



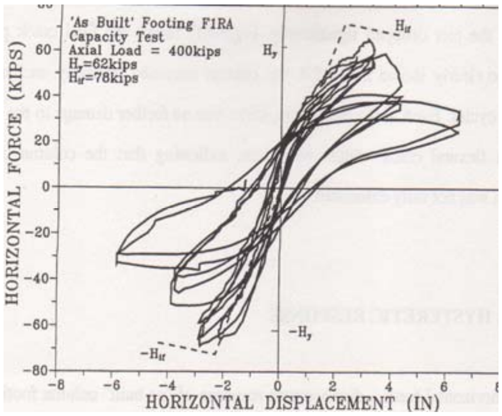
Level II

Level III

Level IV

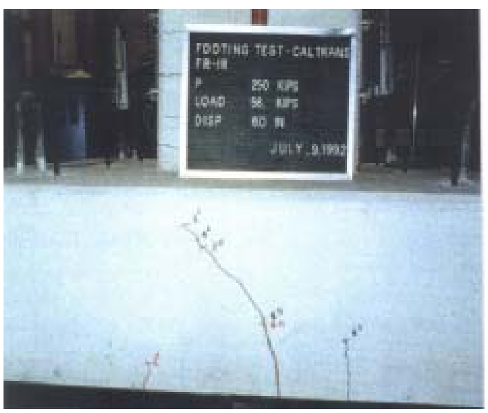
Level V

F6 – Flexural – Brittle



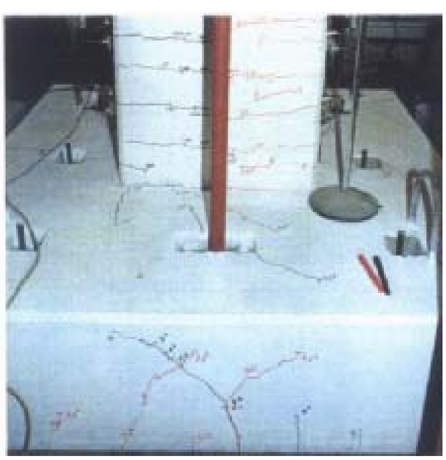
F-d Graph

Level II

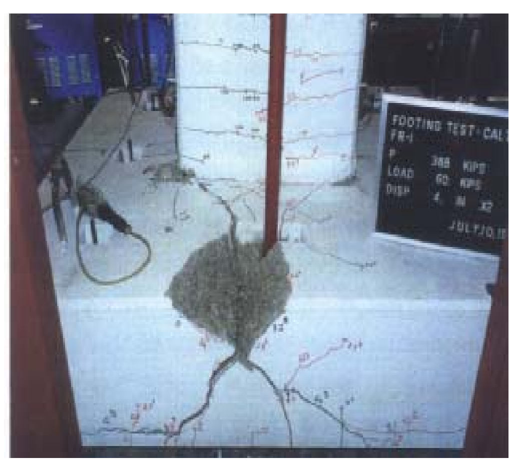


Level III

Level IV

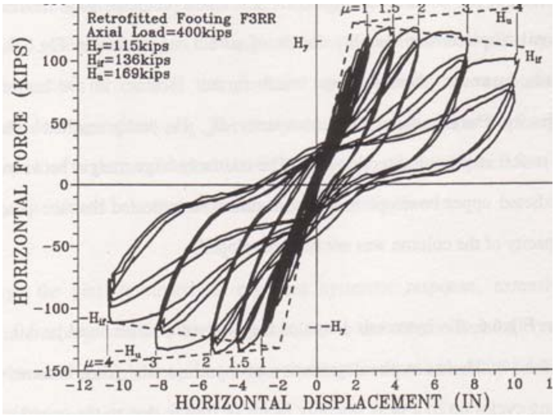


Level V



Level V column-footing shear cracks

F7 – Flexural - Ductile



F-d Graph

Level II

Level III

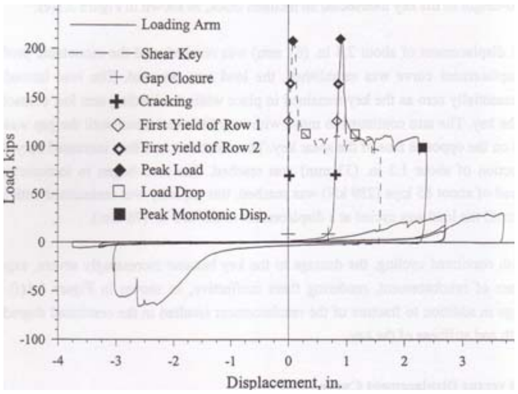
Level IV

Level V

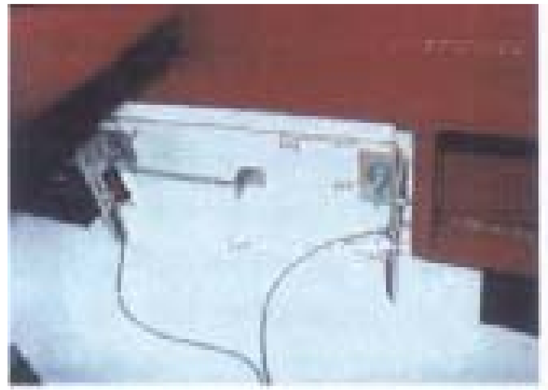
Level V permanent deformation

Abutments/Shear Keys

SK1 – Shear - Brittle



F-d Graph



Level I

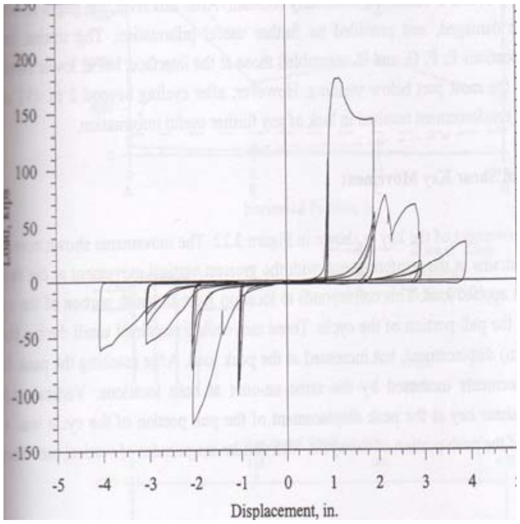
Level II

Level III

Level IV

Level V

SK2 – Shear - Brittle



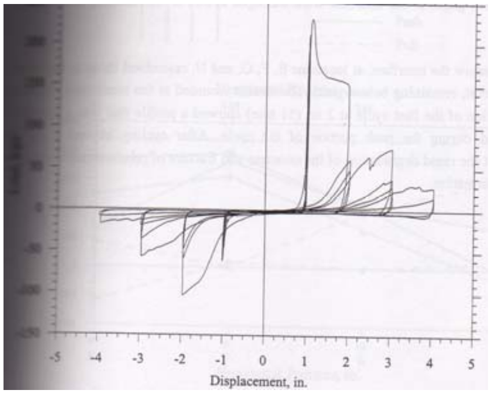
F-d Graph

Level I

Level III

Level V

SK3 – Shear - Brittle



F-d Graph

Level I

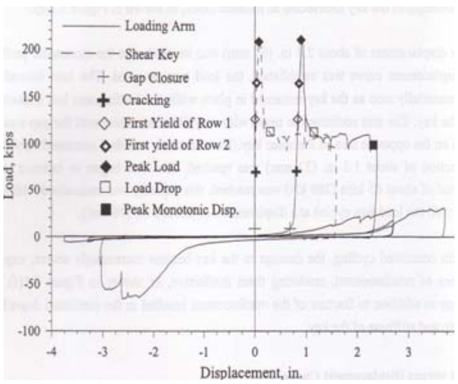
Level II

Level III

Level IV

Level V

SK4 – Shear - Brittle

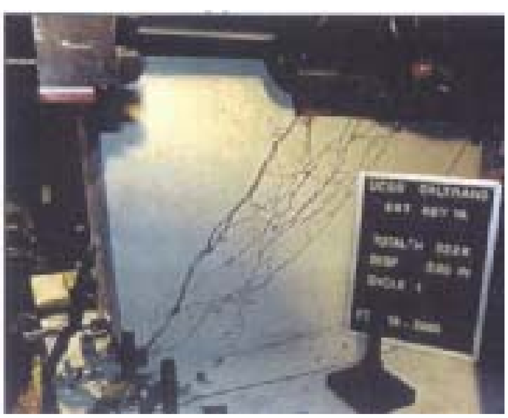


F-d Graph

Level II

Level II

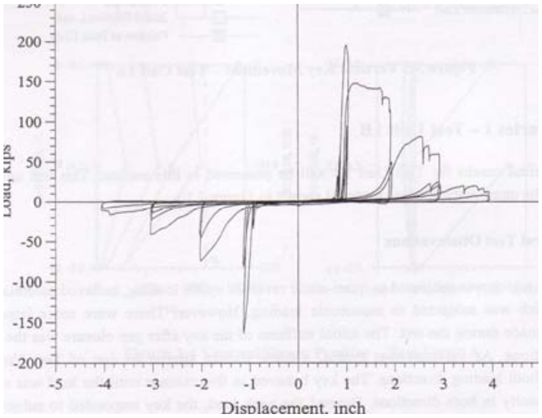
Level III



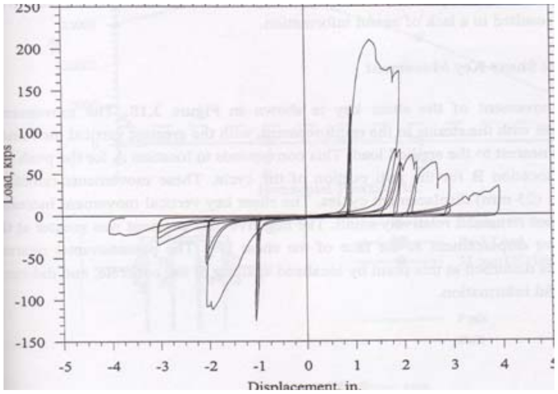
Level IV

Level V

SK5 – Shear - Brittle

	
F-d Graph	Level I
	
Level II	Level III
	
Level IV	Level V

SK6 – Shear – Brittle



F-d Graph

Level I

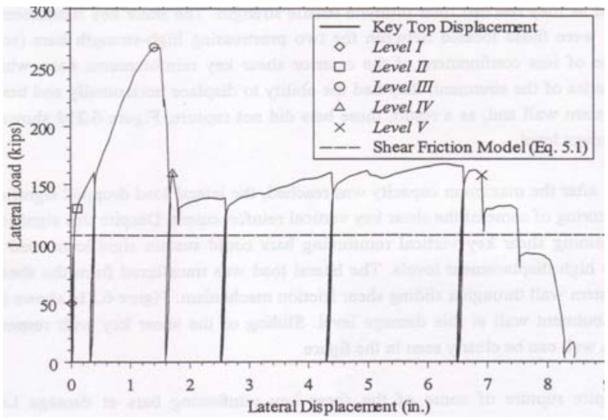
Level II

Level III

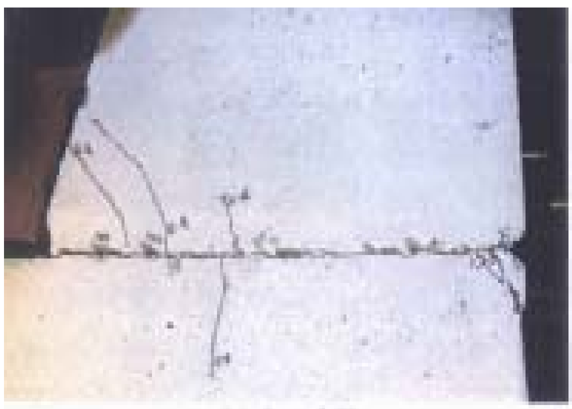
Level IV

Level V

SK7 – Shear

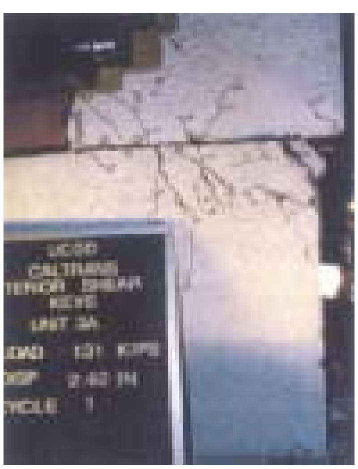


Level I



Level II

Level III

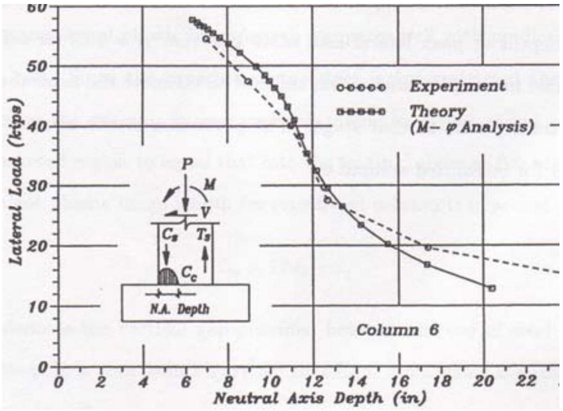


Level IV

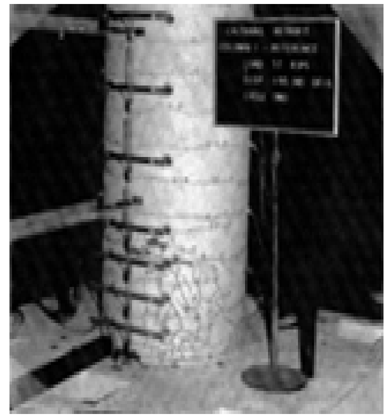
Level V

Retrofit

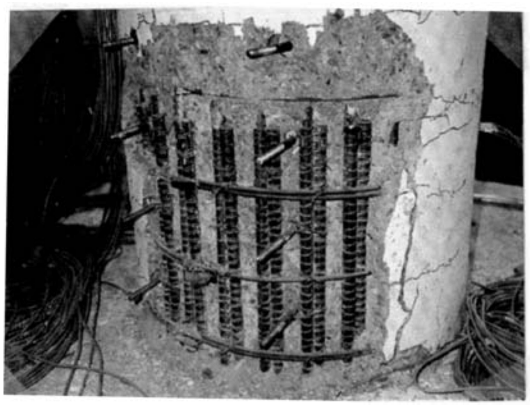
R1 – Flexural



F-d Graph

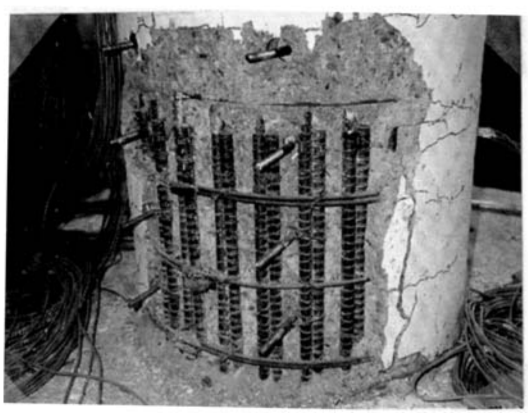


Without Retrofit



Without - Level IV

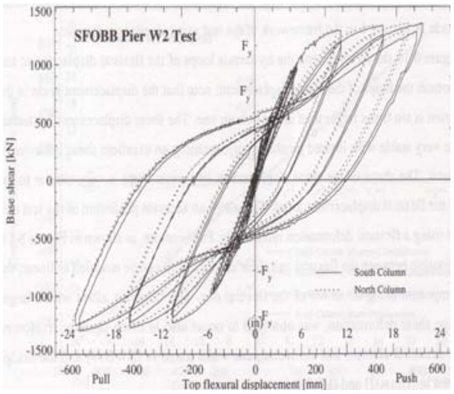
Level III

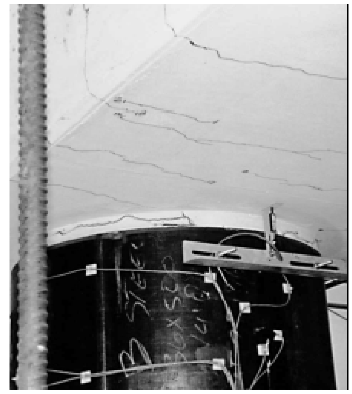


Level V permanent deformation

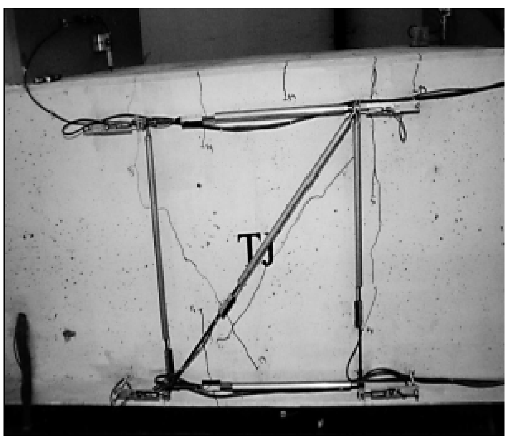
Level V bars rupture

R2 – Flexural - Ductile

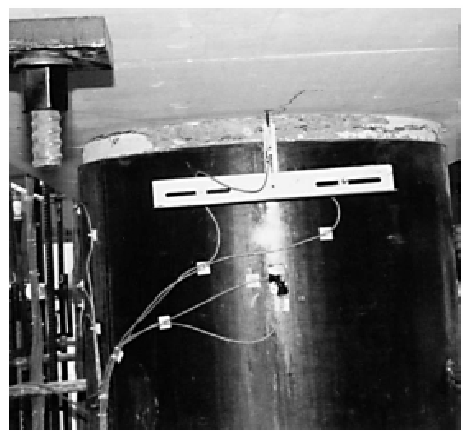




Level I



Level II shear cracking at joint

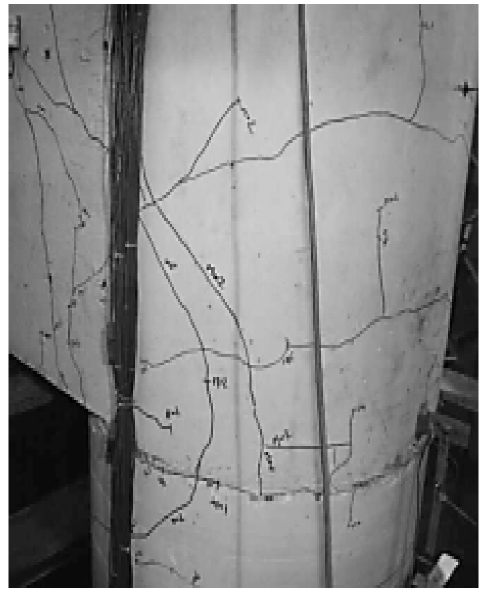
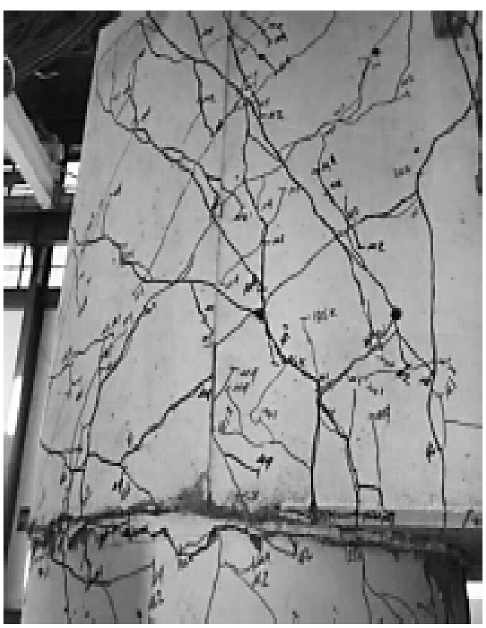


Level III spalling at gap region of cap beam

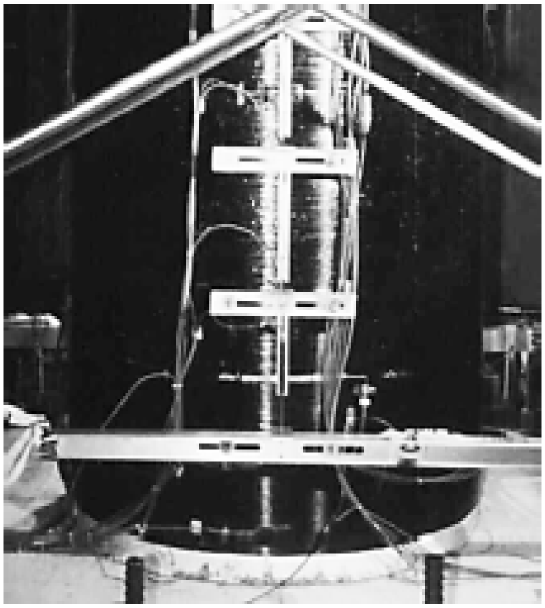
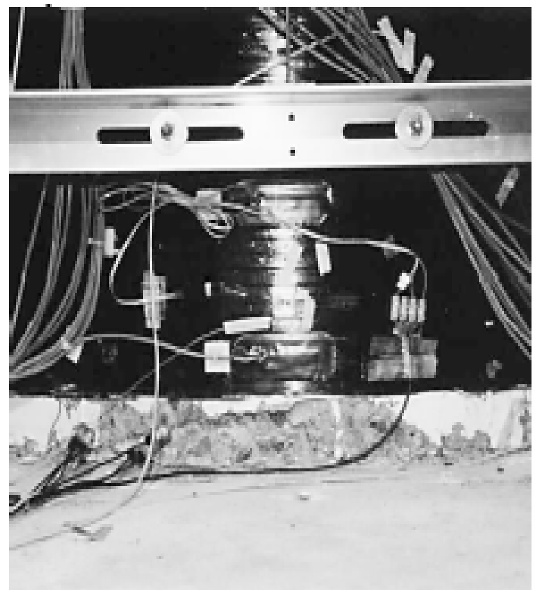
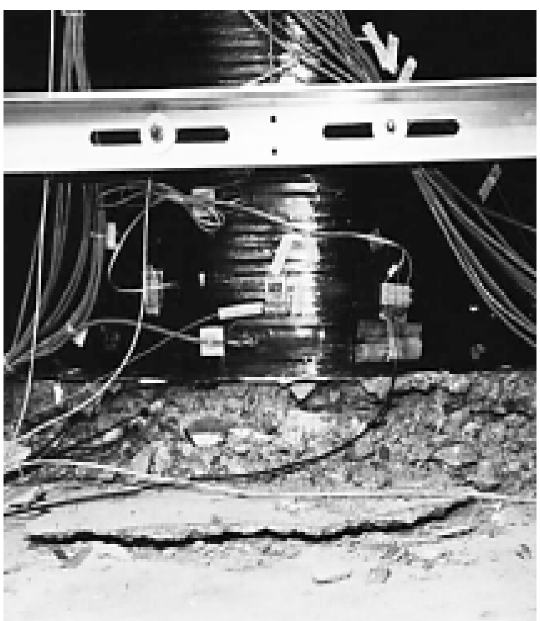
Level IV cap beam penetration of reinforcement

Level V - fracture of long. Bars

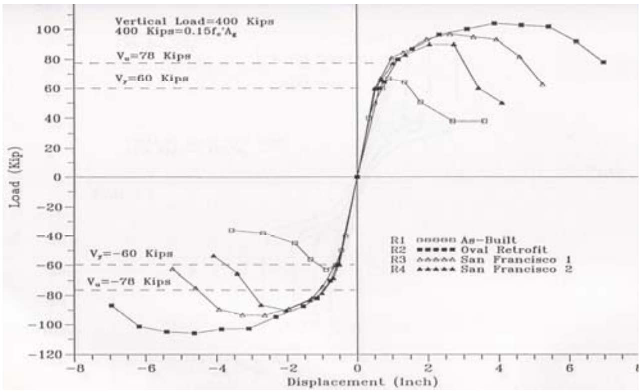
R3 – Flexural

	
Level II flexural cracks at joint	Level III joint shear cracks (from pull out)
	
Level IV splitting cracks of cap beam	Level IV

R4 – Flexural

	
Level II first cracks at interface	Level III cracks in jacket filaments and gap
	
Level IV extensive spalling at plastic hinge	Level V jacket cracks, bar rupture

R5 – Flexural – Ductile



F-d Graph

Level III without retrofit

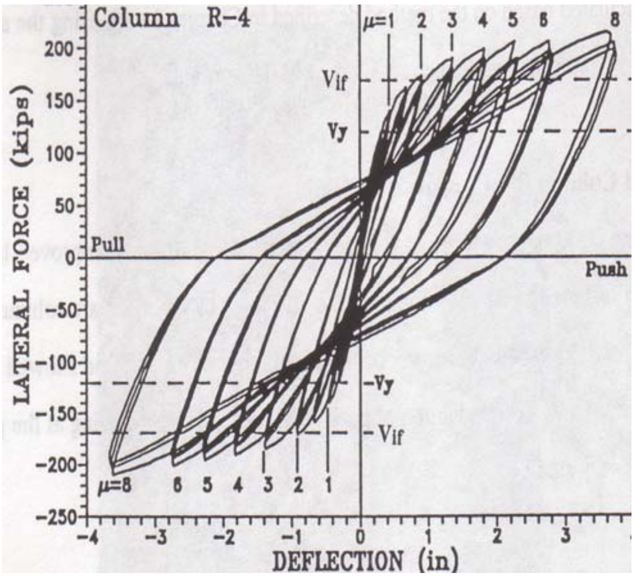
Level V without retrofit

Test setup – retrofit

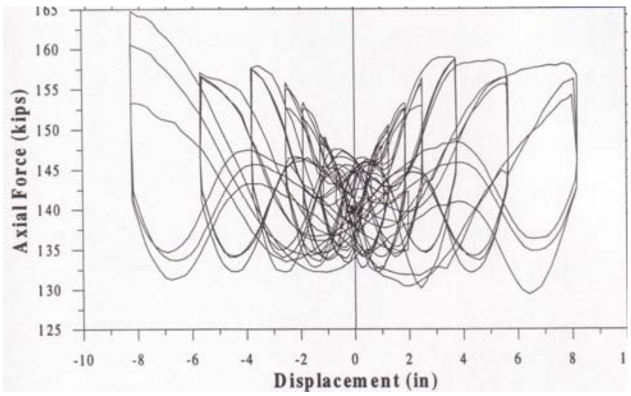
Level IV after removal of jacket

Level V after removal of jacket

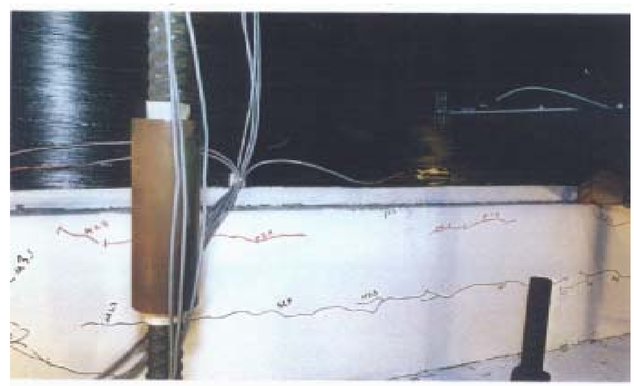
R6 – Shear - Brittle

	
F-d Graph	Test setup
	
Level III spalling at gap region	Level V permanent deformation

R7 – Flexural - Ductile

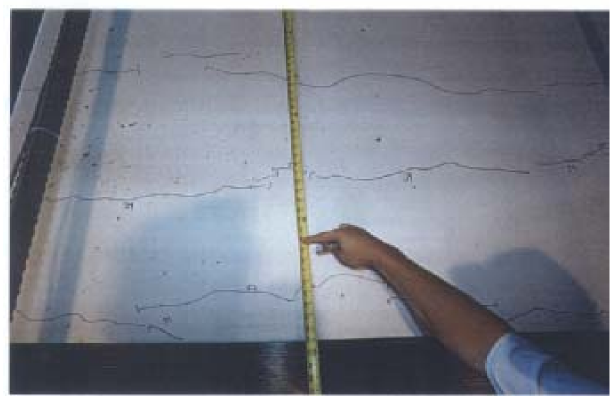


F-d Graph

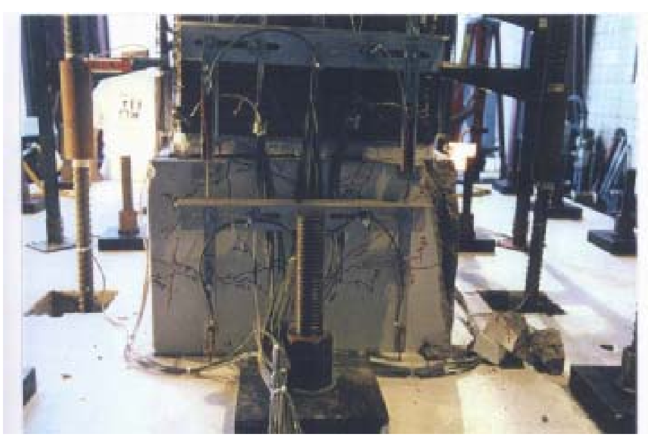


Level I - Cracks on Pedestal

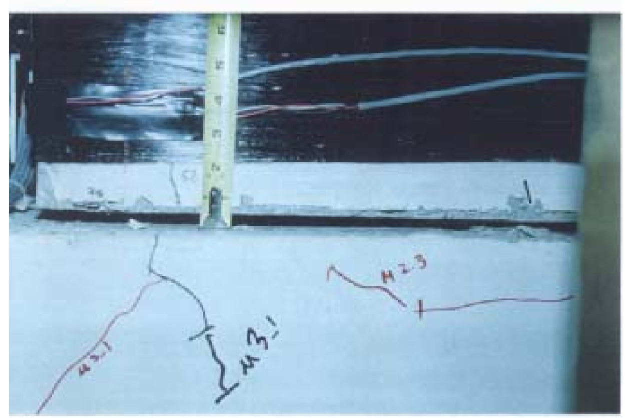
Level I - First vertical on column interface



Level II - Above jacket cracks

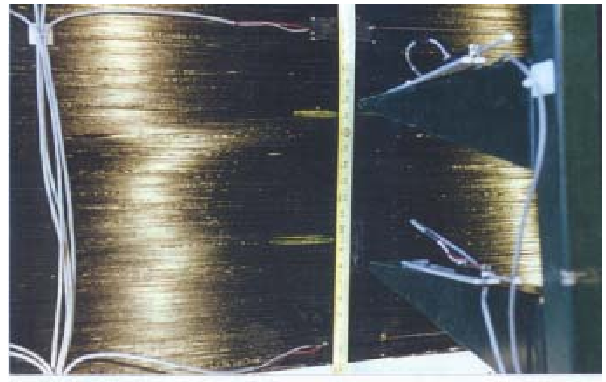
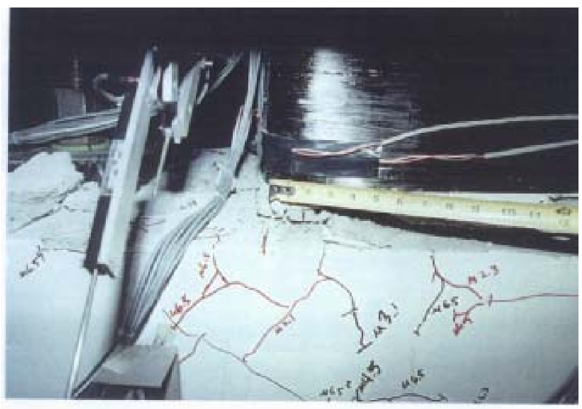
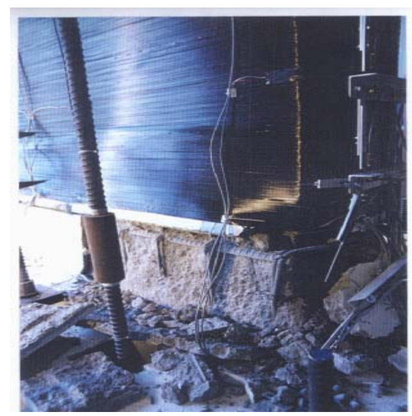


Level III - Spalling of cover concrete at pedestal

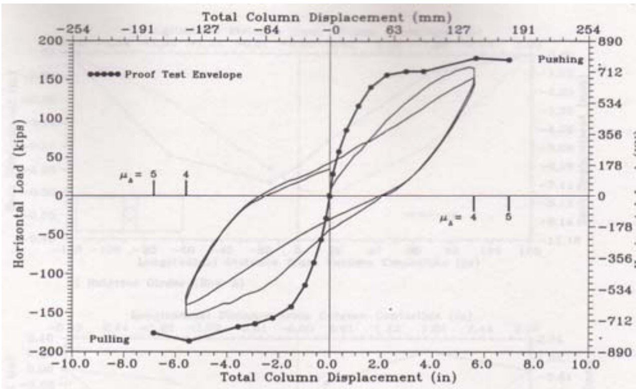
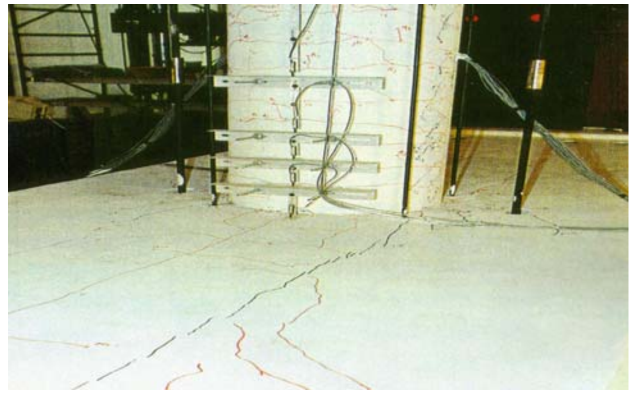
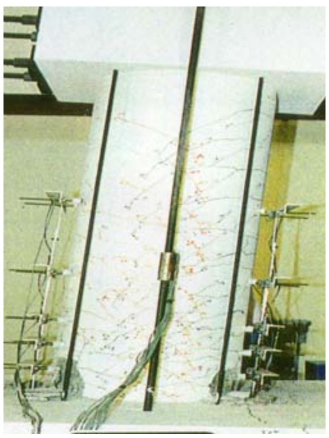
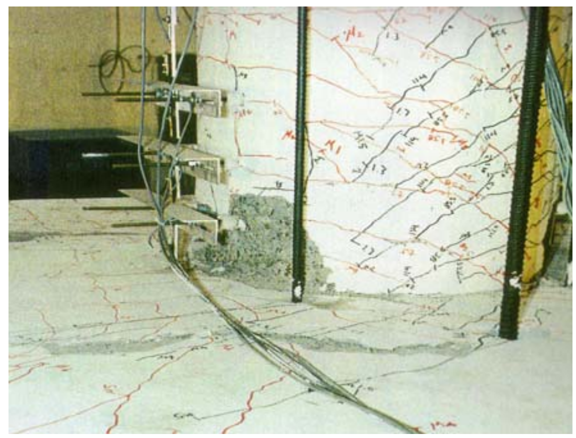


Level IV - Gap between pedestal column

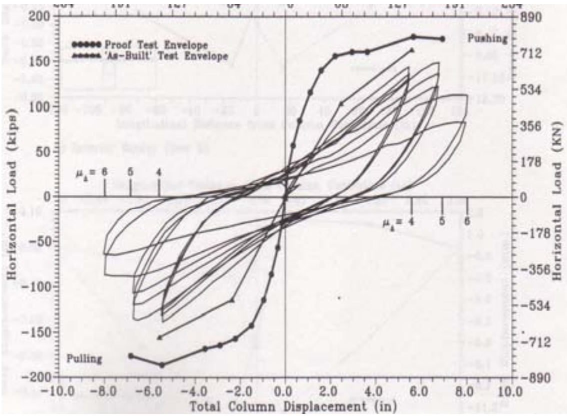
R7 – Flexural

	
Concrete cones around starter bars	Level IV Dilation of jacket
	
Level V - Sliding of column	Level V
	
Level V	

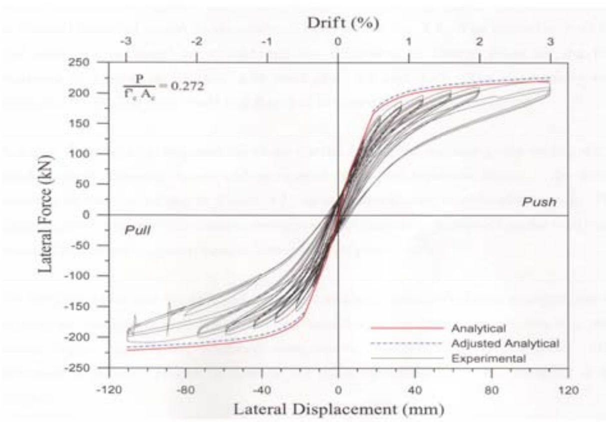
R8 – Flexural – Brittle

	
F-d Graph	Level II
	
Level III	Level III
	
Level IV	Level V

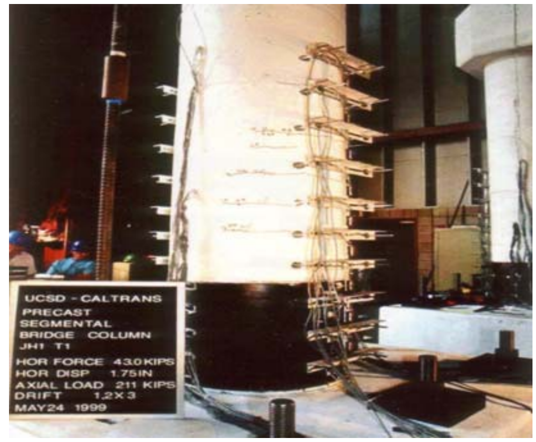
R9 – Flexural – Ductile

	
F-d Graph	Level III
	
Level V	Level V
	
Level V	

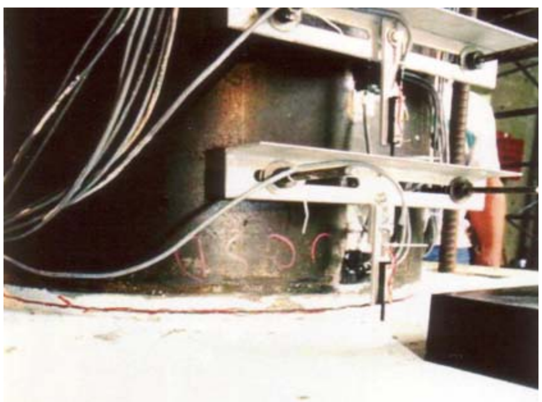
R10 – Flexural - Ductile



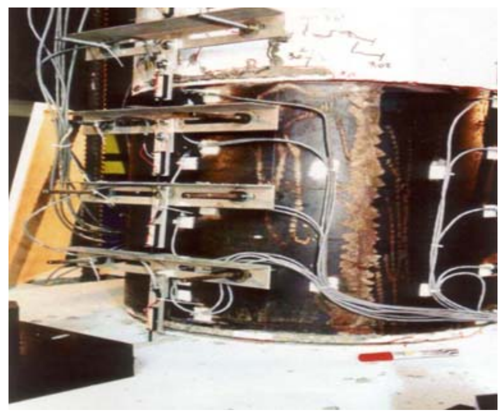
F-d Graph



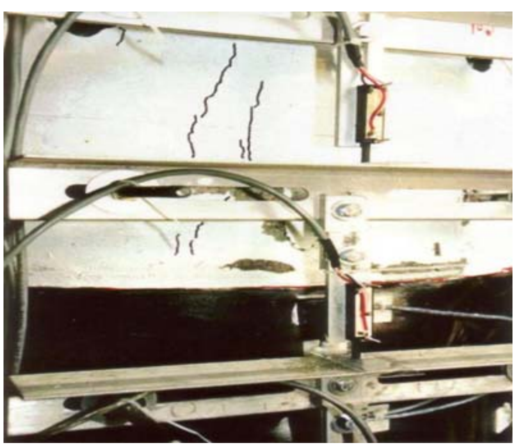
Level I



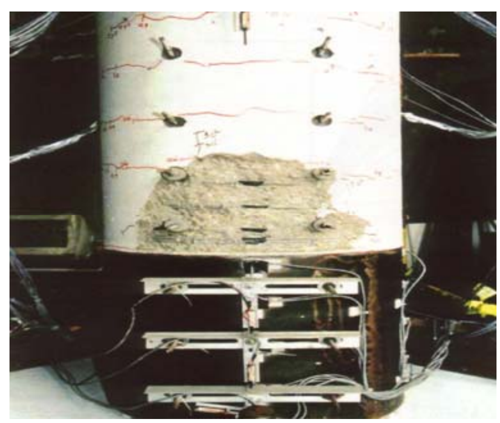
Level II



Level III

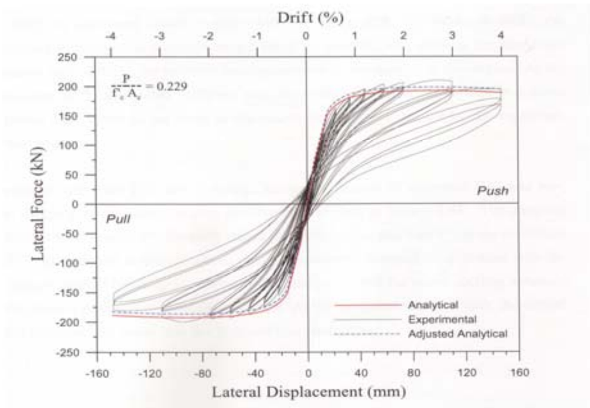


Level IV



Level V

R11 – Flexural - Ductile



F-d Graph

Level II

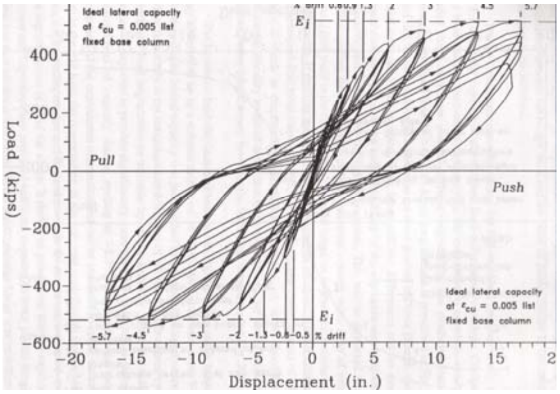
Level IV

Level IV (Residual crack at end of test)

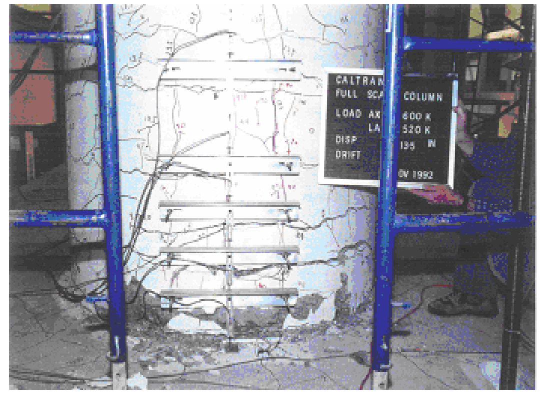
Sub-Assemblages - Systems

Column Superstructure Sub-Assemblages

SM1 – Flexural - Ductile

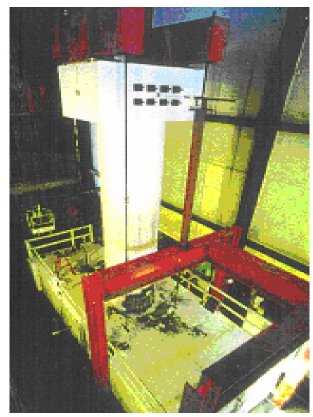


F-d Graph



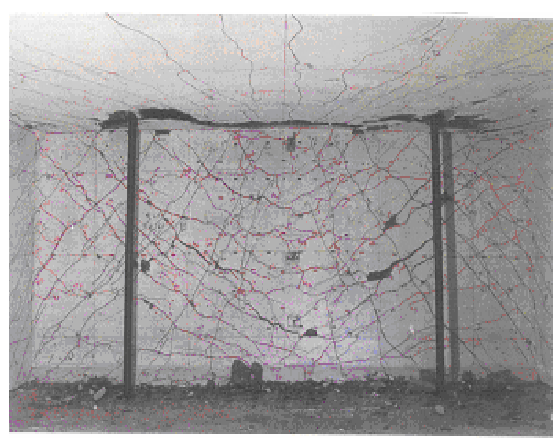
Level III

Level IV



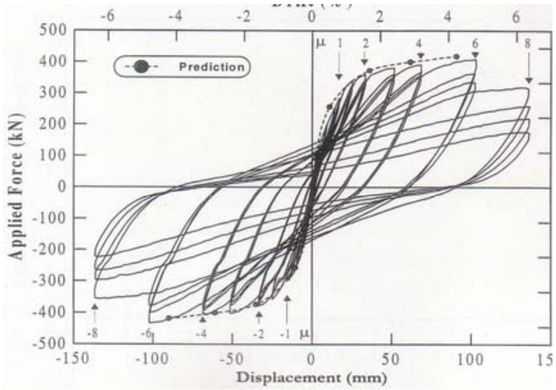
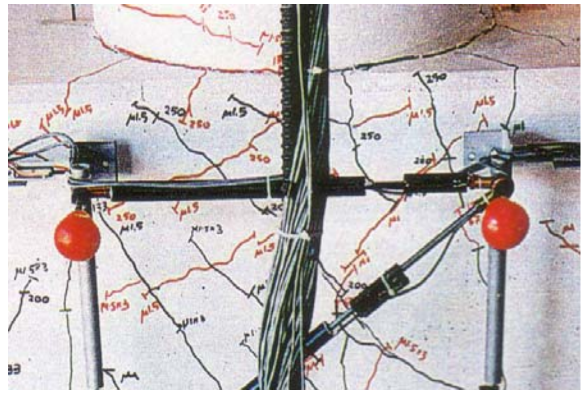
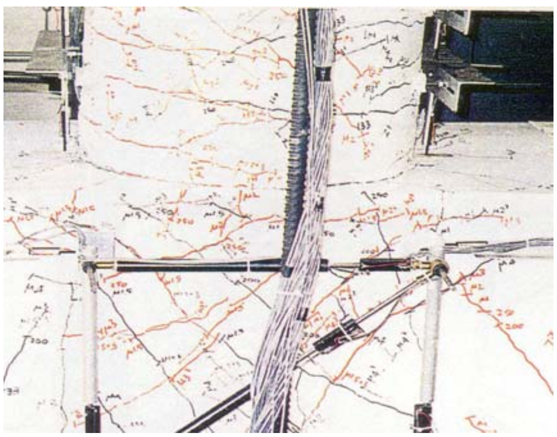
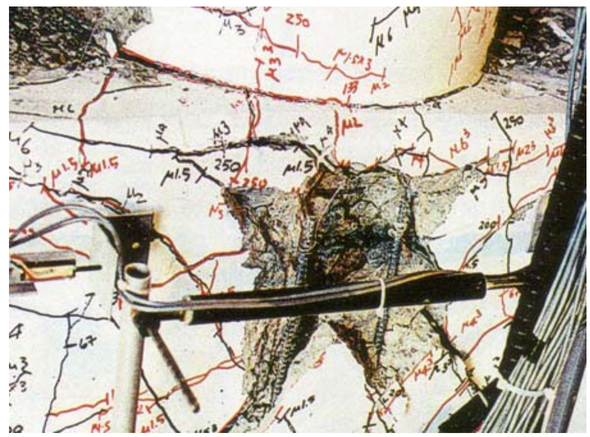
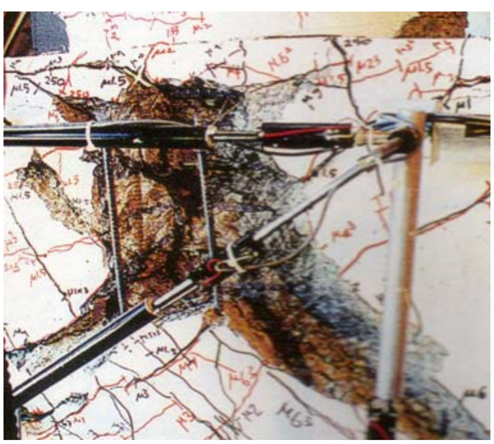
Level V

Level IV superstructure cracks

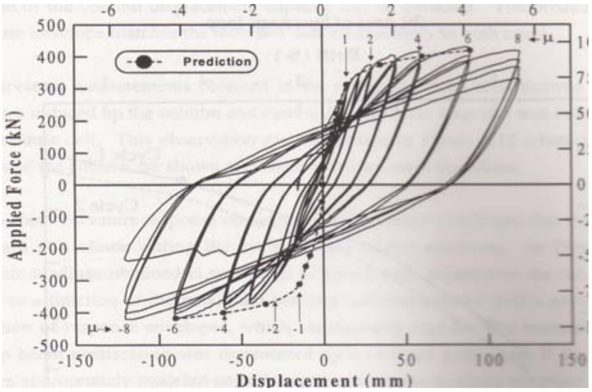
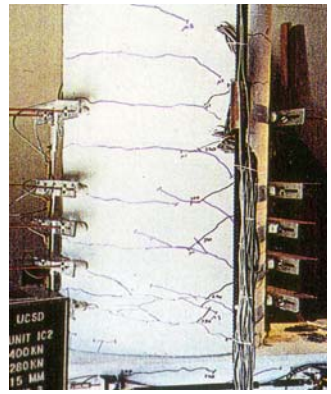
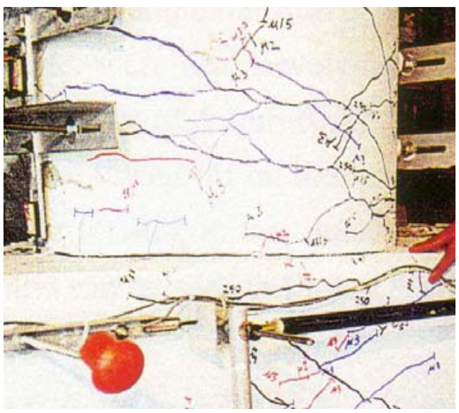
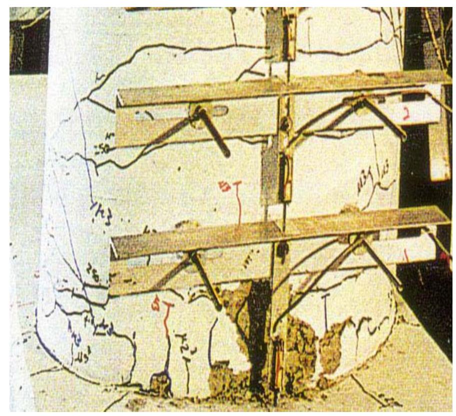
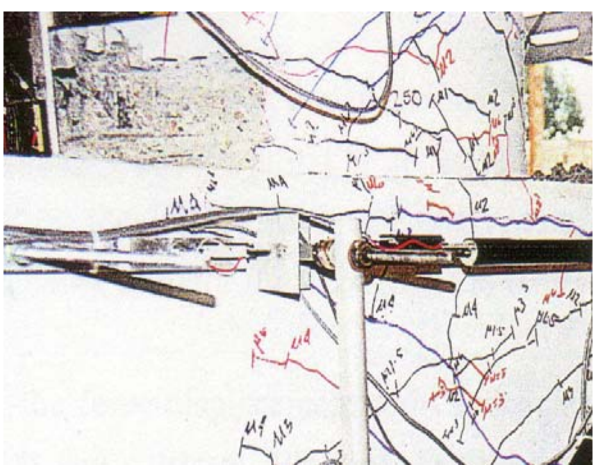
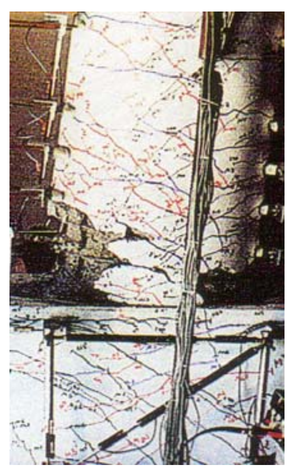


Level IV superstructure cracks

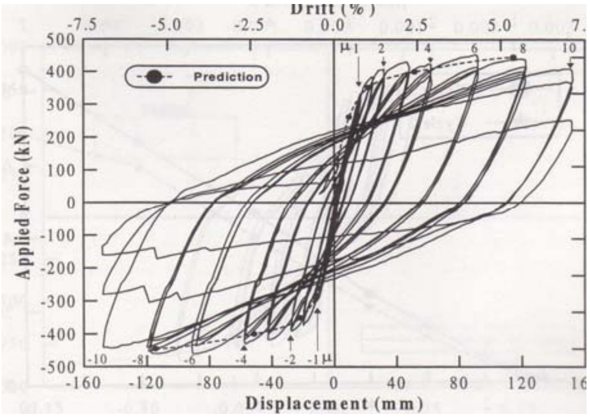
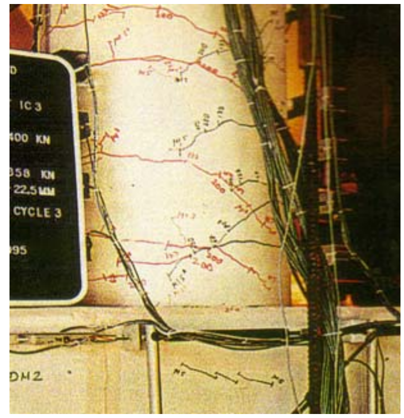
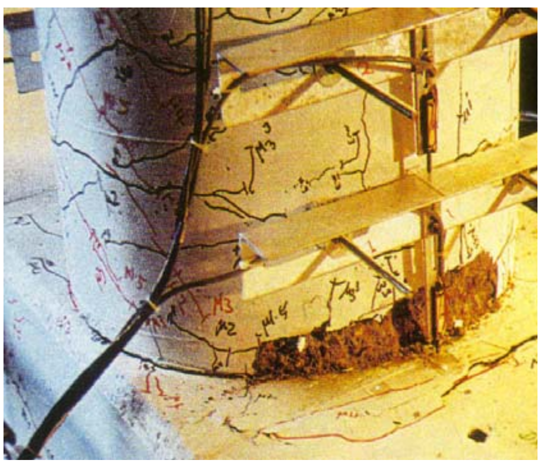
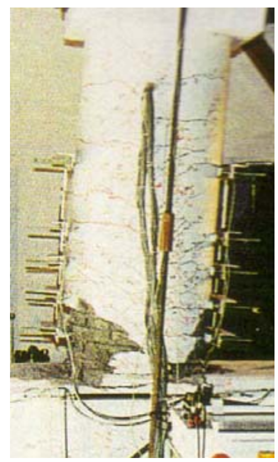
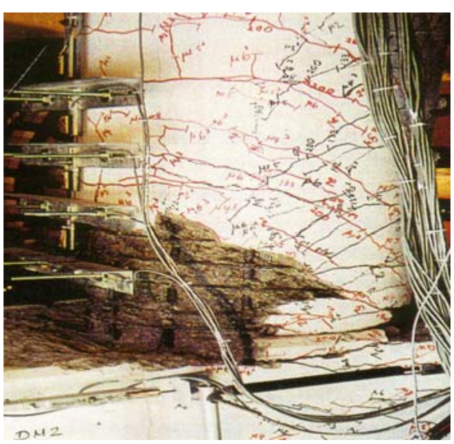
SM2 – Flexural – Ductile

	
F-d Graph	Level II
	
Level III	Level IV
	
Level V	Level V

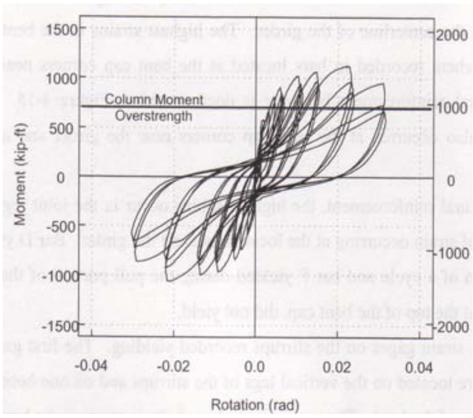
SM3 – Flexural – Ductile

	
F-d Graph	Level II
	
Level III	Level IV
	
Level IV	Level V

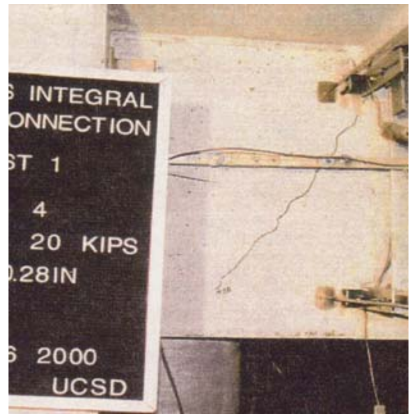
SM4 – Flexural - Ductile

	
F-d Graph	Level III
	
Level IV	Level IV
	
Level IV	

SM5 – Shear - Brittle



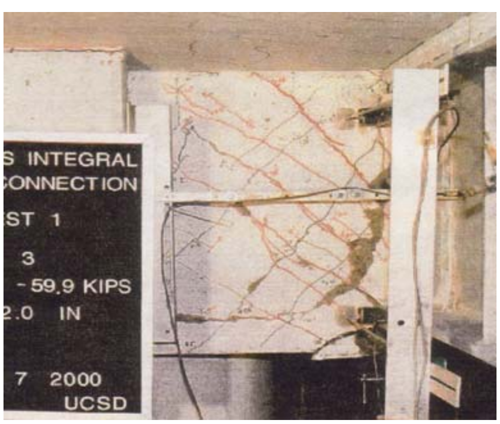
F-d Graph



Level III

Level III at bottom

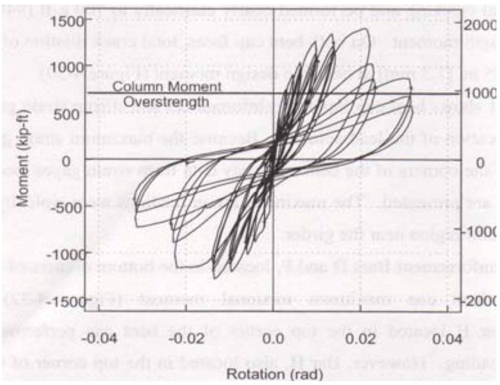
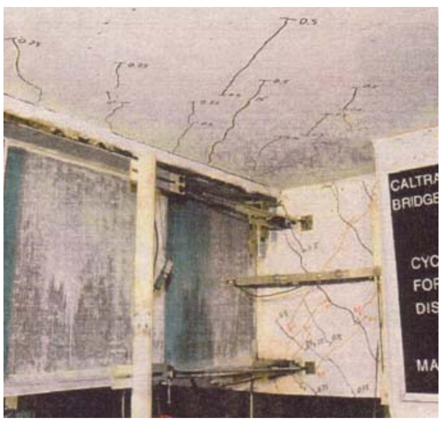
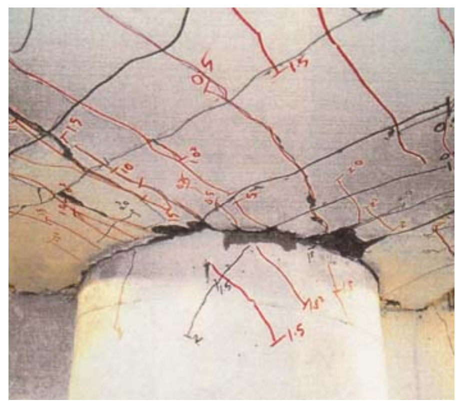
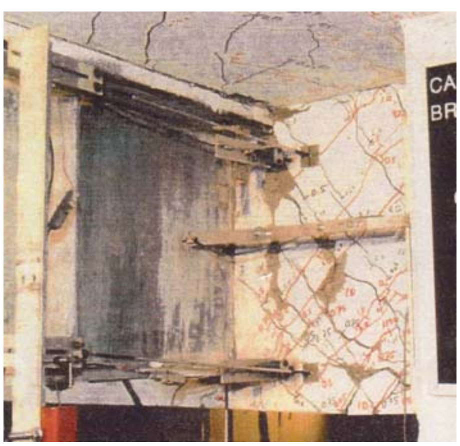
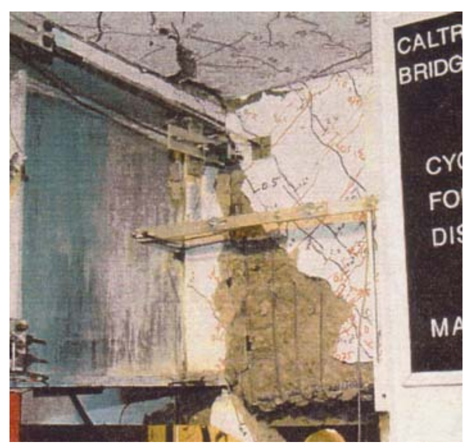
Level IV



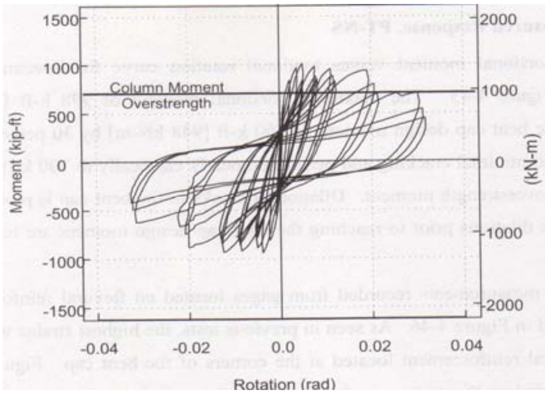
Level IV

Level V Girder

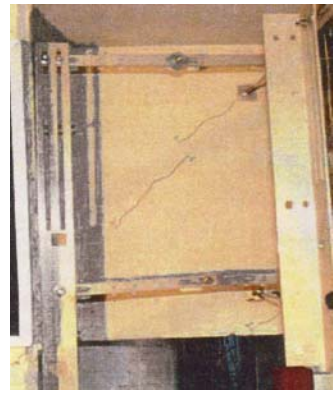
SM6 – Shear – Brittle

	
F-d Graph	Level III
	
Level IV	Level IV
	
Level IV	Level V

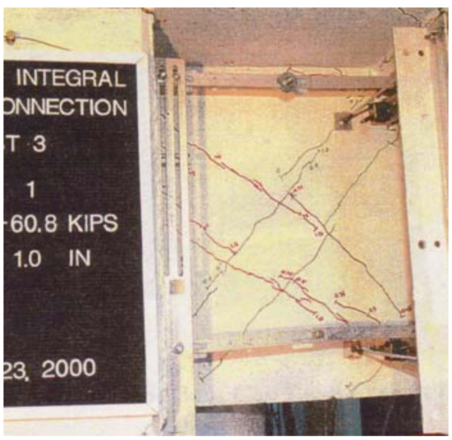
SM7 – Shear – Brittle



F-d Graph

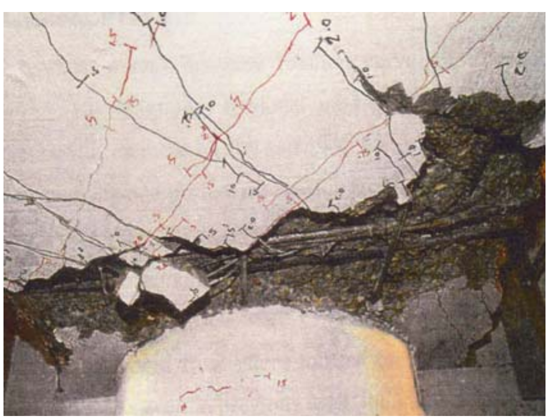


Level II



Level III

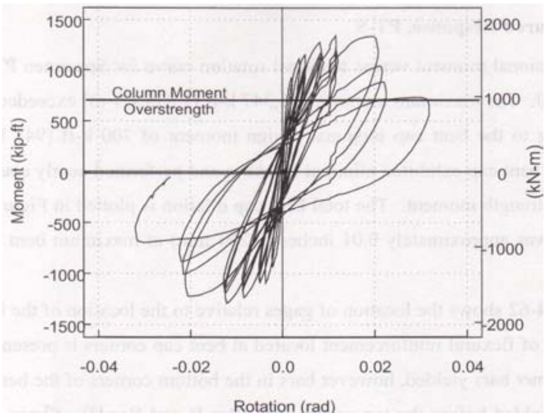
Level IV



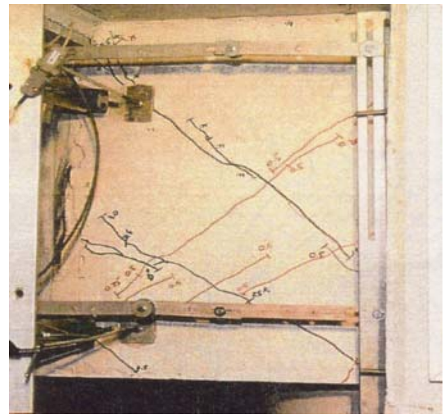
Level IV bent cap

Level V bent cap/girder

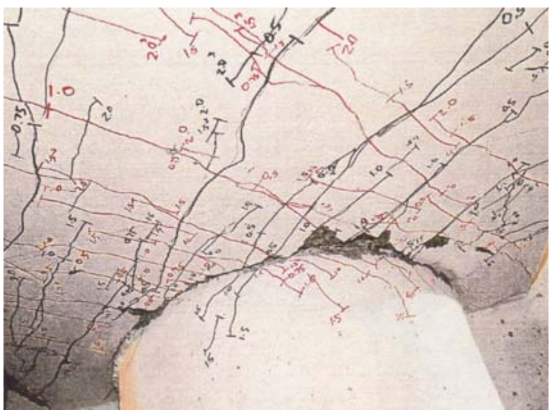
SM8 – Shear – Brittle



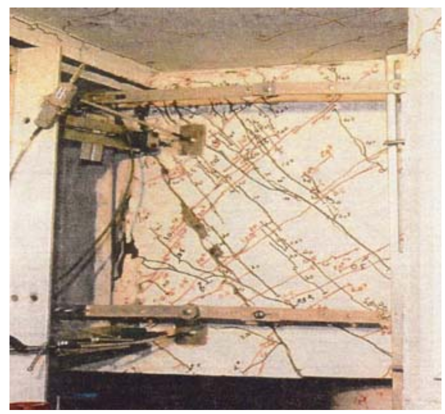
F-d Graph



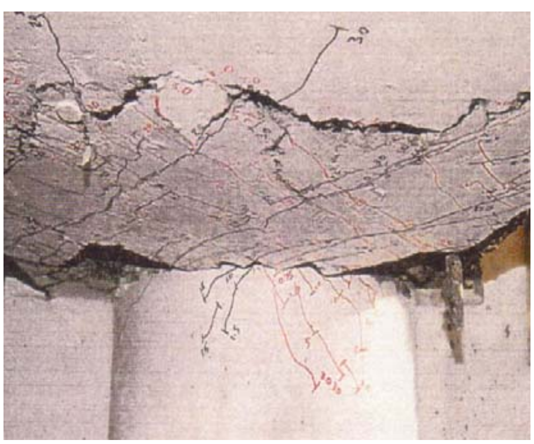
Level II



Level III



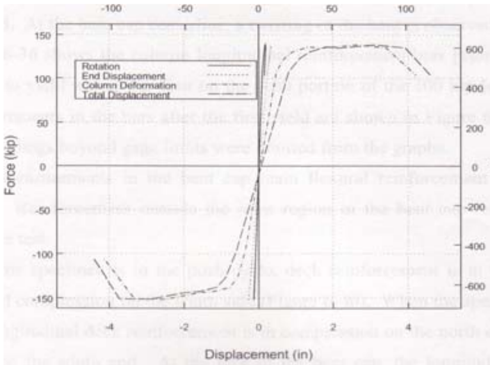
Level IV



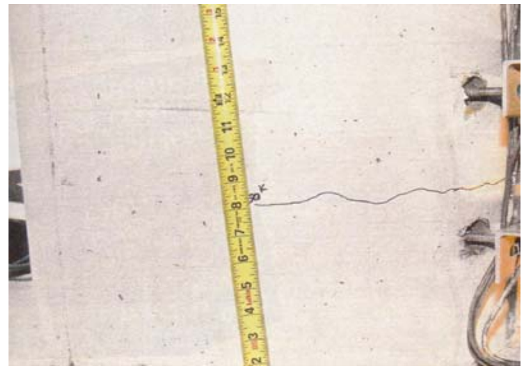
Level V

Level V

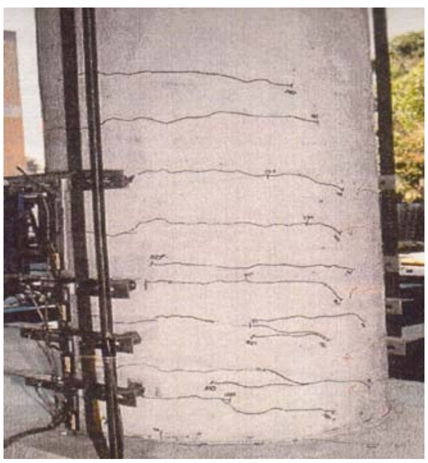
SM9 – Flexural – Ductile



F-d Graph



Level II



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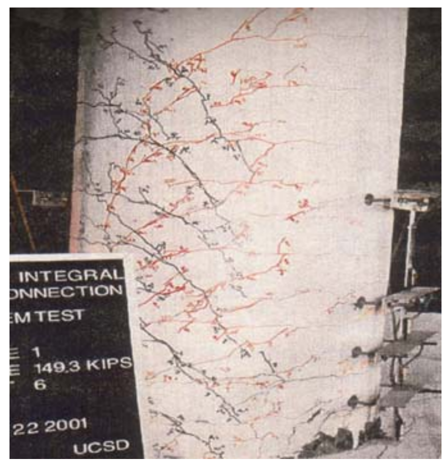
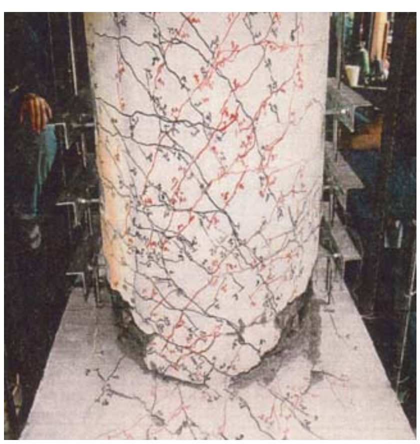
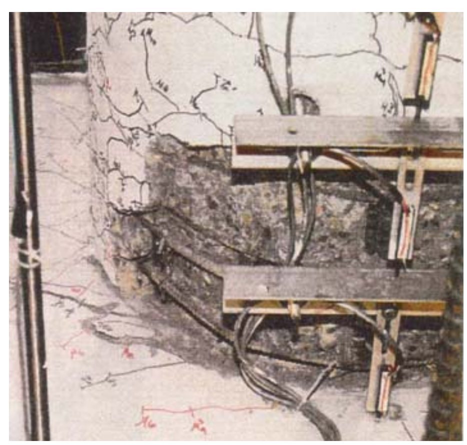


Level III



Level IV



Level V

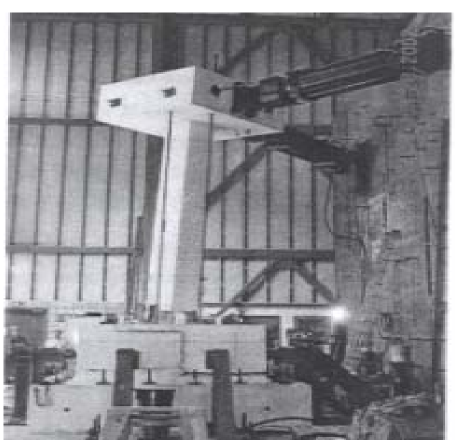
Column Foundation Sub-Assemblages

SM10 – Flexural

Test setup

Level III

Level V pile cap rotation

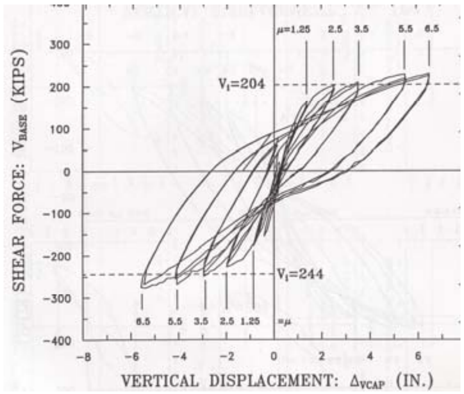


Level V residual displacement

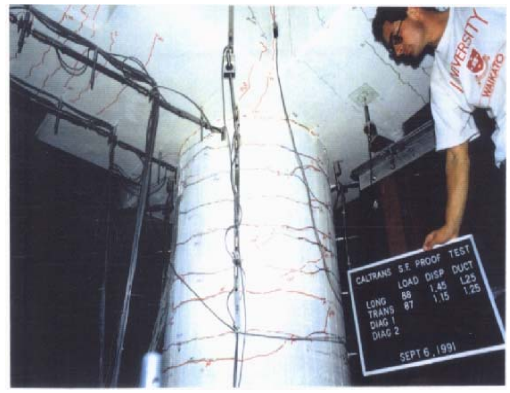
Level V

Double Deck Viaduct

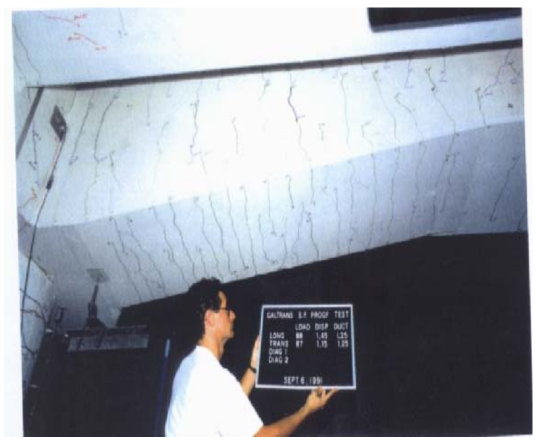
SM11 – Flexural - Ductile



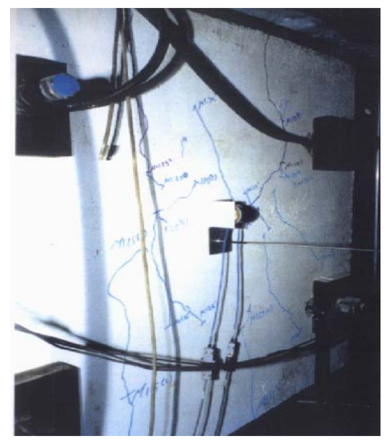
F-d Graph



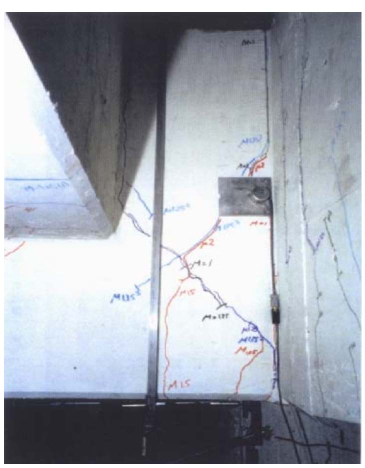
Level II



Level II edge girder



Level II outside face cap column

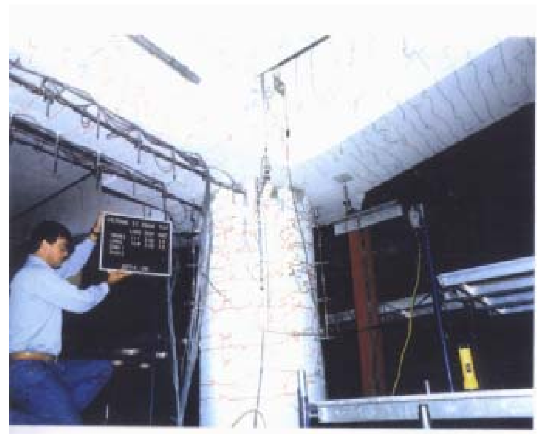


Level II cap beam between superstructure-girder

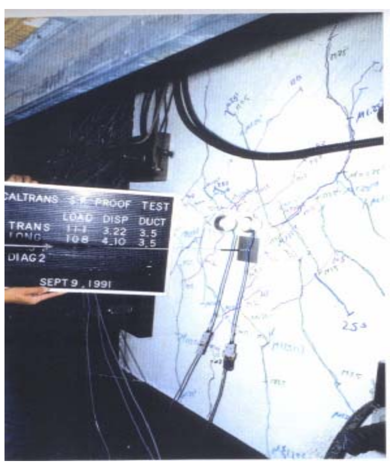
Level III

SM11 – Flexural – Ductile

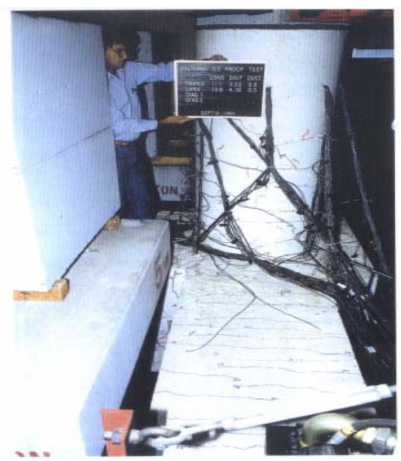
Level III outside face cap column



Level III

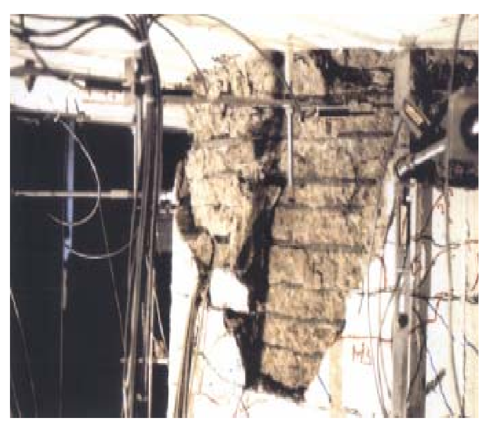


Level IV outside face cap column



Level IV top of edge girder

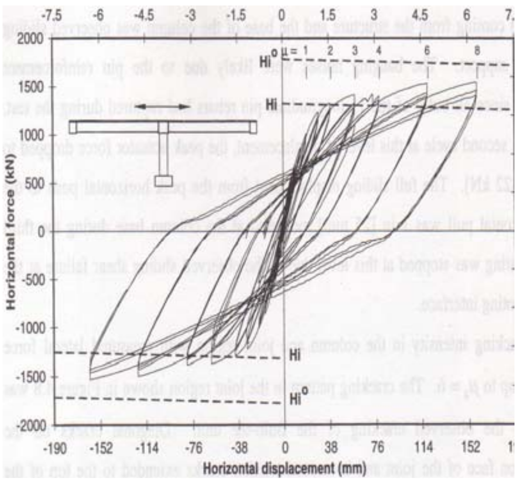
Level IV



Level V

Precast

SM12 – Flexural – Ductile



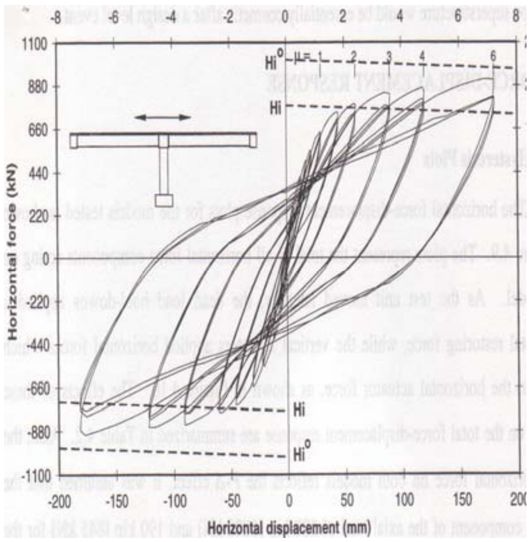
F-d Graph

Level III

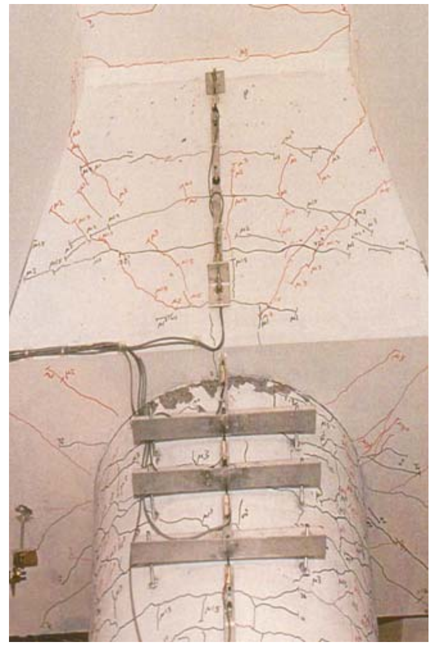
Level III

Level IV

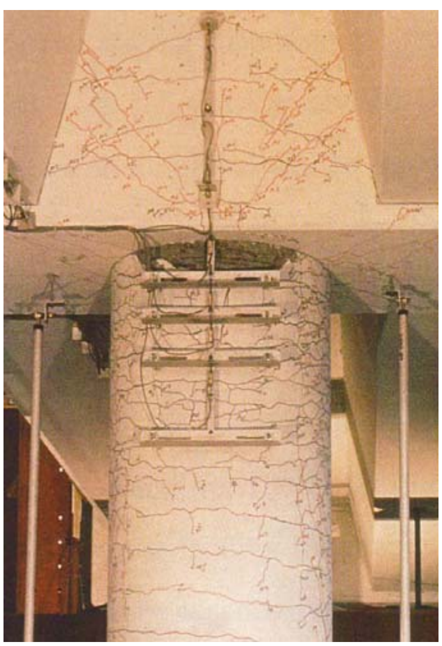
SM13 – Flexural – Ductile



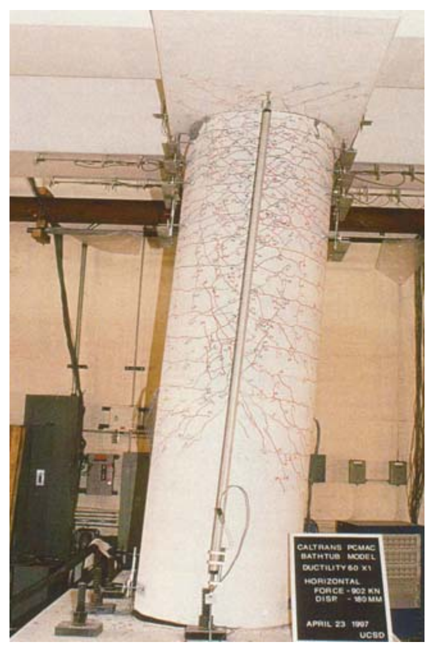
F-d Graph



Level III

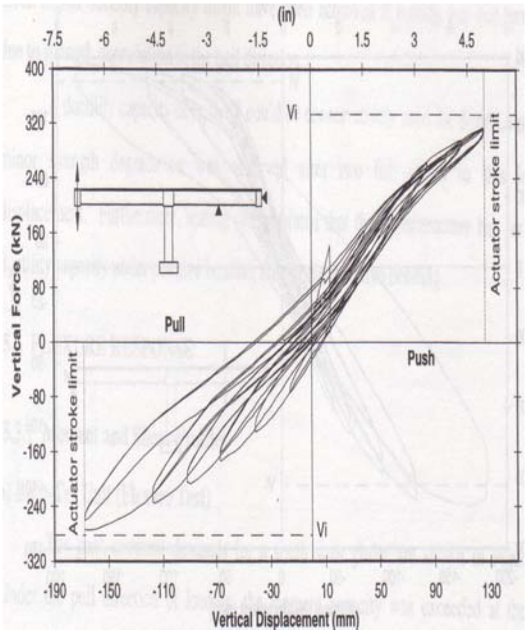


Level IV

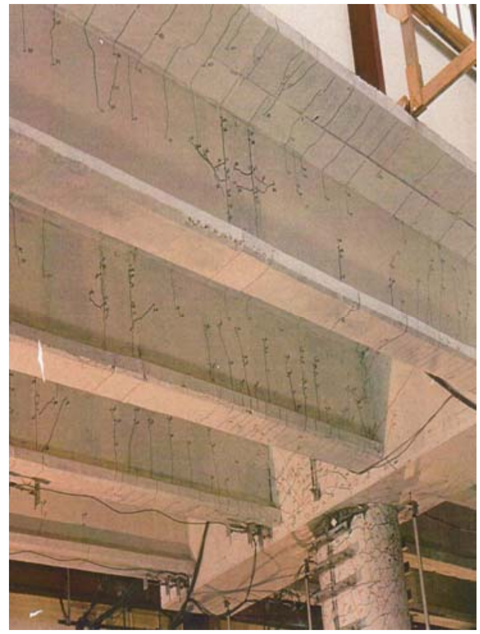


Level V

SM14 – Shear – Brittle

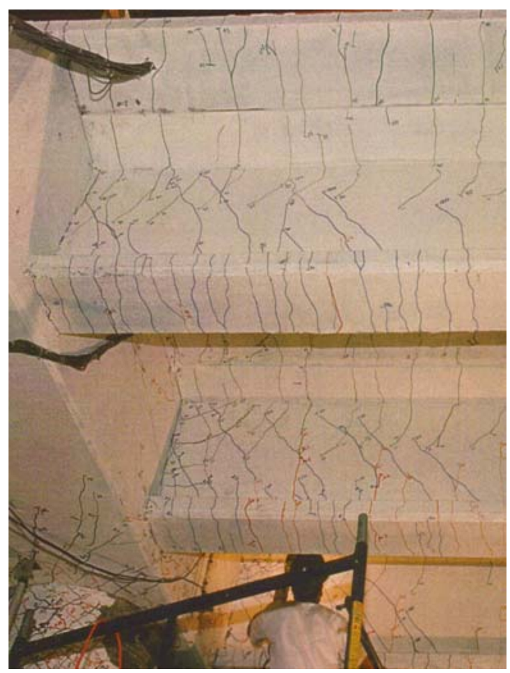


F-d Graph



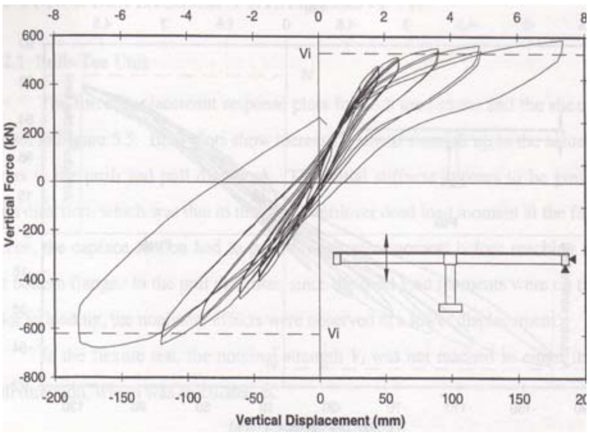
Level III

Level IV

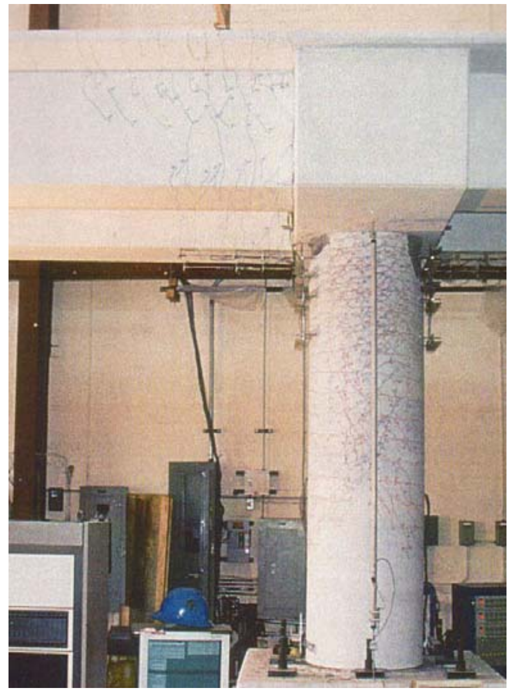


Level IV

SM15 – Flexural - Ductile

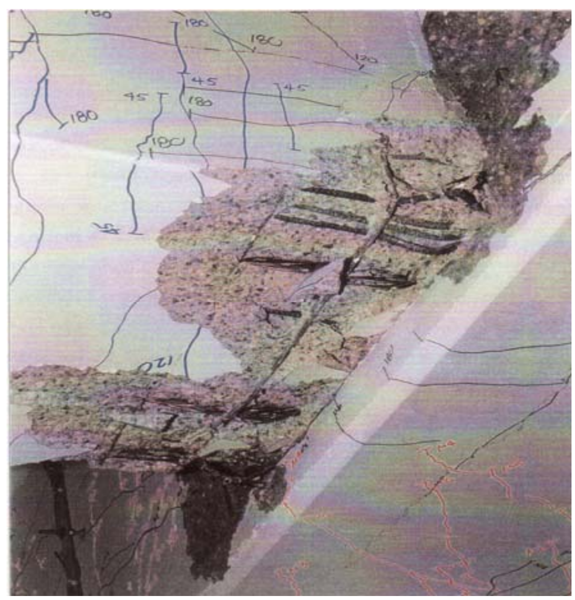


F-d Graph



Level III

Level IV



Level V

Part II

Field photo database - Earthquake events

Classification according to Earthquake

San Fernando, USA 1971

San Fernando, USA 1971

Failure – buckling of long bars

Failure – buckling of long bars

Shear failure

Shear failure

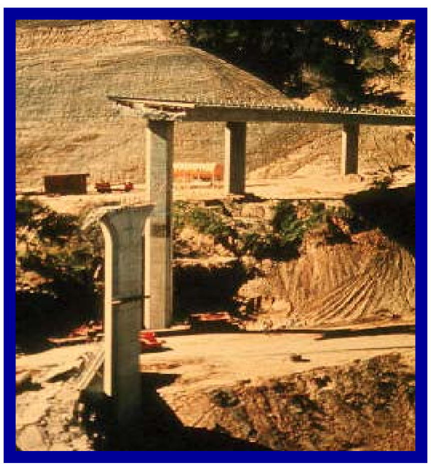
Failure at Column Base

Shear failure

San Fernando, USA 1971

Total failure

Total failure



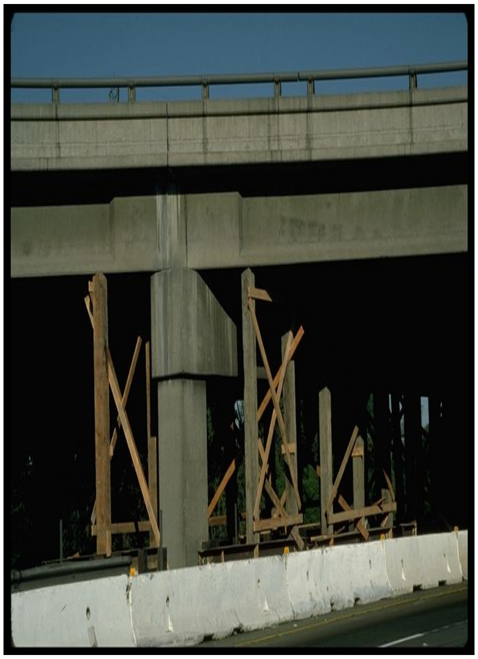
Span failure

Pullout Failure

Exterior shear key failure

Imperial Valley, USA 1979

Imperial Valley, USA 1979

	
	Abutment – Level V
	
Shear- Level V	Abutment – Level V

New River Bridge

Whittier Narrows, USA 1987

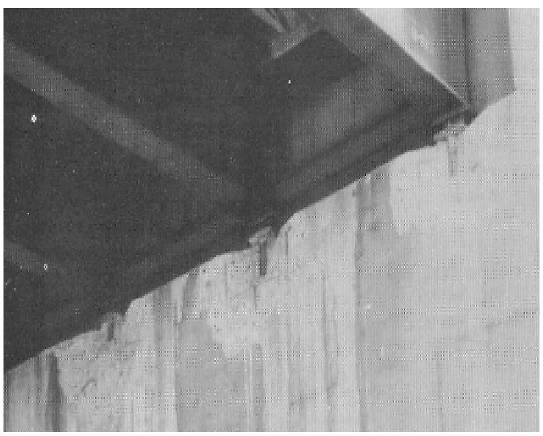
Whittier Narrows, USA 1987

	
Cracks at column-beam interface Level III	Top column spalling –Level II
	
Shear – Level V	Shear – Level V
	
Shear – Level V	Shear – Level V

Whittier Narrows, USA 1987

Joint shear crack- Level V

Cap beam top – bottom spalling –Level III



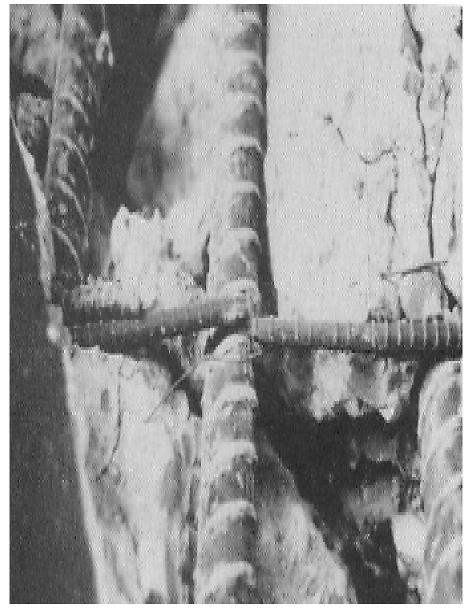
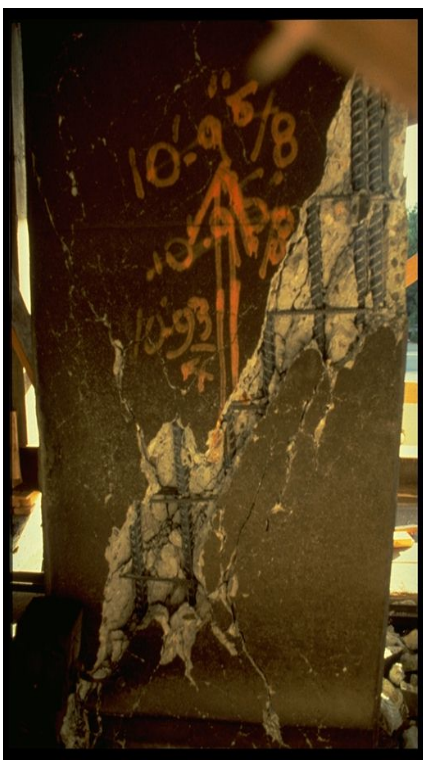
Abutment damage – Level IV

Abutment spalling-Level III

Abutment rocker support keeper plates failure

Superstructure pounding – Level IV

Whittier Narrows, USA 1987

	
Shear Level V	Fractured steel bars Level V
	
Shear Level - V	Shear Level –Level V

Loma Prieta, USA 1989

Loma Prieta, USA 1989

Flexural – Level III

Flexural – Level IV

Shear Level IV

Shear Level IV

Shear Level V

Shear – Level V

Loma Prieta, USA 1989

	
Shear – Level V	Shear – Level V
	
Shear failure	Joint Shear – Level V

Loma Prieta, USA 1989

Shear failure

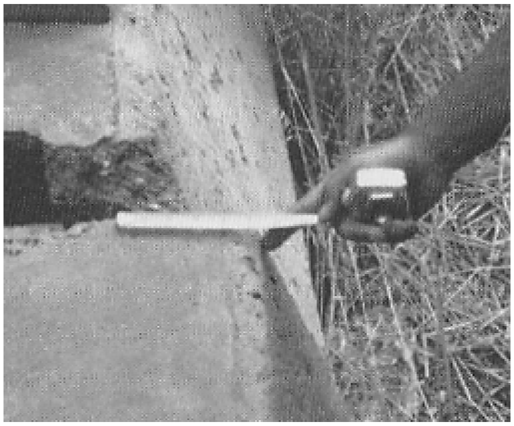
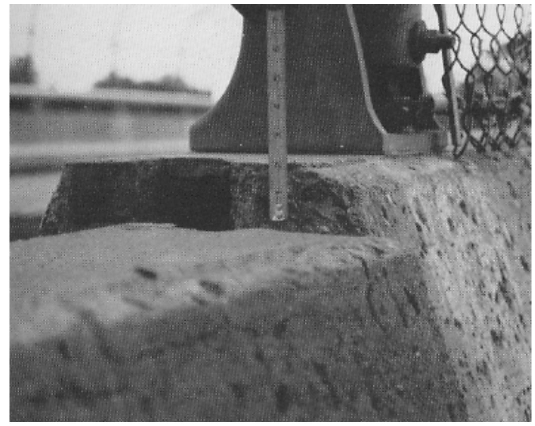
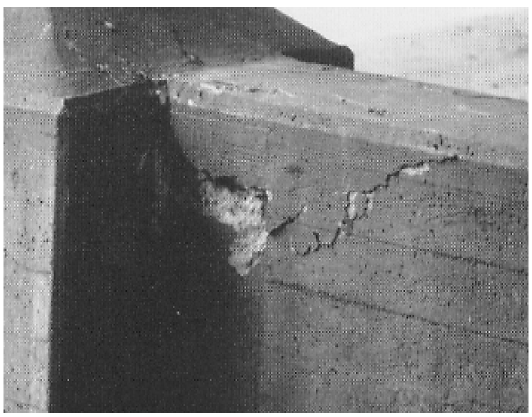
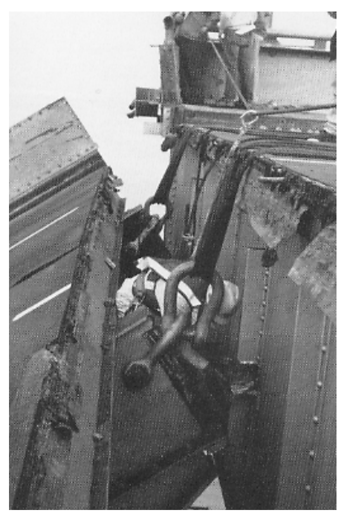
Shear failure

Joint damage – Level V

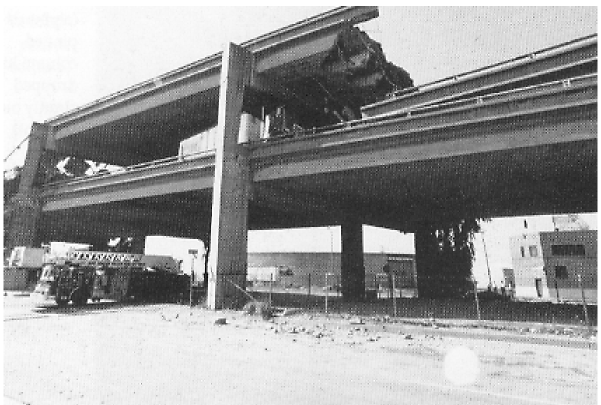
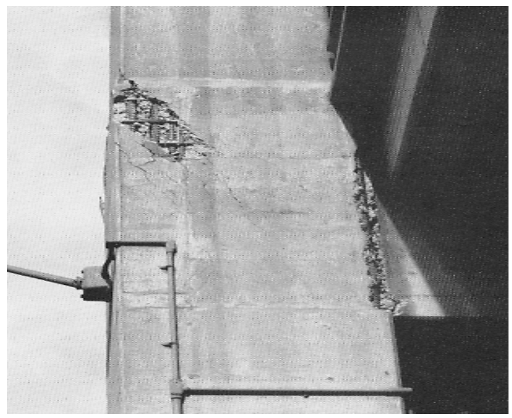
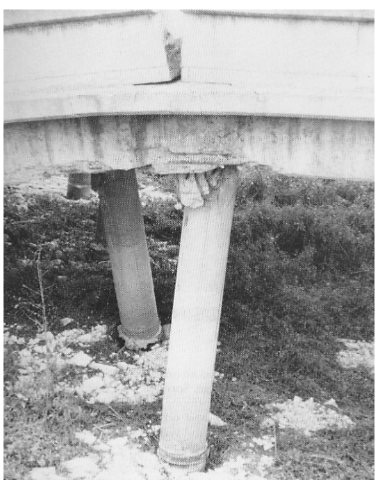
Loma Prieta, USA 1989

	
Joint failure	Joint failure
	
Joint failure	Collapse of girder bridge
	
Total failure	Total failure

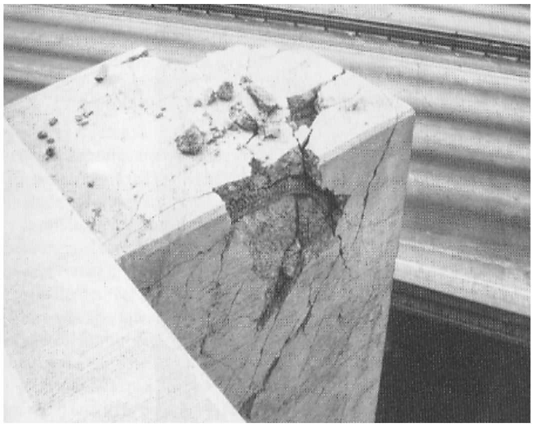
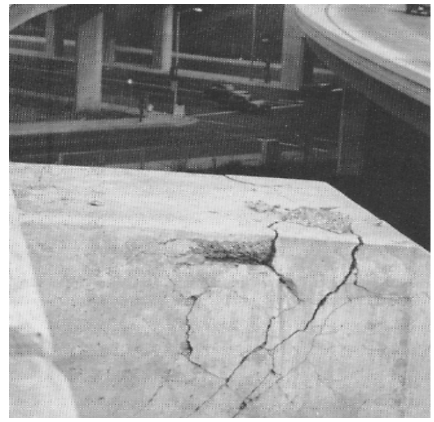
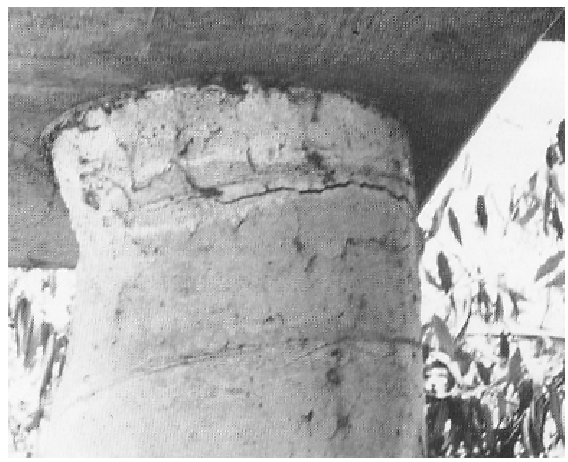
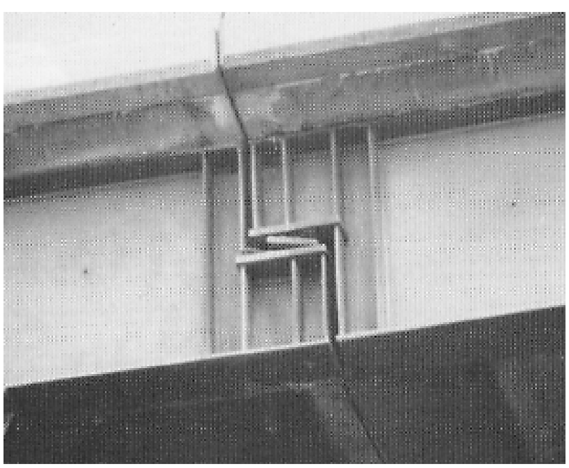
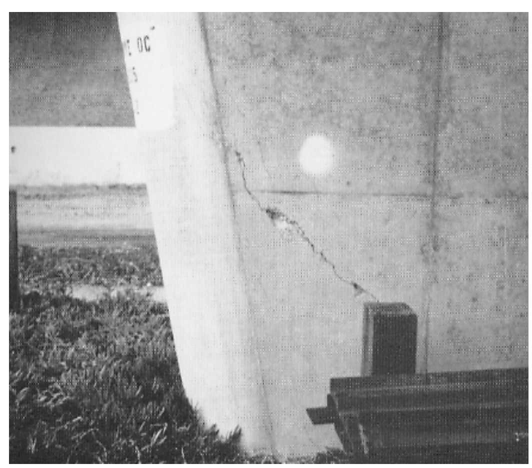
Loma Prieta, USA 1989

	
Abutment horizontal offset – Level V	Abutment vertical offset – Level V
	
Beam damage – Level IV	Total Failure
	
Total Failure	Failure angle seats (Oakland Bay Bridge)

Loma Prieta, USA 1989

	
Total Failure	Collapsed deck (Struve Slough Bridge)
	
Collapsed deck (Cypress Street Viaduct)	Shear cracking- Level IV
	
Lateral Displacement – Level V(Struve Slough)	Deck cut-through by piers (Struve Bridge)

Loma Prieta, USA 1989

	
Joint-Level V	Joint-Level V (I-980)
	
Spalled concrete at base - Level IV	Level V (Corralitos Creek Bridge)
	
Misaligned hinge – Level V	Shear Crack – Level IV (Mora Drive Overpass)

Erzincan, Turkey 1992

Erzincan, Turkey 1992

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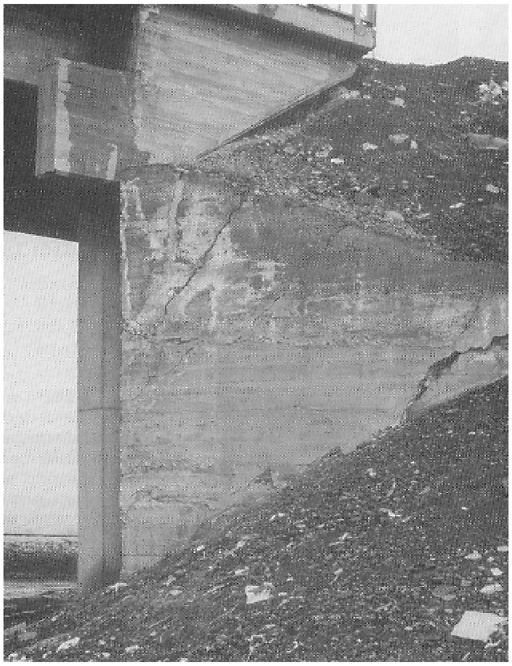
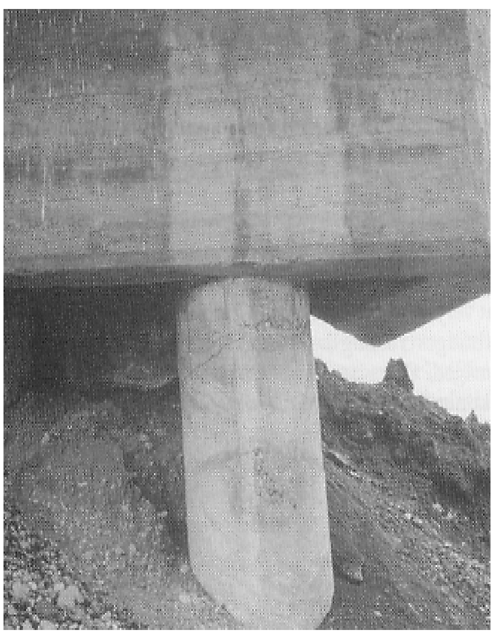
<tr><td></td><td></td></tr>
<tr><td>Cracking of abutment wall – Level IV</td><td>Pounding above piers – Level V</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Shear crack on column – Level IV</td><td></td></tr>
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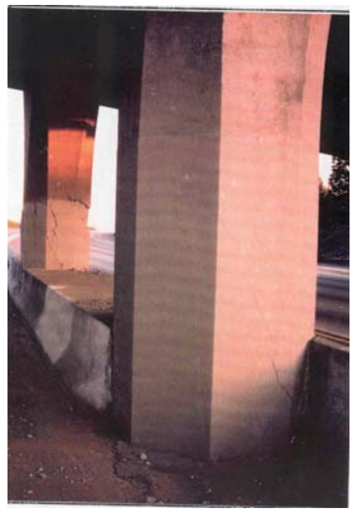
Kemah Highway

Northridge, USA 1994

Northridge, USA 1994

	
Flexural – Level II	Flexural – Level III
	
Flexural Level III	Flexural Level IV
	
Flexural Level IV	

Northridge, USA 1994

	
Shear Level III	Shear Level III
	
Shear Level IV	Shear Level IV
	
Shear – Level IV	Shear – Level V

Northridge, USA 1994

	
Shear Level V	Shear Level V
	
Shear Level V	Shear Level V
	
Shear Level V	Shear Level V

Northridge, USA 1994

	
Shear failure	Shear failure
	
Shear failure	Shear failure
	
Shear failure	Shear failure

Northridge, USA 1994

Column superstructure spalling Level III

Column foundation Flexural Level III

Shear collar failure

Shear collar failure

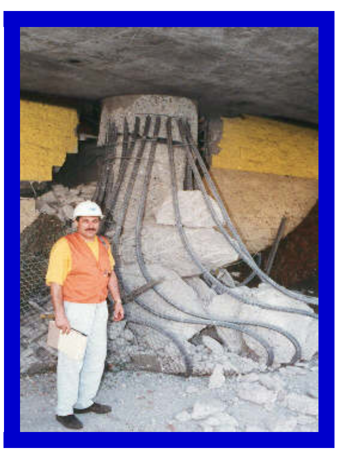
Total Failure

Shear cracks in abutment Level - IV

Northridge, USA 1994

	
Lap splice retrofit	Lap splice retrofit
	
Lap splice retrofit	Lap splice retrofit

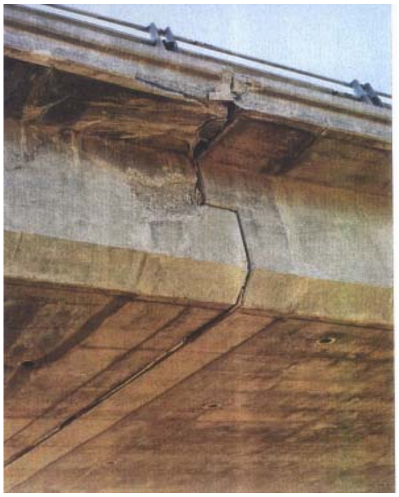
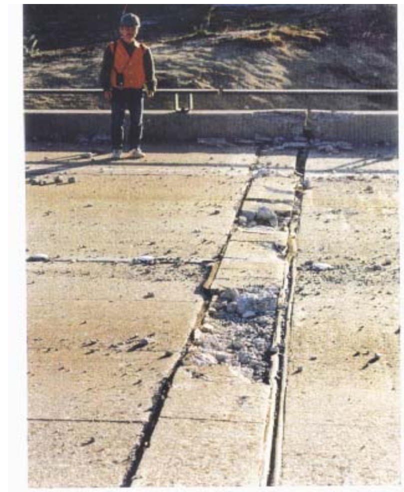
Northridge, USA 1994

	
Shear – Level V	Shear failure
	
Shear – Level V	Shear failure
	
Failure	Shear – Level V

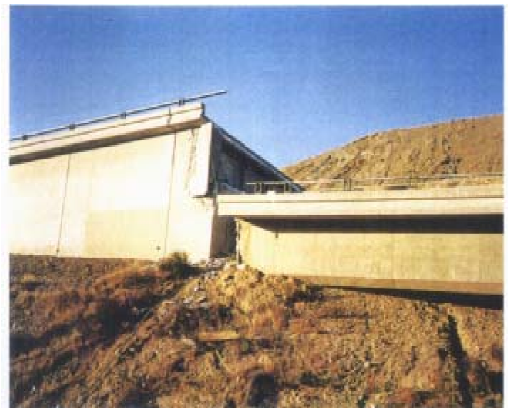
Northridge, USA 1994

	
Total failure	Total failure
	
Total failure	Total failure
	
Total failure	Total failure

Northridge, USA 1994

	
Pounding at movement joint – Level IV	Pounding at movement joint – Level IV
	
Abutment damage- Level IV	Abutment damage-Level V
	
Deck failure	Damaged movement joint – Level IV

Northridge, USA 1994

	
Failure	Abutment – wing - wall failure
	
Abutment failure	Hinge fractured restrainer rods
	
Hinge restrainer pullout	Hinge restrainer pullout close to abutment

Northridge, USA 1994

	
Deck collapse	Abutment Failure
	
Failure of anchor bolts for a girder	Spalling – Level IV
	
Disturbed soil – Level IV	Separation of soil and column- Level V

Northridge, USA 1994

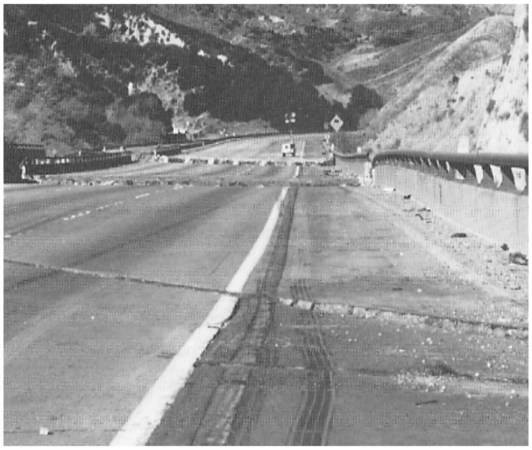
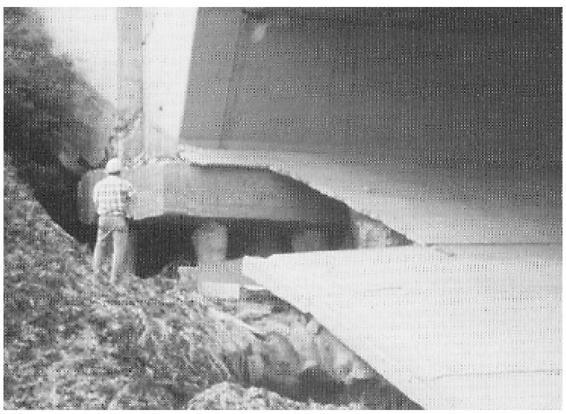
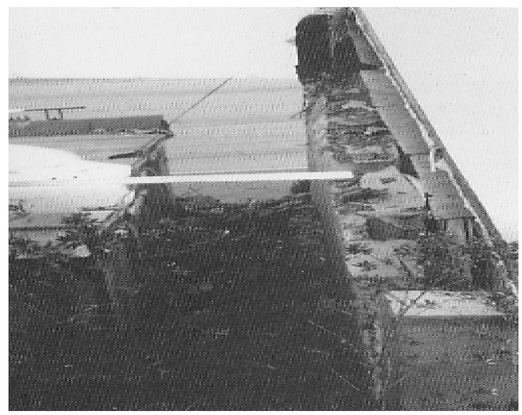
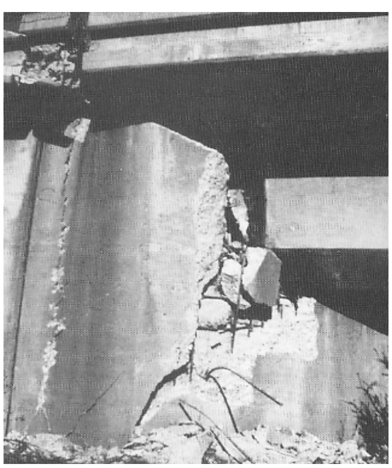
Soil separation

Barrier cracking – Level IV

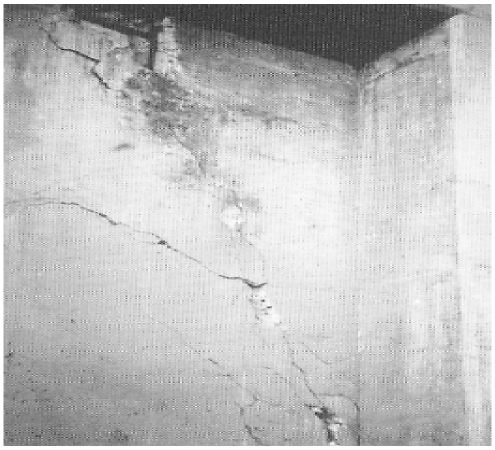
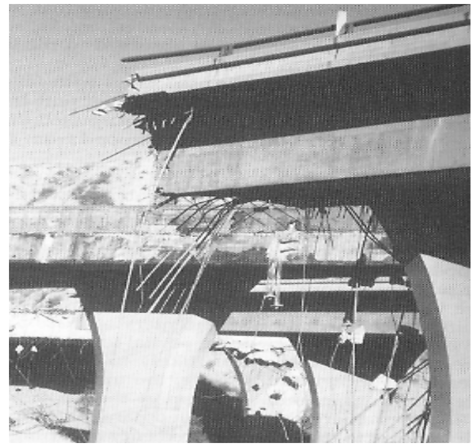
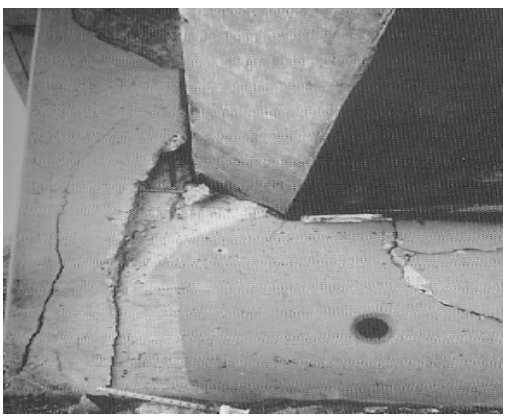
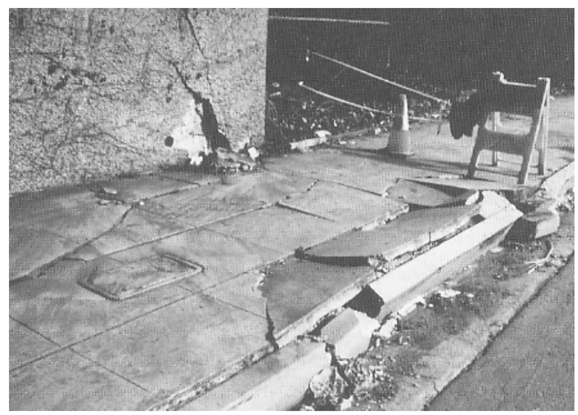
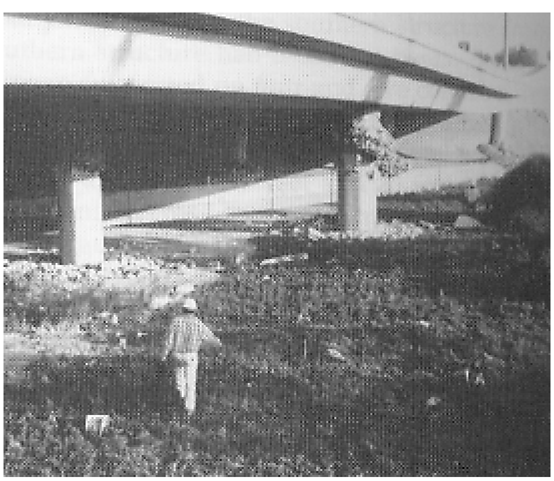
Deck damage- Level IV

Curb separation – Level IV

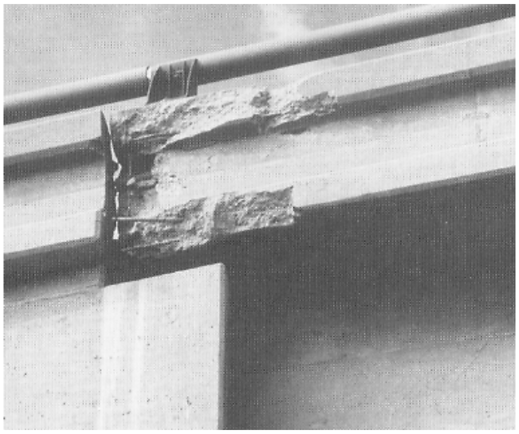
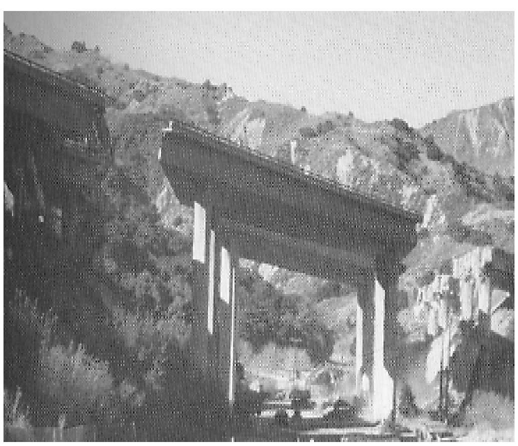
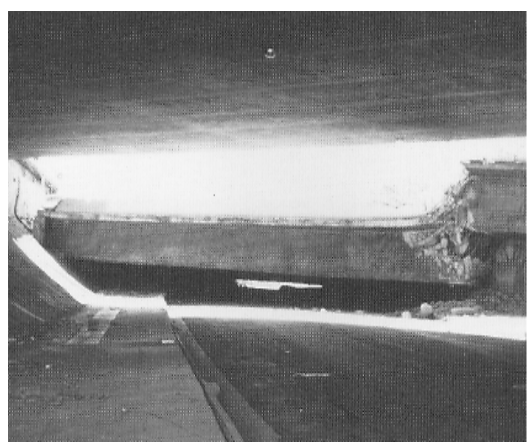
Northridge, USA 1994

	
Joint movement – Level V	Abutment connection cracks –Level V
	
Abutment damage – Level IV	Abutment connection failure
	
Abutment failure	Abutment failure

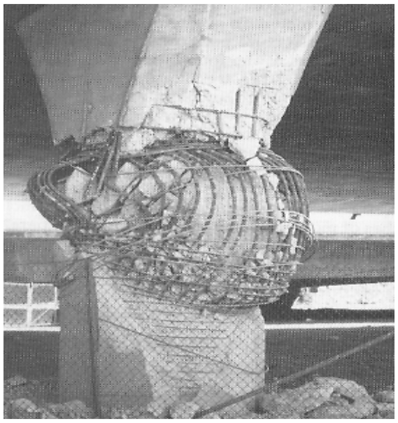
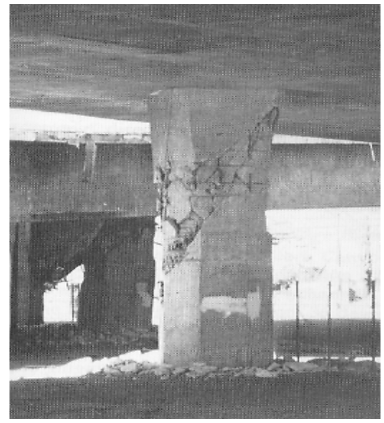
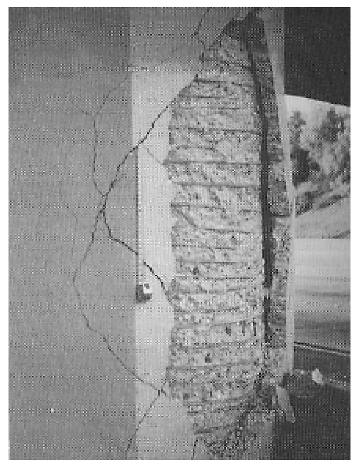
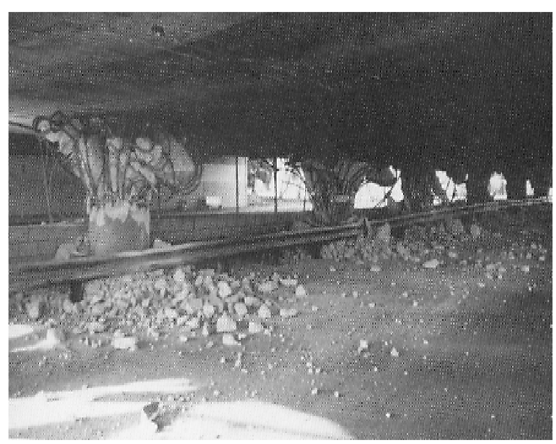
Northridge, USA 1994

	
Abutment – Level V	Deck Collapse
	
Abutment Failure	
	
Column Failure	Column Base Failure

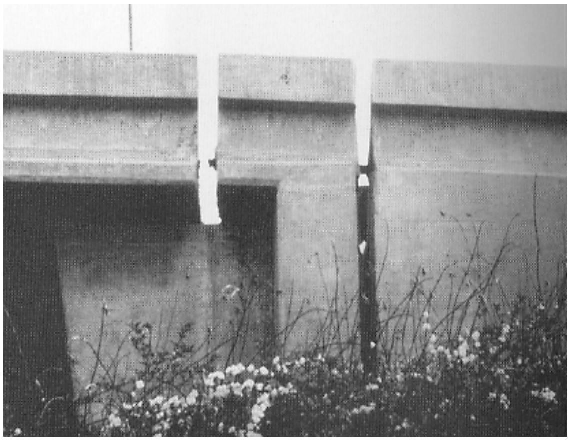
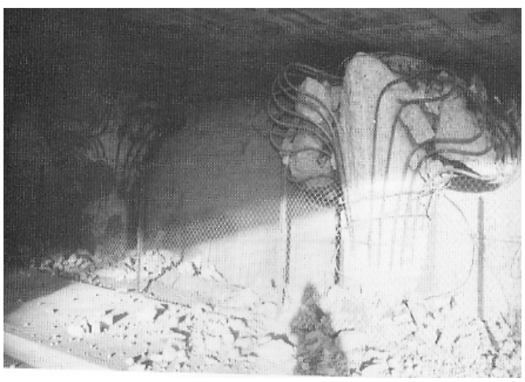
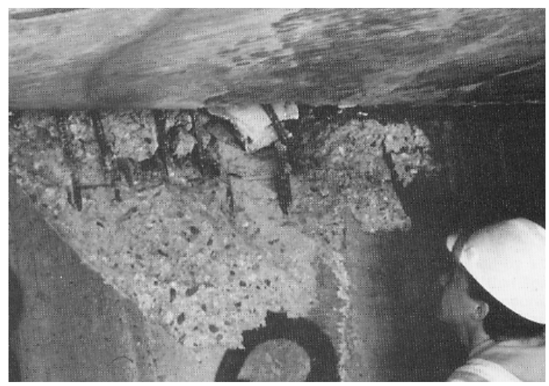
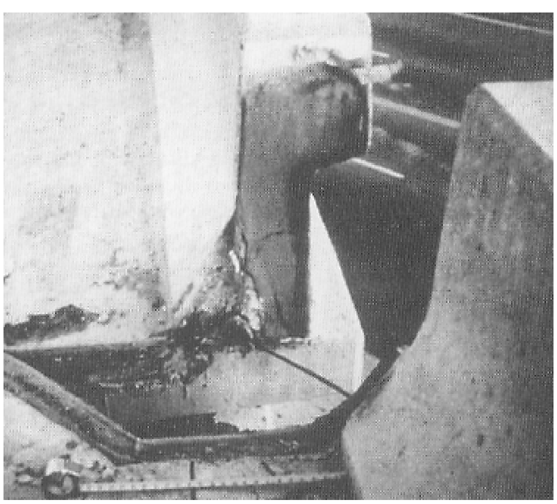
Northridge, USA 1994

	
Superstructure – Level IV	Abutment Failure
	
Total Failure	Span Colapse
	
(Gavin Canyon Undercrossing) –Span Collapse	Deck Collapse

Northridge, USA 1994

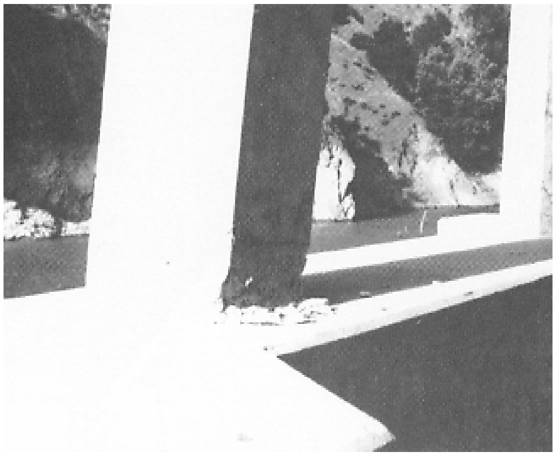
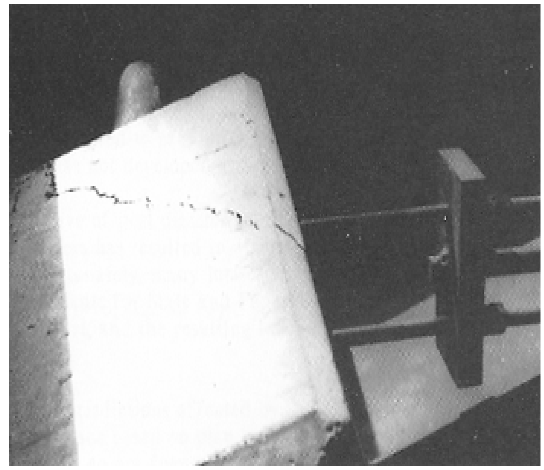
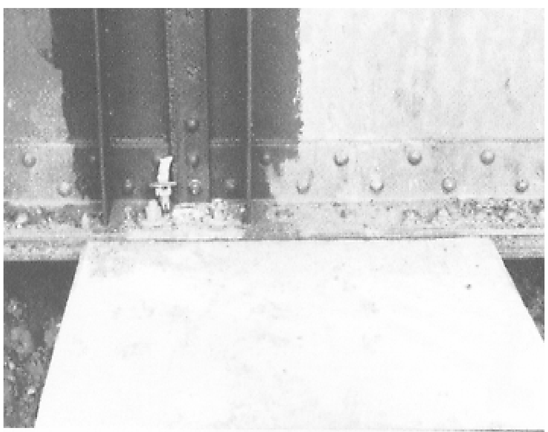
	
Shear Failure	Shear - Level V
	
Shear Level V	Shear Level V
	
Column Failure	Column Failure

Northridge, USA 1994

	
Deck and Abutment displacements – Level V	Deck Failure
	
Column Failure	Internal Shear keys damage –Level V
	
Abutment/Deck displacement – Level V	Abutment – Level V

Morgan Hill, USA 1994

Morgan Hill, USA 1994

	
Column – Level V	Abutment Restrainer Failure
	
Sheared off bolts	

Highway Bridge

Kobe, Japan 1995

Kobe, Japan 1995

Flexural level IV

Flexural level IV

Shear Level V

Shear Level V

Shear Level V

Shear failure

Kobe, Japan 1995

Shear failure

Shear failure

Shear failure

Shear failure

Shear failure

Shear failure

Kobe, Japan 1995

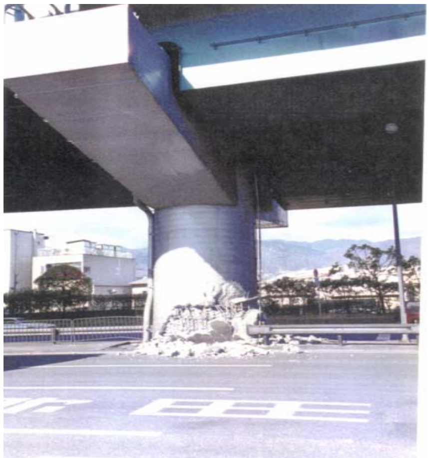
Shear failure

Shear failure

Shear failure

Shear failure

Kobe, Japan 1995



Shear failure

Total failure

Total failure

Total failure

Column failure

Total failure

Kobe, Japan 1995

	
Total failure	Column Weld failure
	
Total failure	Total failure
	
Total failure	Total failure

Kobe, Japan 1995

	
Totral failure	Total failure-Weld failure
	
Total failure-permanent deformation	Girder failure

Adana-Ceyhan 1998

Adana-Ceyhan 1998

	
	Superstructure- Level IV
	
Superstructure- Level V	Superstructure- Level IV

The Ceyhan Bridge

Izmit, Turkey 1999

Izmit, Turkey 1999

Total failure

Abutment-Level III

Abutment-Level III

Abutment-Level III

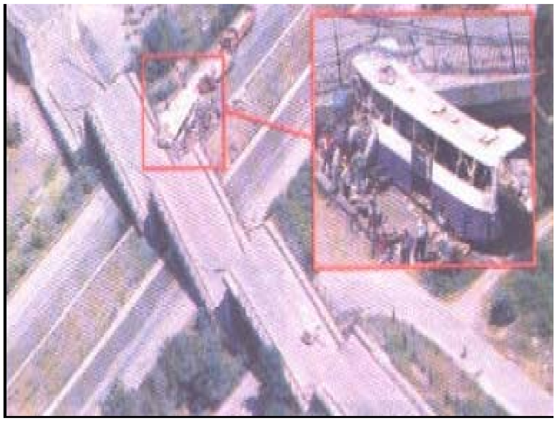
Span Collapse

Failure of bearing pad

Izmit, Turkey 1999

	
Superstructure-Level V	Abutment-Level V
	
Superstructure-Level V	Superstructure-Level V
	
Superstructure-Level V	Transversal movement – Level V

Izmit, Turkey 1999

	
Total failure-prestressed beam girder bridge	Spalling due to Girder impact –Level IV

Duzce, Turkey 1999

Duzce, Trukey 1999

	
Slope failure	Longitudinal movement-Level V

Chi-Chi, Taiwan 1999

Chi-Chi, Taiwan 1999

	
Flexural – Level V	Rupture of long reinforcement at joint
	
Joint column damage Level IV	Reinforcement fracture
	
Shear failure	Shear Failure

Chi-Chi, Taiwan 1999

	
Column shear-off	Separation at construction joint
	
Superstructure drop off	Column failure to excessive ground movement
	
Spans separation	Ground separation near pier

Chi-Chi, Taiwan 1999

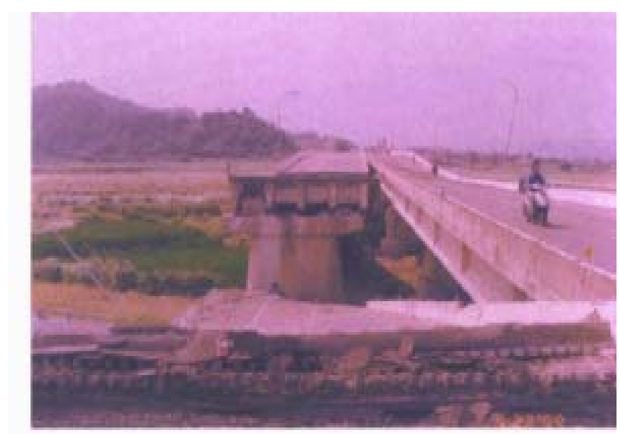
Abutment slumping

Wing wall and embankment failure

Permanent deck transverse displacement – Level V

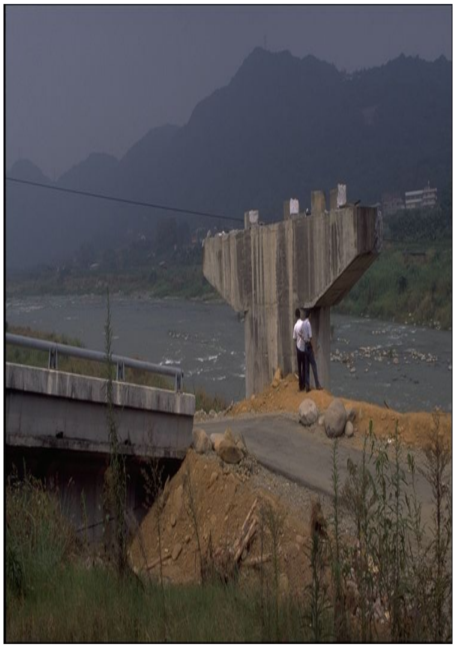
Soil liquefaction around pier

Uneven bridge deck due to pier settlement

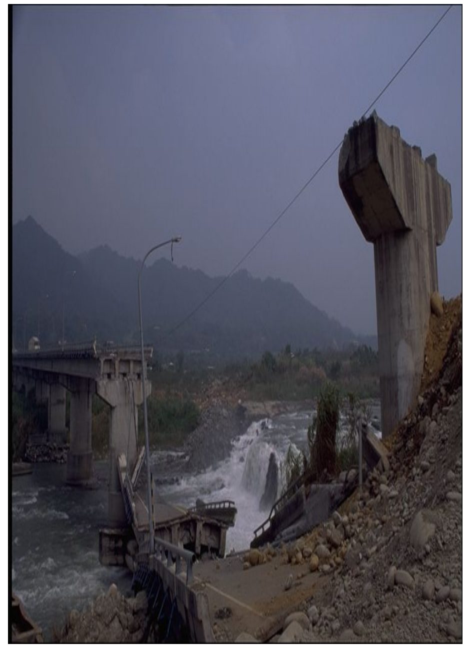


Unseating of superstructure

Chi-Chi, Taiwan 1999

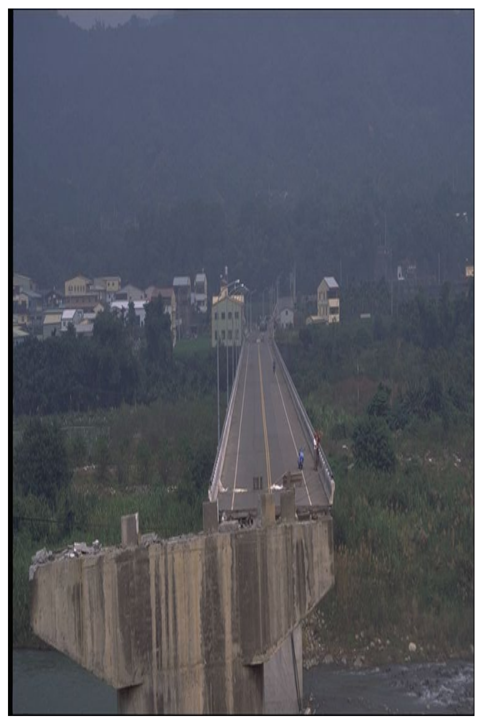


Unseating of Superstructure



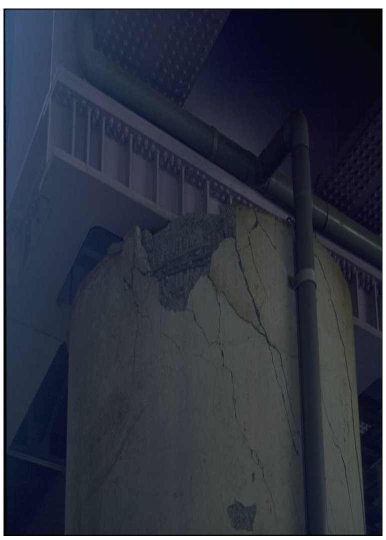
Unseating of Superstructure

Unseating of Superstructure



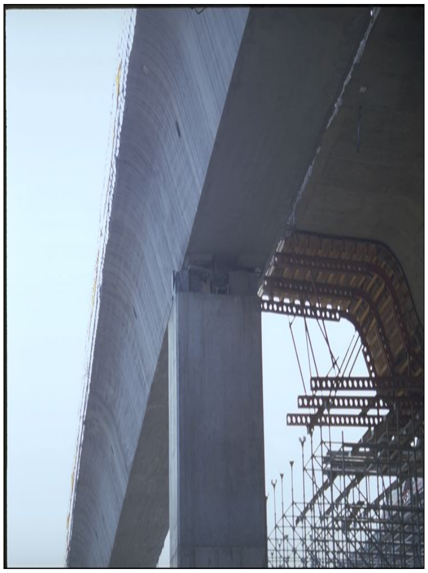
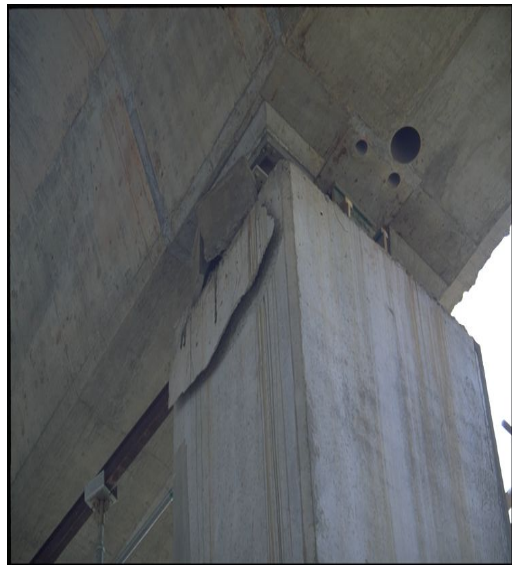
Unseating of Superstructure

Chi-Chi, Taiwan 1999

	
Shear cracking-Level IV	Shear cracking-Level IV
	
Shear cracking-Level IV	

Mau-uo-Shi Bridge

Chi-Chi, Taiwan 1999

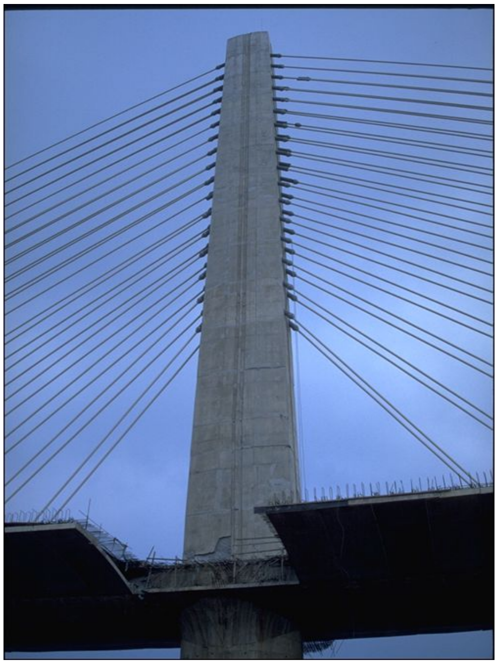
	
Column Damage, Level V	Column, Bearing Damage, Level V
	
Lateral movement - Level V	Bearing Damage – Level V

Chi-Chi, Taiwan 1999

	
	Shear-Level V
	
Shear-Level V	Total Failure
	
Unseating of Superstructure	Shear-Level IV

I-jiang Bridge

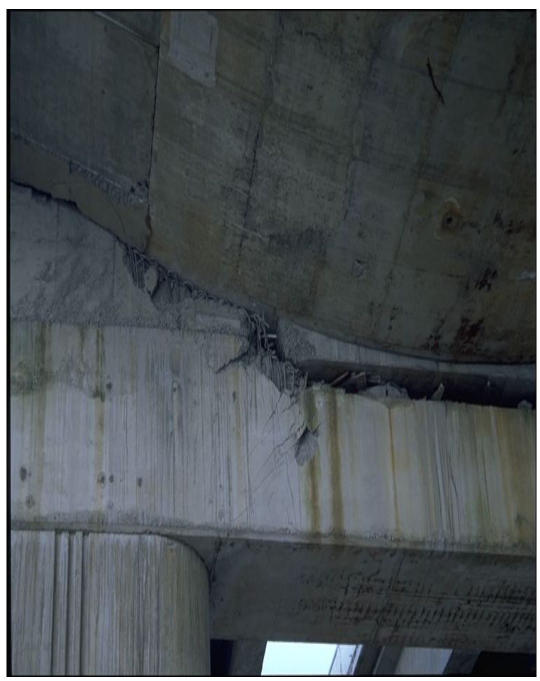
Chi-Chi, Taiwan 1999



Superstructure Failure

Superstructure Failure

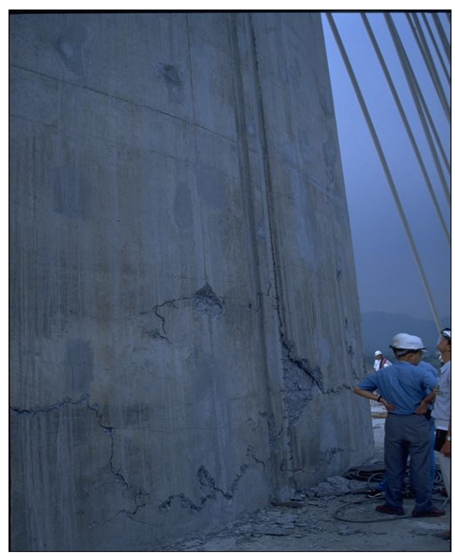
Excessive movement-Level V



Cap Beam-Superstructure-Level V

Jyi Lu Bridge

Chi-Chi, Taiwan 1999

	
Cap Beam-Superstructure-Level V	Column-Shear-Level IV
	
Column-Shear-Level IV	Column-Shear-Level IV

Jyi Lu Bridge

Chi-Chi, Taiwan 1999

Total Failure

Total Failure

Total Failure

Total Failure

Total Failure

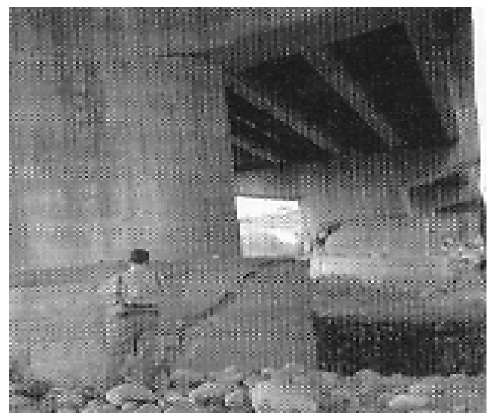
Shih-Wui Bridge

Chi-Chi, Taiwan 1999

	
Total Failure	Total Failure
	
Total Failure	

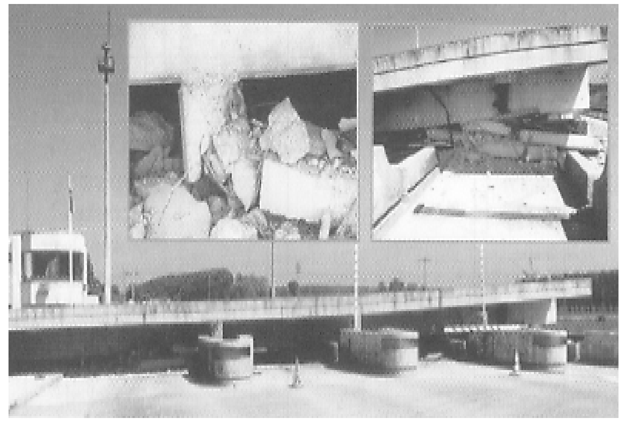
Ming Ju Bridge

Chi-Chi, Taiwan 1999

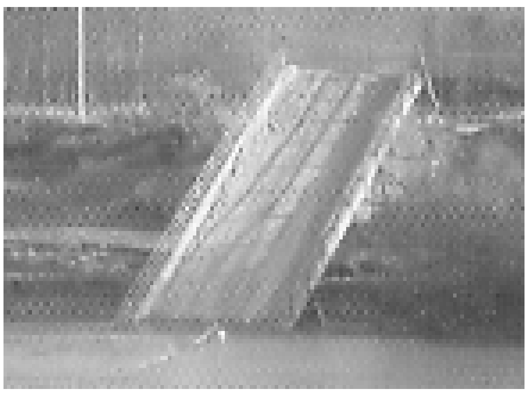
	
Total Failure	Expansion of joints-Level V
	
Shear-Level V	Shear Failure (Wu Shu Bridge)
	
Total Failure (Pin ling bridge)	

Kocaeli, Turkey 1999

Kocaeli, Turkey 1999

	
Deck failure (tectonic compression zones)	Shear Failure
	
Deck failure	Abutment failure (TEM bridge)
	
Abutment damage (Sakarya River)	Deck failure

Kocaeli, Turkey 1999

<table>
<tr><td></td><td></td></tr>
<tr><td>Level IV -Displaced spans (TEM Sakarya Viaduct)</td><td>Total Failure (TEM Arifiye Road Bridge)</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Total Failure (Sakarya Bridge)</td><td></td></tr>
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Mid Niigata Prefecture Earthquake, Japan 2004

Mid Niigata Prefecture Earthquake, Japan 2004

Shear-Level V

Shear-Level V

Shear-Level V

Shear-Level V

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Mid Niigata Prefecture Earthquake, Japan 2004

	
Shear-Level V	Shear-Level V
	
Shear-Level V	Shear-Level V

Mid Niigata Prefecture Earthquake, Japan 2004

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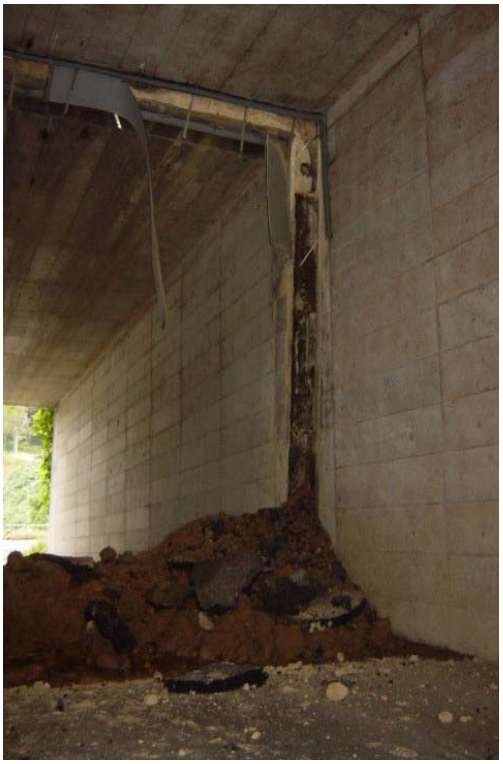
<tr><td>Abutment-Level V</td><td>Abutment-Level V</td></tr>
<tr><td></td><td></td></tr>
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Classification according to type of Damage

Columns

Flexural Damage

Flexural Damage

	
Level III	Level V
	
Level V	Failure
	
Level II	Level III

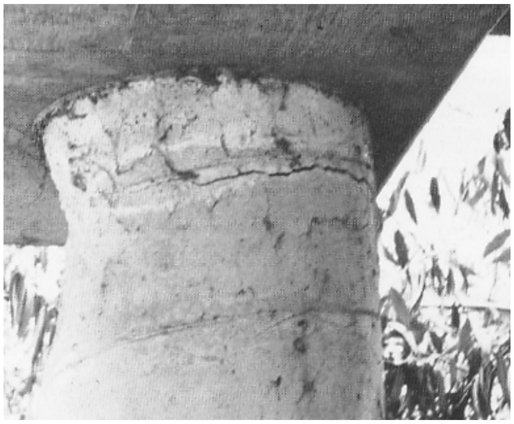
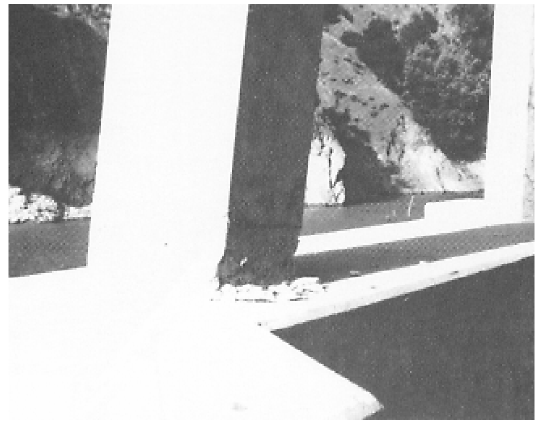
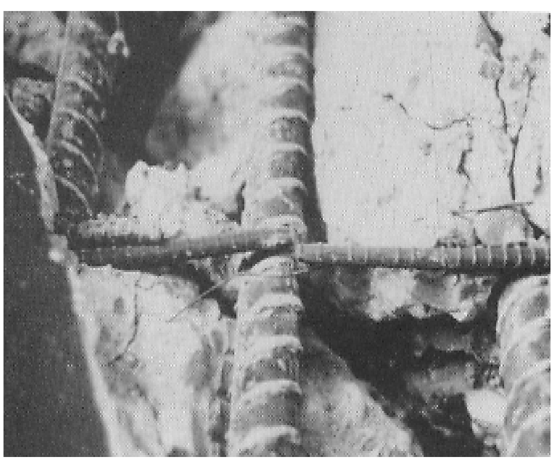
Flexural Damage

	
Level II	Level IV
	
Level II	Level III
	
Level III	Level IV

Flexural Damage

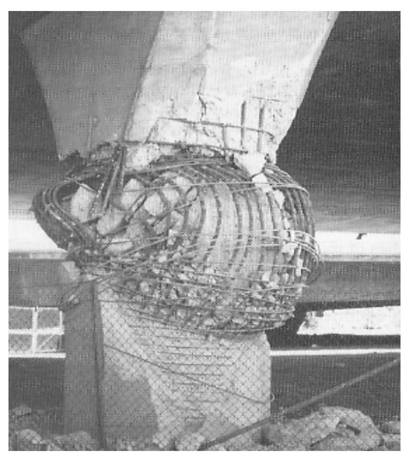
	
Level IV	Level III
	
Level IV	Level IV
	
Level V	Level III

Flexural Damage

	
Level III	Level V
	
Failure	Level V
	
Level V Fractured steel bars	Failure

Shear Damage

Shear Damage

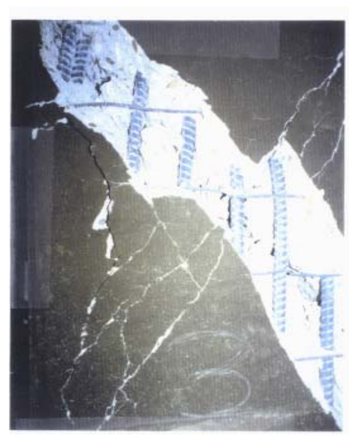
	
Failure	Failure
	
Failure	Failure
	
Failure	Failure

Shear Damage

Fialure

Level V

Level V

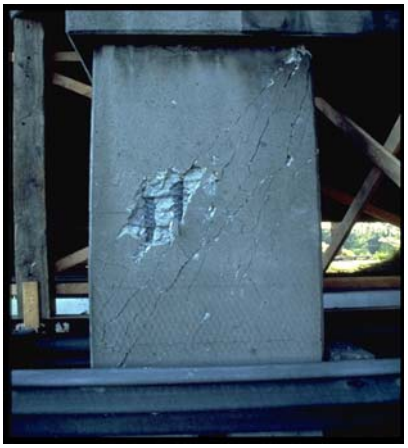
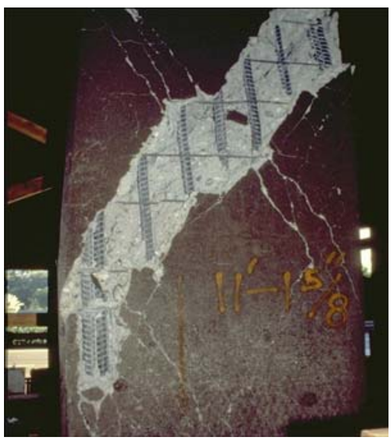
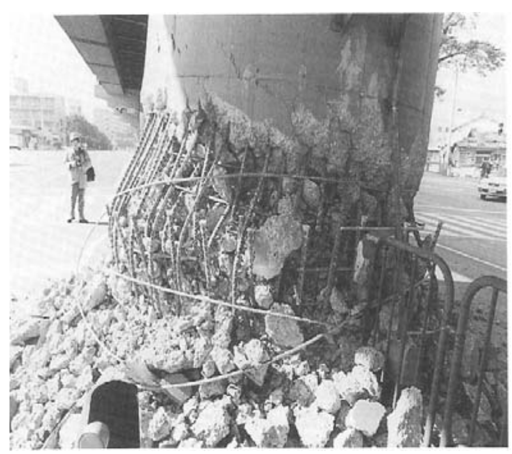


Level V

Level V

Level V

Shear Damage

	
Level V	Level V
	
Level V	Level V
	
Failure	Weld Failure

Shear Damage

	
Level IV	Level III
	
Level III	Level IV
	
Level IV	Level IV

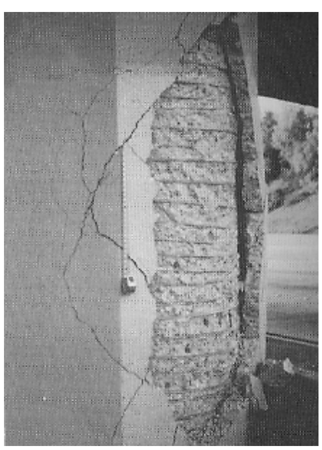
Shear Damage

	
Level V	Level V
	
Level V	Level V
	
Level V	Level V

Shear Damage

	
Failure	Failure
	
Failure	Failure
	
Failure	Failure

Shear Damage

<table>
<tr><td></td><td></td></tr>
<tr><td>Level V</td><td>Failure</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Level IV</td><td>Failure</td></tr>
<tr><td></td><td></td></tr>
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Shear Damage

Level V

Shear collar failure

Level V

Level V

Level V

Level V

Shear Damage

Failure

Failure

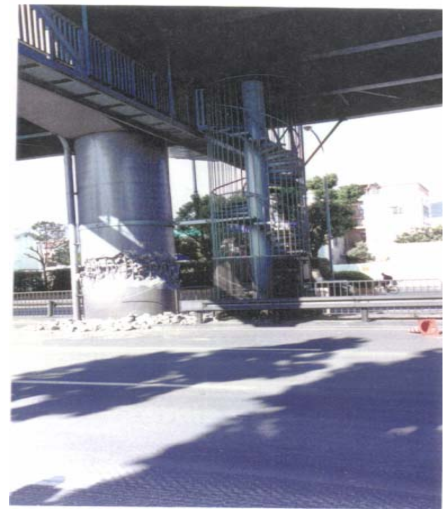
Failure

Failure

Failure

Failure

Shear Damage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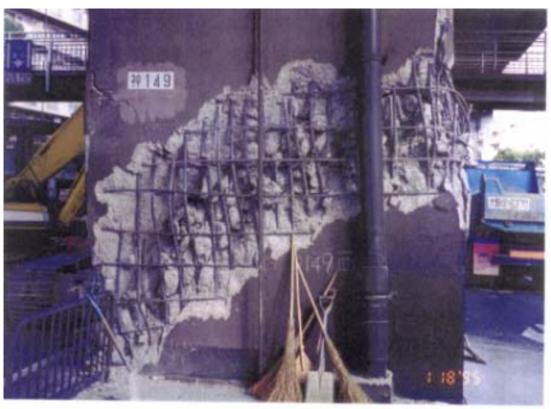
	
Level V	Level V
	
Failure	Failure

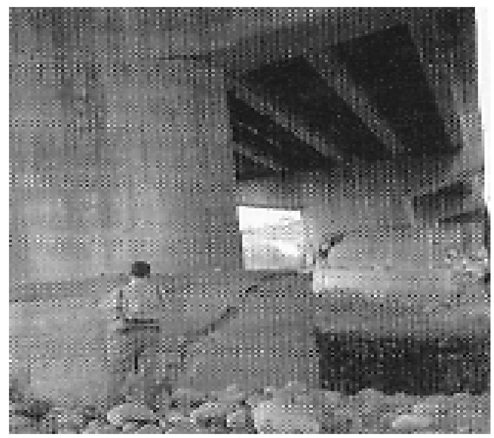
Shear Damage

	
Failure	Level V
	
Level V	Level IV
	
Level IV	Level V

Shear Damage

	
Level V	Level V
	
Level V	Level V
	
Level V	Level V

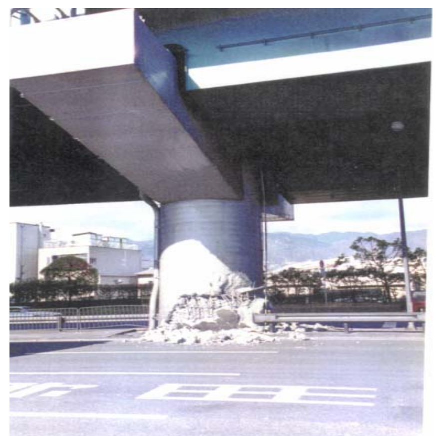
Shear Damage

	
Level IV	Level V
	
Level IV	Level V
	
Level IV	Failure

Shear Damage

	
Total failure	Total failure
	
Failure	Total failure
	
Failure	Level IV

Shear Damage

	
Level V	Failure
	
Failure	Level V
	
Level IV	Level IV

Shear Damage

Failure

Total failure

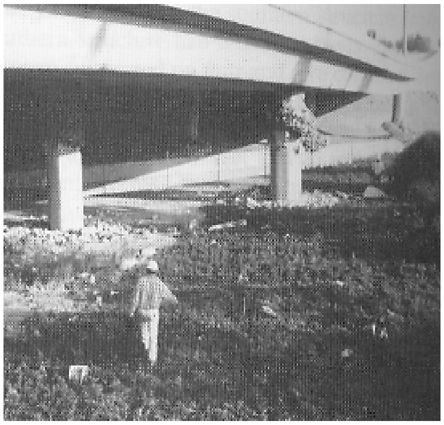
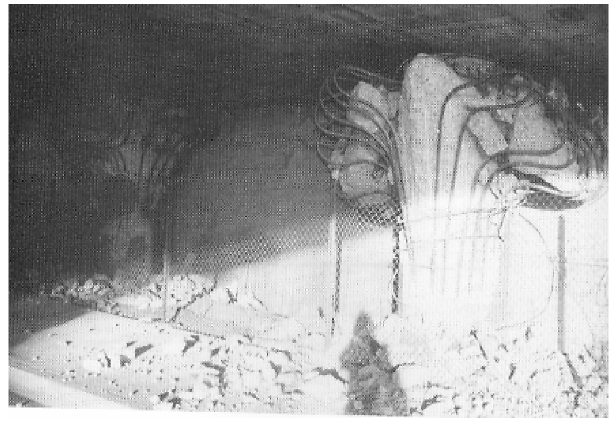
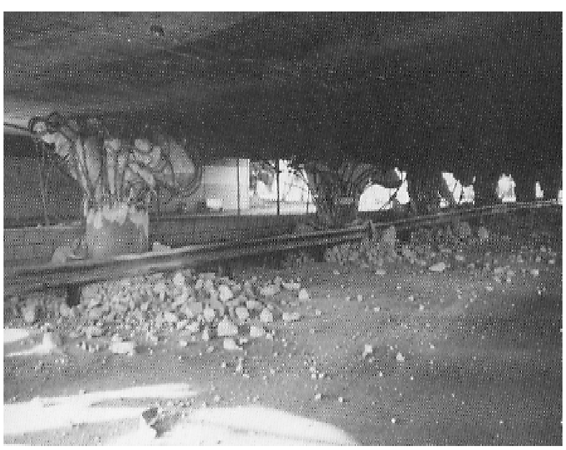
Total failure

Total failure

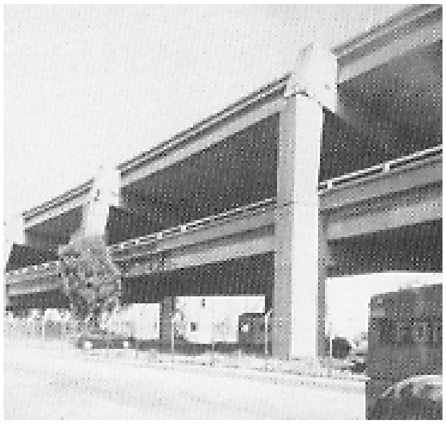
Total failure

Total failure

Shear Damage

	
Failure	Failure
	
Failure	Failure
	
Failure	Failure

Shear Damage

	
Failure	

Retrofit

Retrofit

Lap splice retrofit

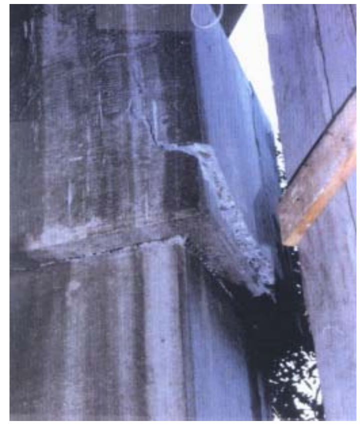
Lap splice retrofit

Lap splice retrofit

Lap splice retrofit

Joint Damage

Joint Damage



Joint-Shear Crack Level V

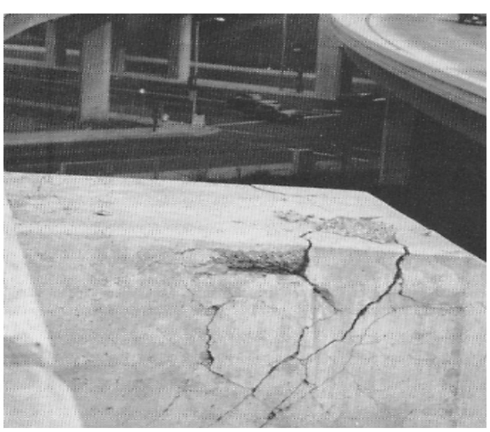
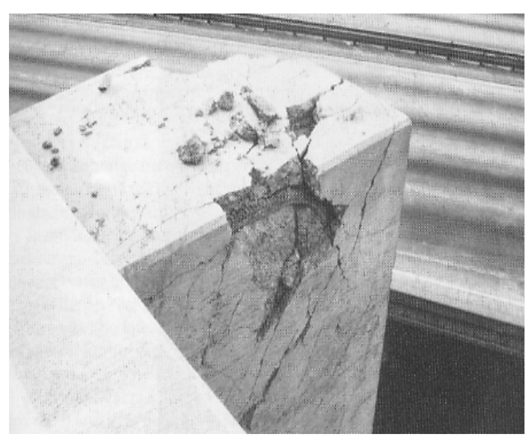
Level IV

Level V

Level V

Level V

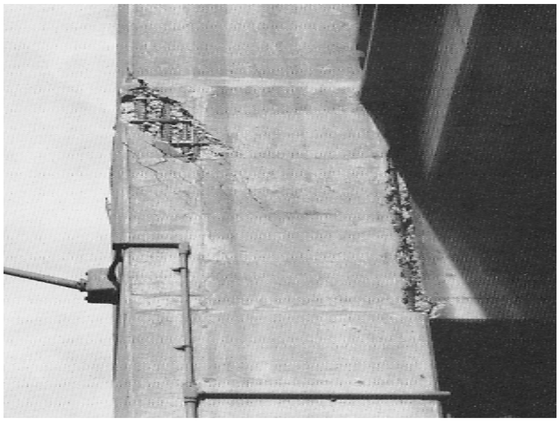
Joint Damage

	
Level V	Column Foundation Pedestal – Level V
	
Column Girder Interface – Level V	Level IV
	
Level V	Level V

Joint Damage

	
Level V	Level V
	
Level V	Level V
	
Joint Shear Failure	Level IV

Joint Damage

	
Level V	

Superstructure

Deck Damage

Deck Damage

Curb separation – Level IV

Barrier cracking – Level IV

Level IV

Level IV

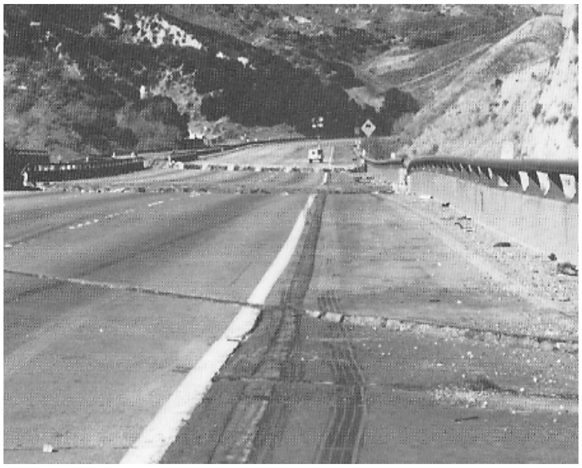
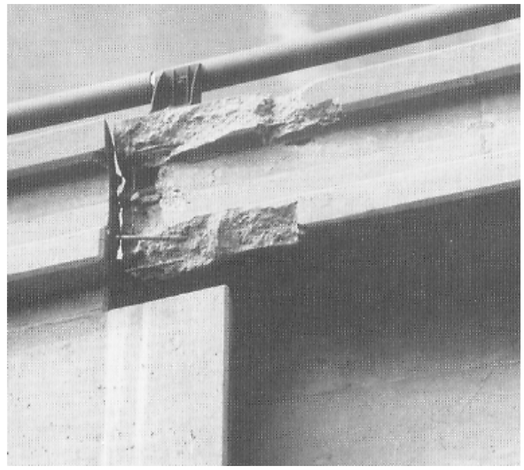
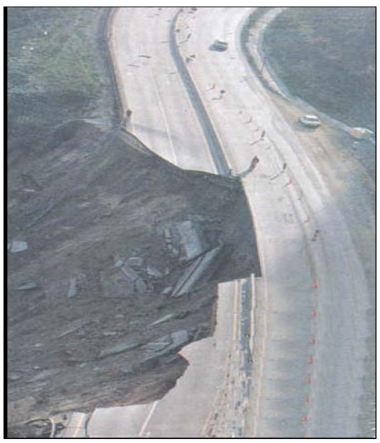
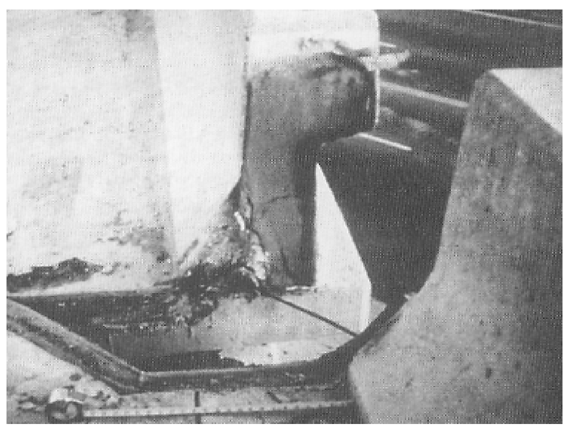
Uneven deck due to pier settlement – Level V

Deck failure (tectonic compression zones)

Deck Damage

	
Failure	Failure
	
Level IV	Level V
	
Deck cut-through by piers	Level V

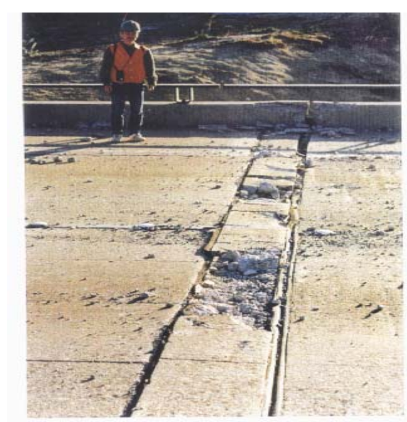
Deck Damage

	
Level V	Level IV
	
Slope failure causes road collapse	Deck and Abutment displacements – Level V
	
Girder bridge collapse	Abutment/Deck displacement – Level V

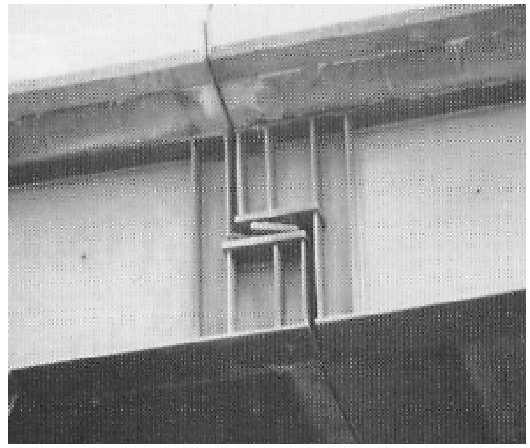
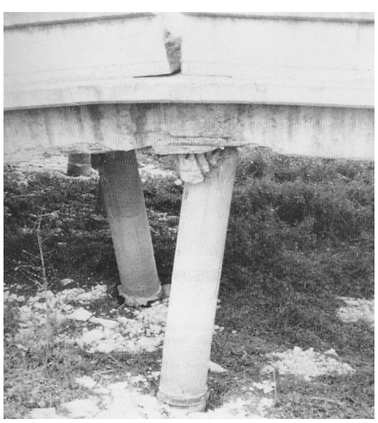
Deck Damage

	
Failure of deck	Level V
	
Level IV	Level V
	
Level IV	Level V

Deck Damage

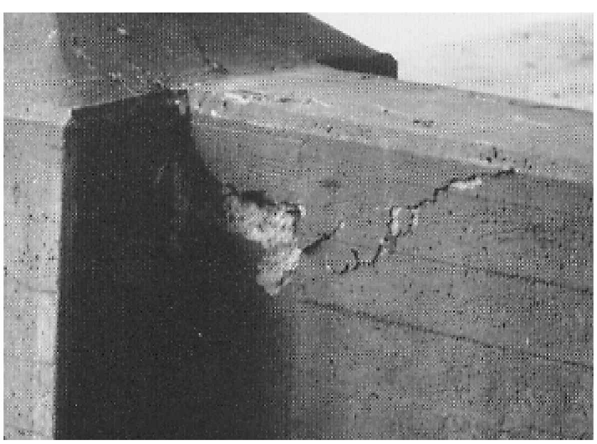
	
Failure	Failure
	
Collapse of girder bridge	Failure
	
Level III	Level IV

Deck Damage

	
Pounding above piers – Level V	Level V
	
Level V	Level V – Expansion of joints
	
Lateral Displacement – Level V	

Cap Beam/Girder

Cap Beam/Girder

	
Buckling – Level V	Level V
	
Level V	Girder Failure
	
Level V	Girder-Level V

Cap Beam/Girder

	
Bottom Spalling Level III	Separation abutment superstructure –Level V

Span Collapse

Span Collapse

Span Collapse

Span Collapse

Span Collapse

Span Collapse

Collapsed span

Span Collapse

Span Collapse

Span Collapse

Span Collapse

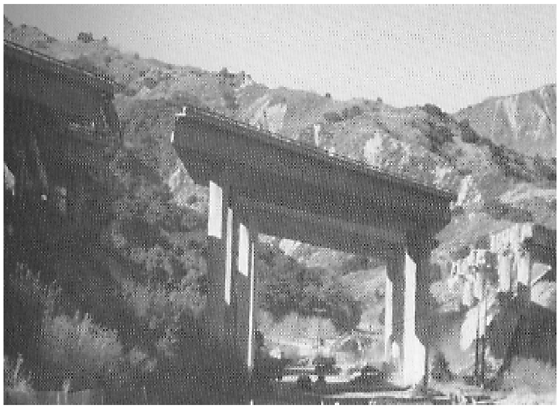
Span Collapse

Span Collapse

Span Collapse

Span Collapse

Span Collapse

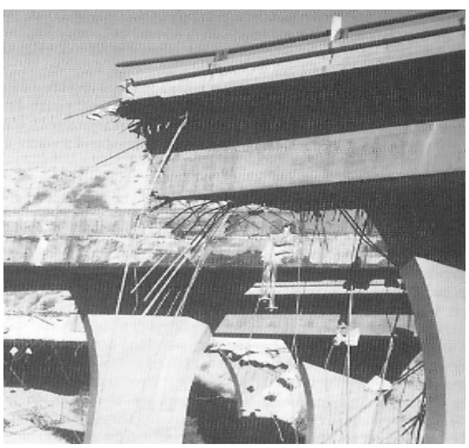


Span Collapse

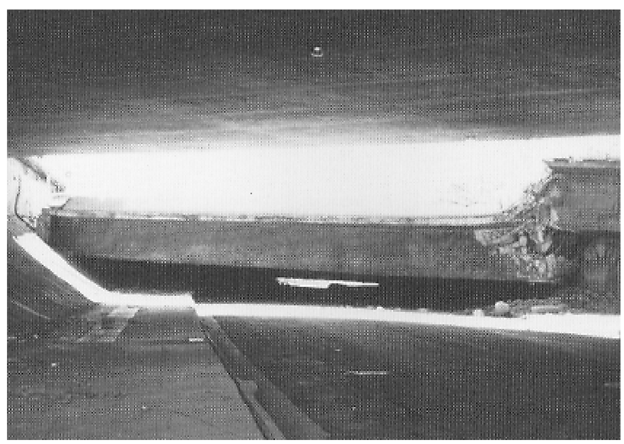
Span Collapse (TEM Arifiye Road Bridge)

Span Collapse

Span Collapse

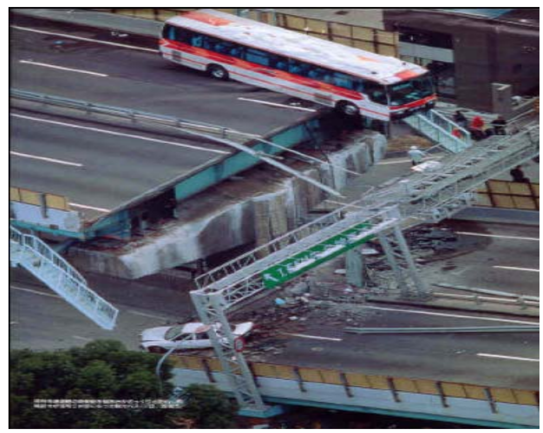


Span Collapse Pin ling bridge



Span Collapse

Span Collapse

	
Span Collapse	Collapsed span
	
Collapsed span	Steel deck collapse

Movement

Movement

	
Lateral movement - Level V	Movement Level IV
	
Movement Level V	Movement Level IV
	
Movement Level V	Movement Level V

Movement

Movement Damaged angle seats

Movement Level V

Movement Level V

Movement Level V

Movement Level V

Movement Level IV

Movement

	
Movement Level IV	Level V Longitudinal movement
	
Level V- Transversal movement	Excessive movement – Level V
	
Level V– Longitudinal movement	

Foundations/Soil Damage

Foundations/Soil Damage

	
Ground crack under a bridge	Soil liquefaction around pier
	
Settlement around bridge column	10 cm. gap between column and soil- Level V
	
Ejected sand	Soil failure due to fault line

Foundations/Soil Damage

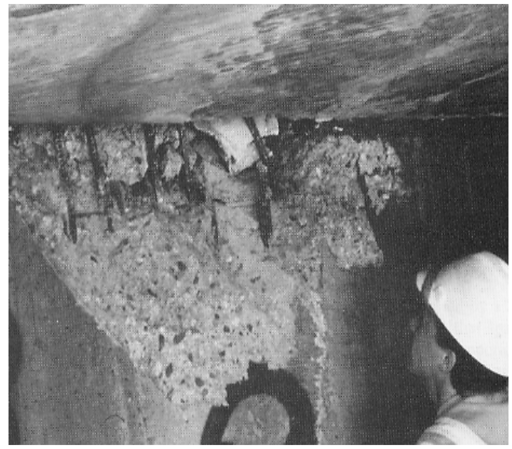
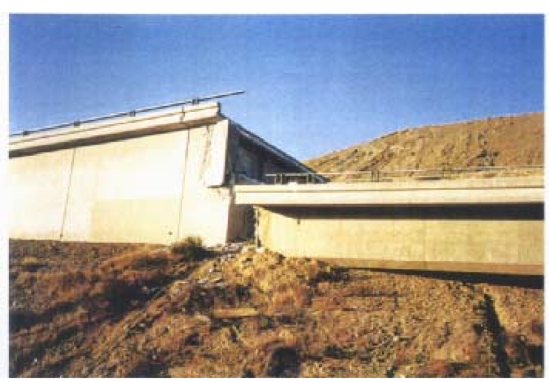
	
	
	

Abutments/Shear Keys

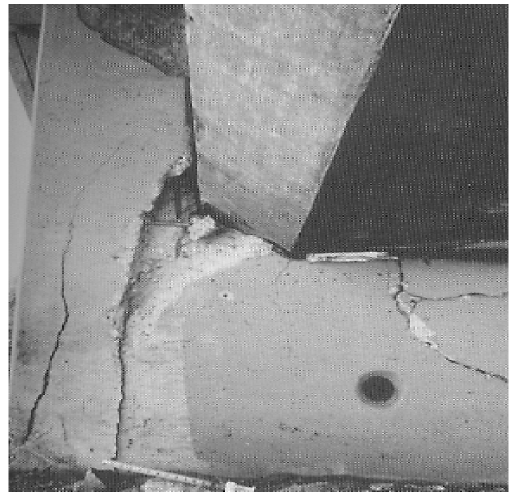
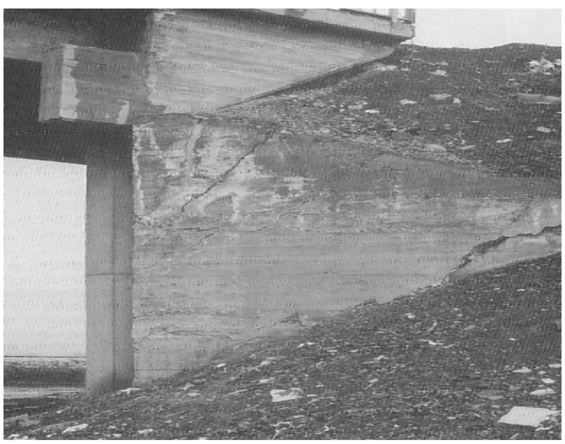
Abutments/Shear Keys

	
Level V	Level IV
	
Level V	Level V
	
Level V	Level III

Abutments/Shear Keys

	
	Internal Shear Keys
	
Failure	Level IV
	
Level V	Failure

Abutments/Shear Keys

	
Failure	Failure
	
Level V	Level III
	
Level III	Level III

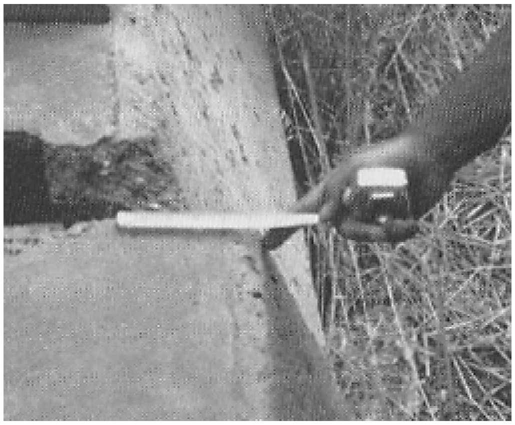
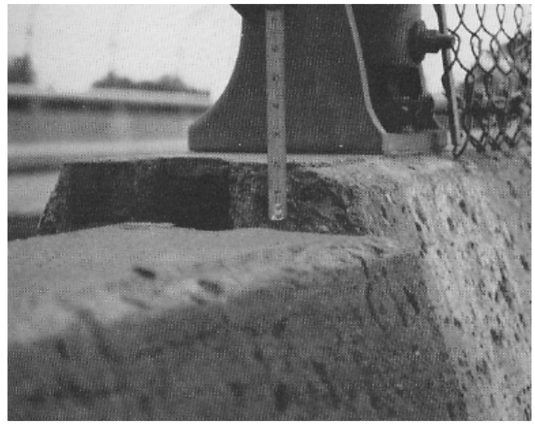
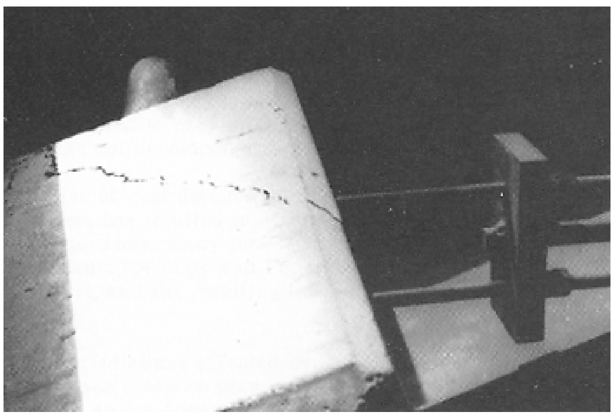
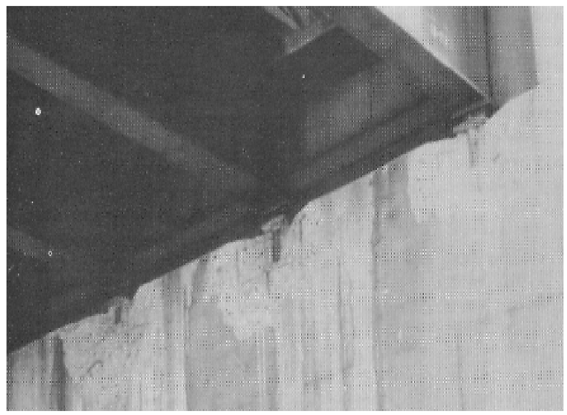
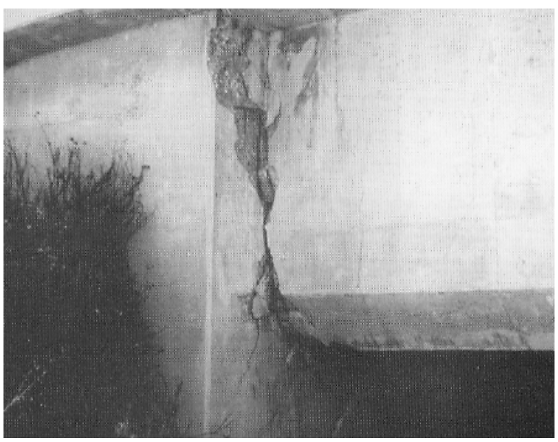
Abutments/Shear Keys

	
Level IV	Failure
	
Level V Transversal movement	Failure
	
Level V Pounding damage	Level V Separation of Abutment

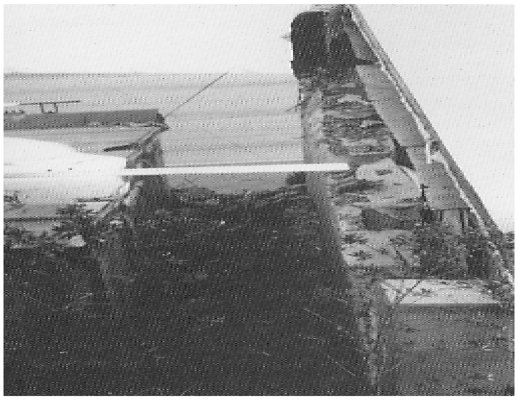
Abutments/Shear Keys

	
Level V	Abutment slumping
	
Level V	Level V
	
Level V	Level V

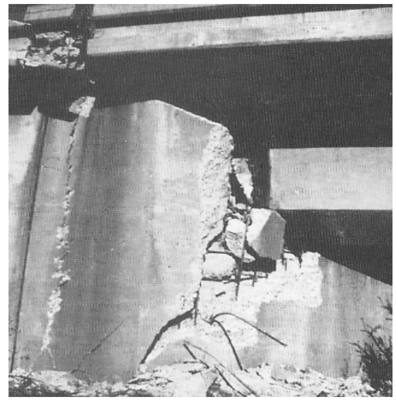
Abutments/Shear Keys

	
Abutment horizontal offset	Abutment vertical offset
	
Level IV	Level IV
	
Level V	Level V

Abutments/Shear Keys

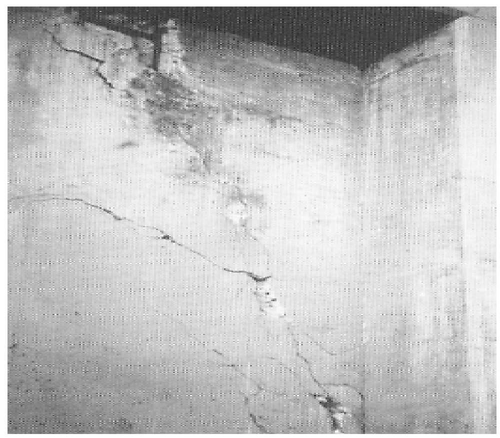


Failure

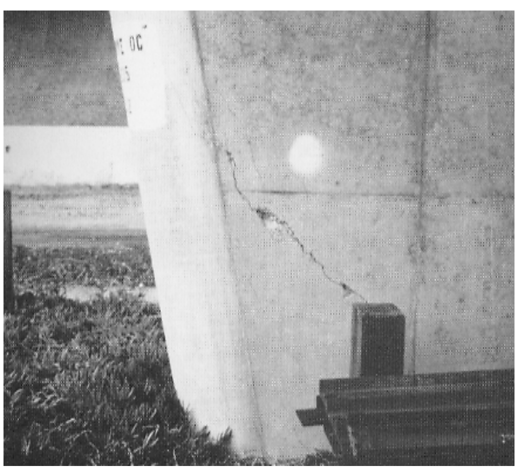


Failure

Failure



Failure



Level IV

Level IV- Crack due to Girder impact

Abutments/Shear Keys

	
Abutment/Superstructure separation	Spalling of concrete at abutment

Bearing Damage

Bearing Damage

Failure of Elastomeric bearing

Failure of anchor bolts on girder

Girder movement causes bearing failure

Failure of bearing pad

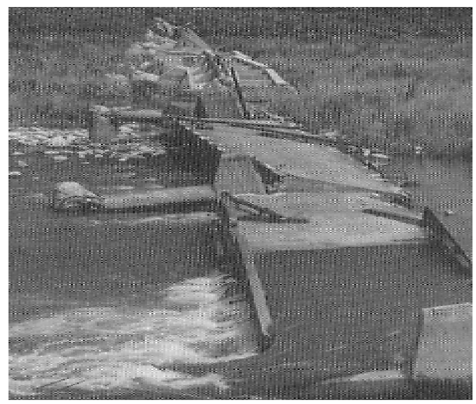
Bearing sliding

Bearing Damage

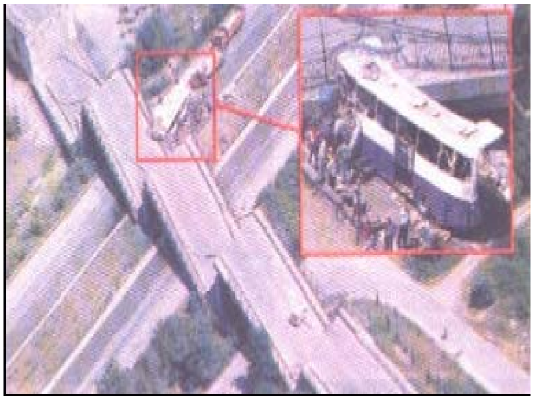
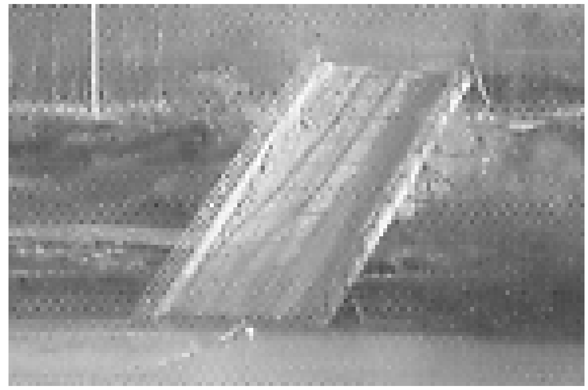
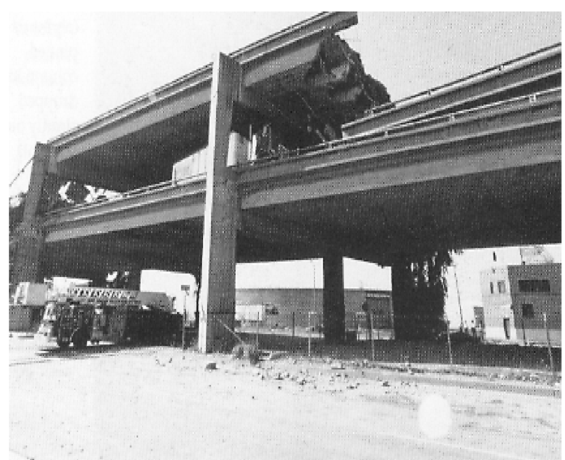
	
	
Level IV	Level IV
	
Level V	

Total Collapse

Total Collapse

	
Total Failure	Total Failure
	
Total Failure	Failure Pin Ling Bridge
	
Total Failure	Total Failure

Total Collapse

	
Failure Pre-stress concrete failure	Total Failure (Sakarya Bridge)
	
Failure	Total Failure
	
Total Failure	Total Failure

Total Collapse

	
Total failure	Total failure
	
Total Failure	Total Failure
	
Total Failure	Pull out failure

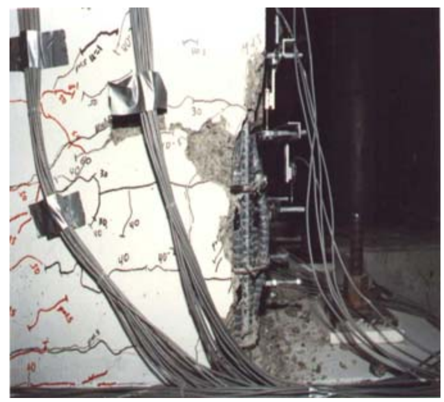
Part III

Correlation of Field photo with Laboratory database

Flexural

Flexural

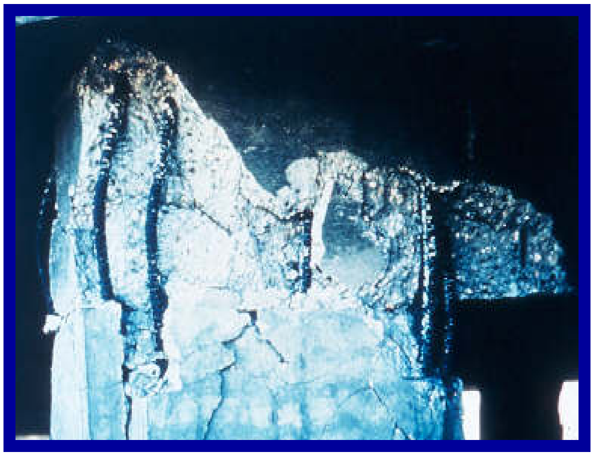
Flexural – Level IV



Flexural – Level IV

Flexural Level V

Flexural

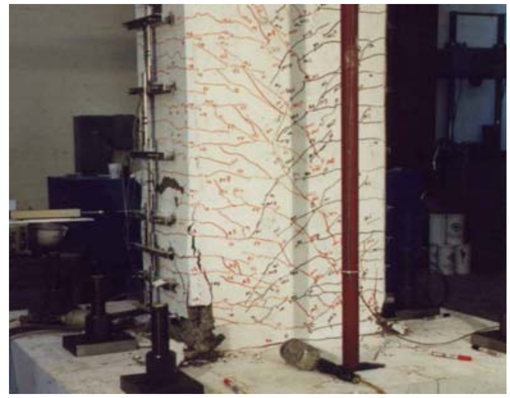


Flexural – Level V

Flexural – Level V

Flexural – Level V

Flexural



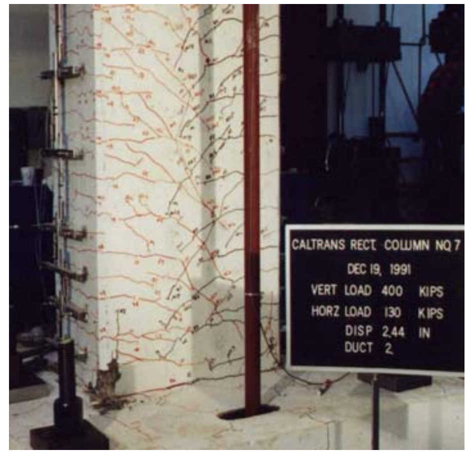
Flexural – Level III

Flexural – Level V – rupture of long. Bars

Flared Columns-Level IV

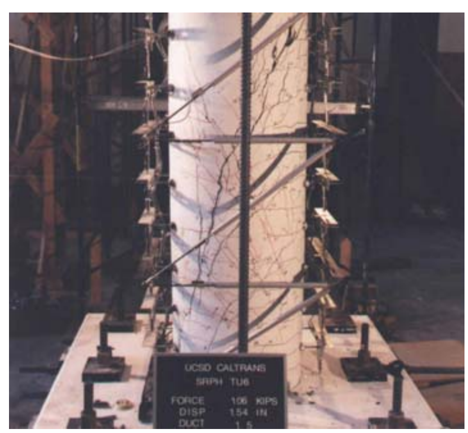
Shear

Shear



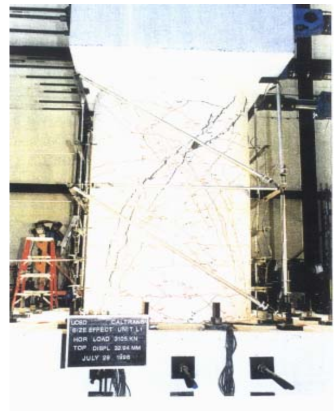
Shear – Level III

Shear - Level V



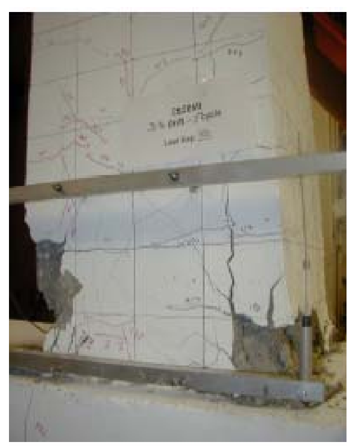
Shear - Level IV

Shear



Shear - Level V

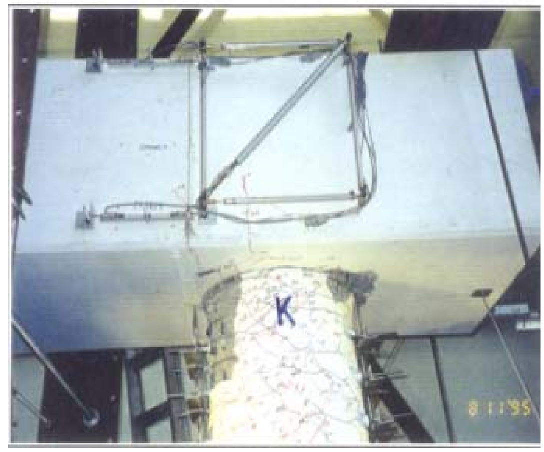
Shear - Level V



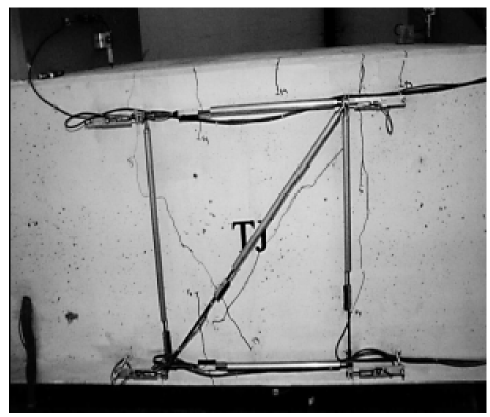
Lap splice – Base – Level IV

Joints

Joints



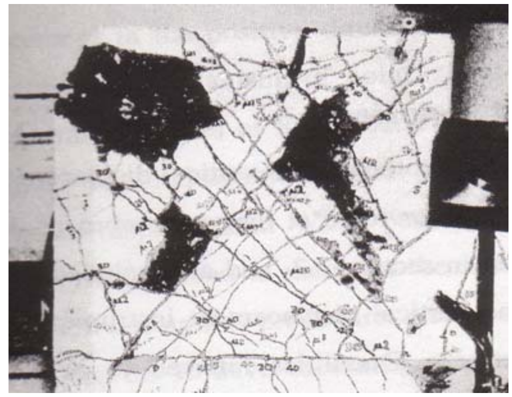
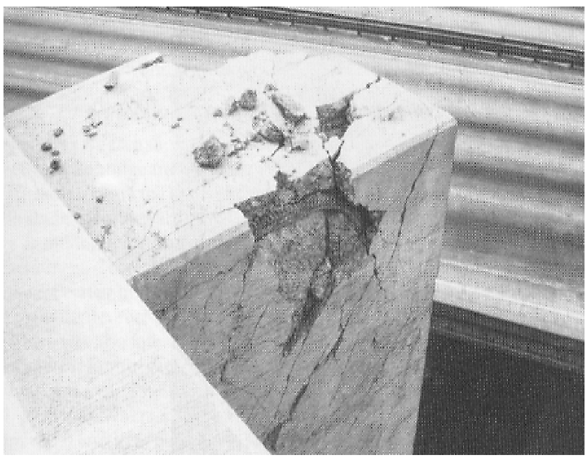
Knee Joint - Level IV



Tee Joint - Level IV

Tee joint – Level V

Joints

	
Level V	
	
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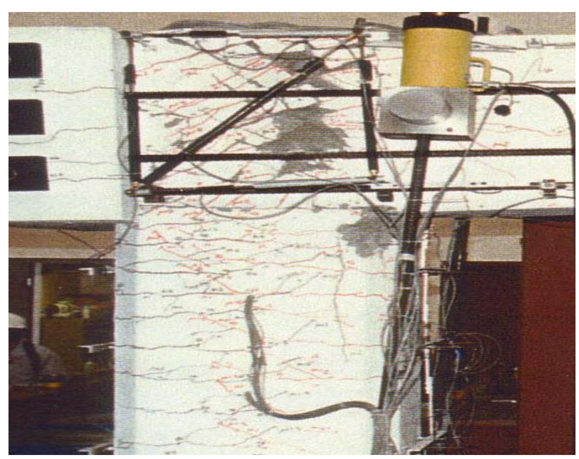
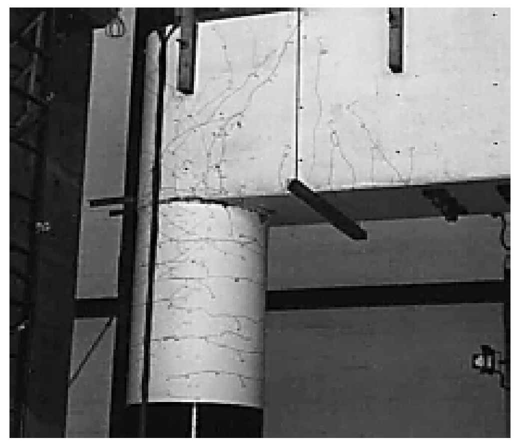
	
Level V	

Cap Beam-Column

Cap Beam-Column

Level III

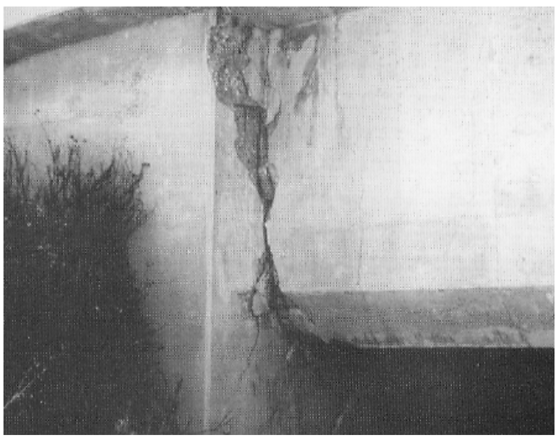


Level IV

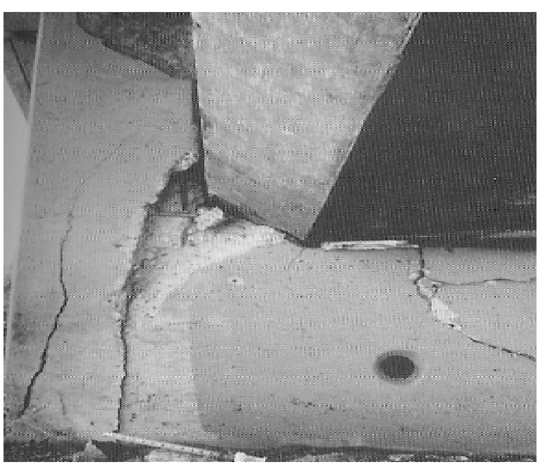
Abutments-Shear Keys

Abutments-Shear Keys

Level V

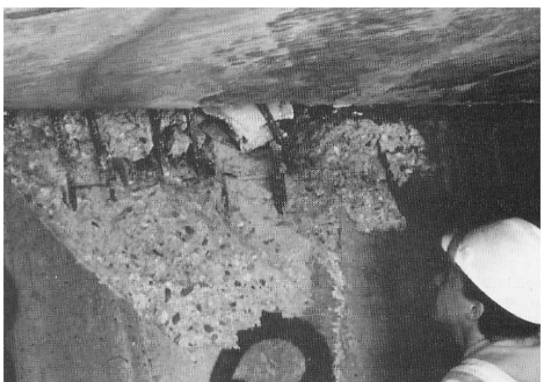
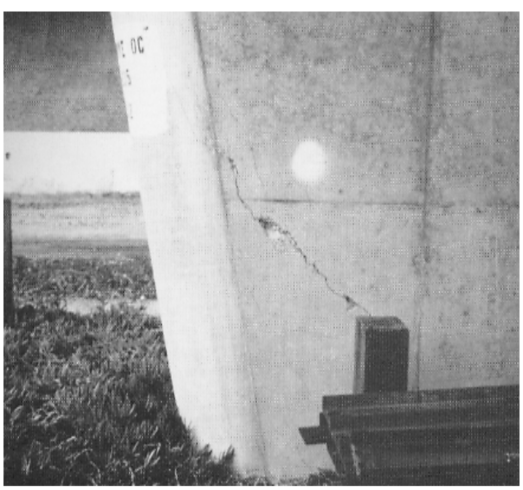


Level V

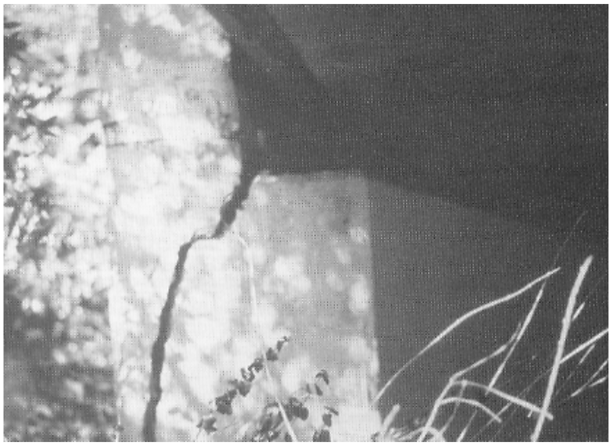
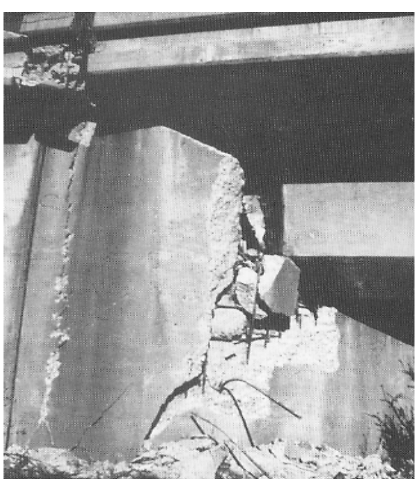


Level III

Abutments-Shear Keys

	
Level IV	
	
Level V	
	
Level IV	

Abutments-Shear Keys

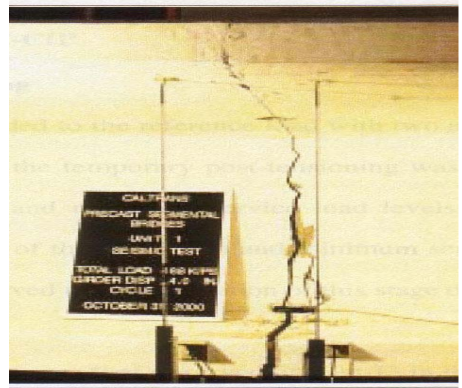
	
Level V	
	
Level v	
	
Level V	

Abutments-Shear Keys

Abutment-Shear key –Level V

Superstructure

Super Structure



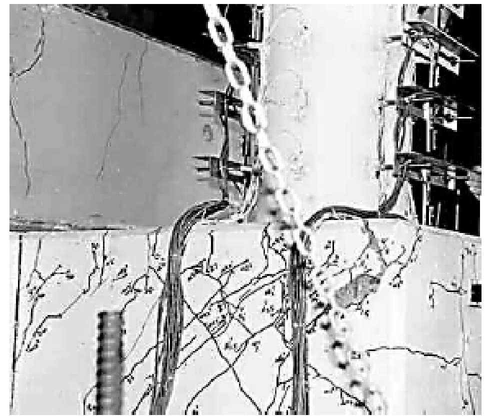
Level IV

Level IV

Level V

Foundation

Foundation

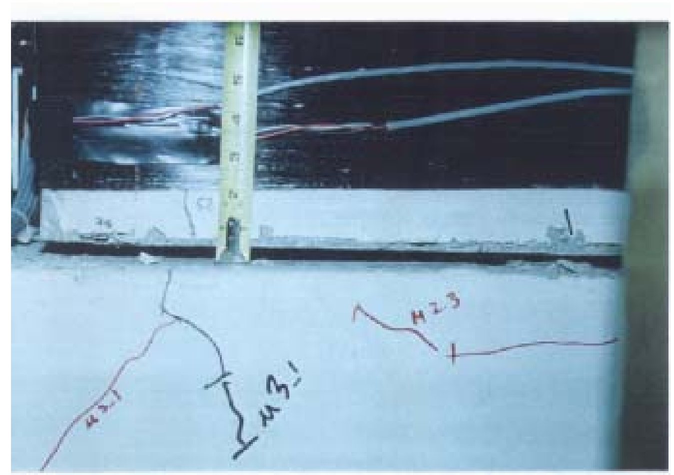


Level V

Level V

Other Cases

Other Cases

Level V –gap between pedestal column

PART IV

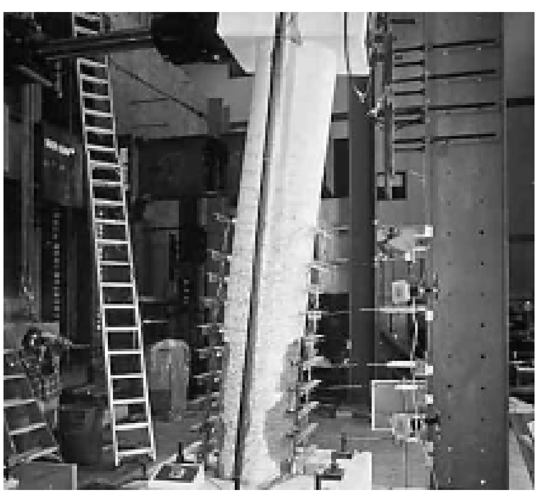
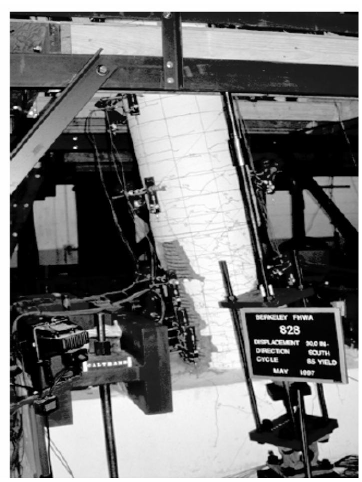
Details of Extreme Performance Levels

Flexural Level V

Buckling of longitudinal reinforcement

Fracture of longitudinal bars and stirrups

Fracture of longitudinal bars

Permanent deformation

Shear Level V

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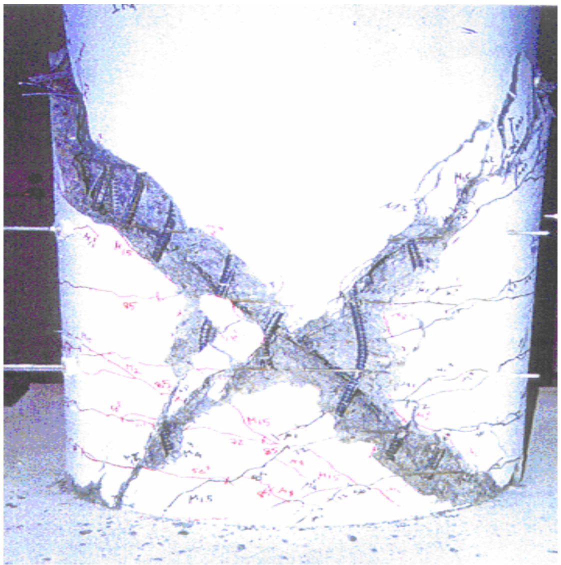
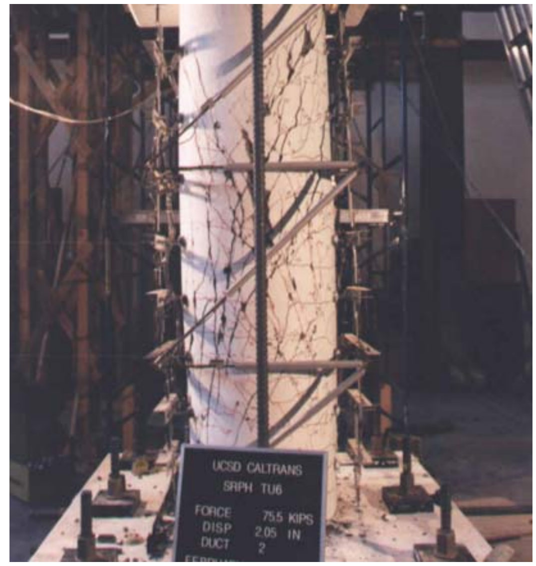
<td></td>
<td>
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<td>diagonal crack (plastic hinge region-base)</td>
<td>Diagonal crack- midheight</td>
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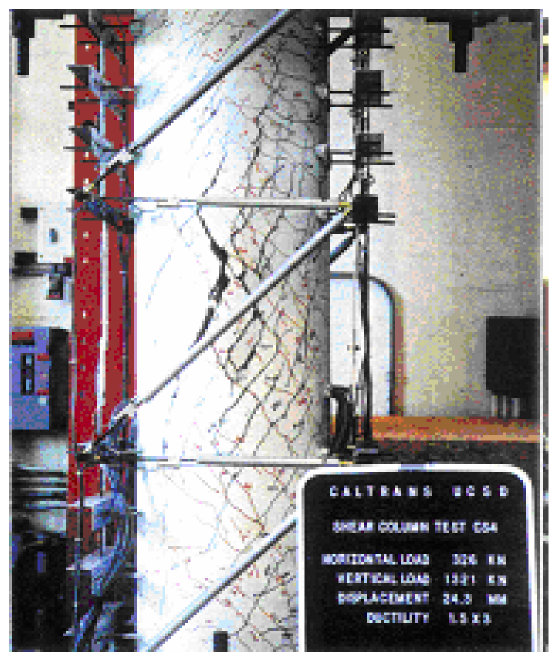
<td>
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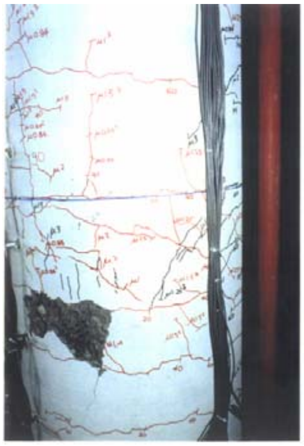
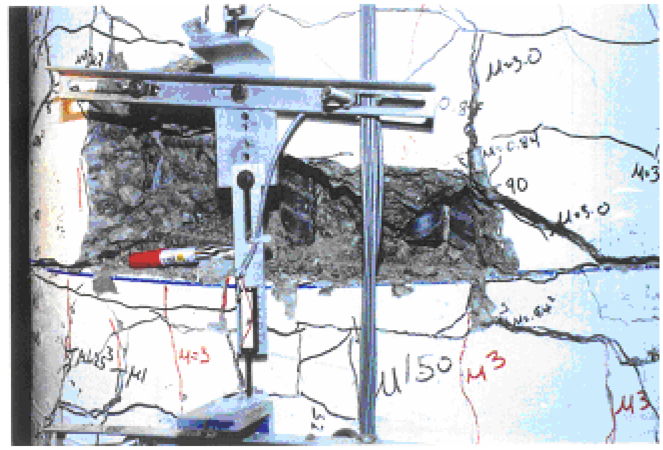
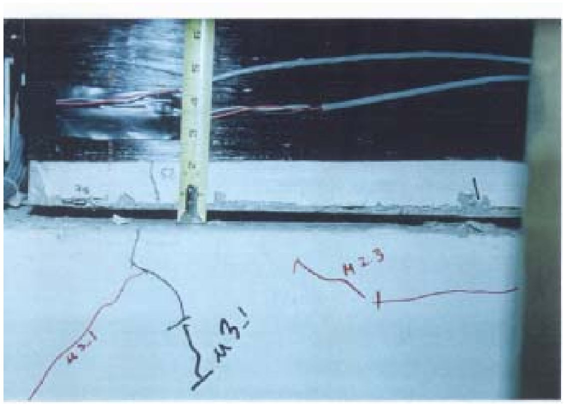
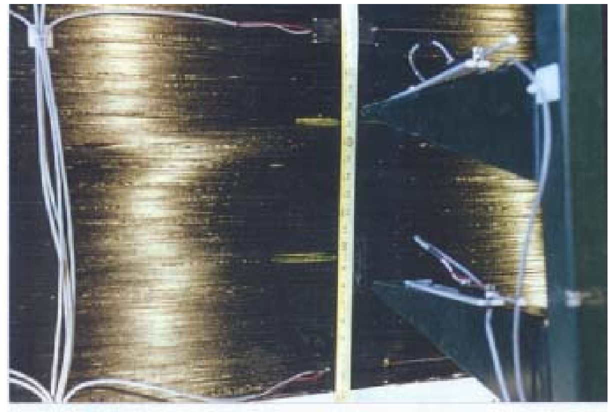
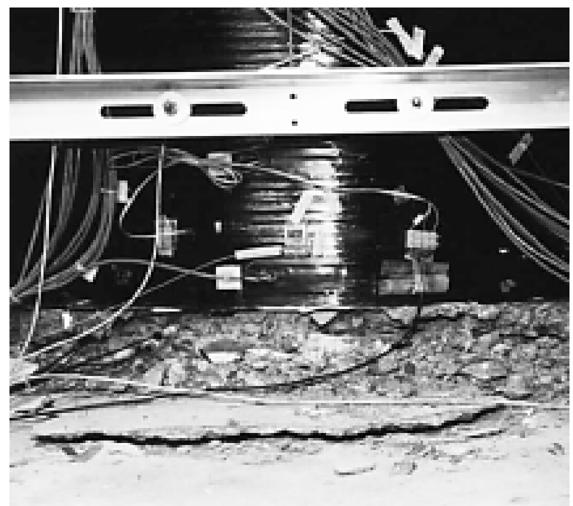
Lap Splice

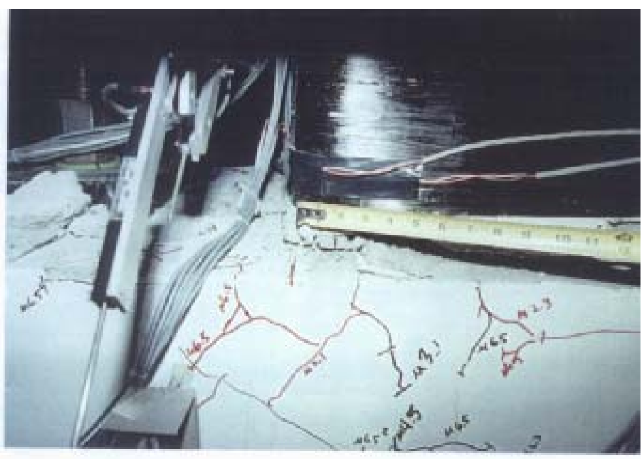
	
Level III -Crack at midheight	Level V - BOND SLIP – space of bars

Retrofit Level IV

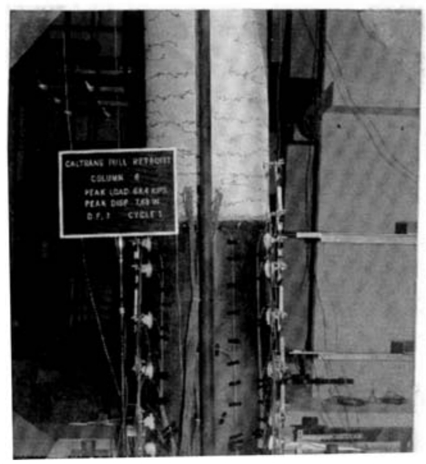
	
Gap between column pedestal	Dilation of jacket
	
Extensive spalling – plastic hinge region	

Retrofit Level V

Buckling of long bars



Sliding of column

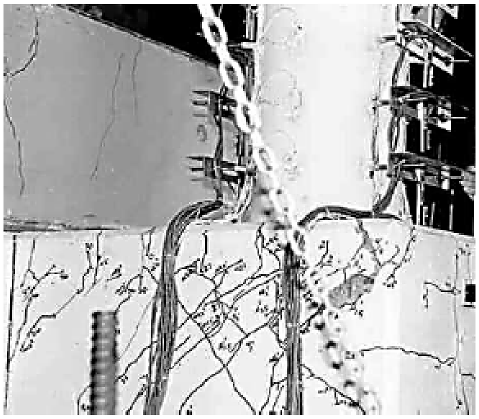
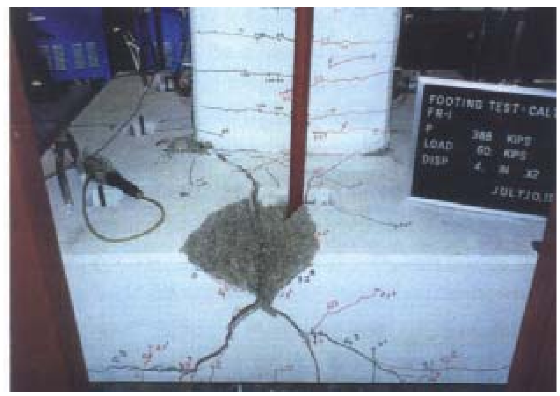


Permanent deformation

Joints Level V

	
Shear crack-tee joint	Shear crack-knees joint

Foundations Level V

	
Shear cracks	Pile cap rotation
	
Shear crack-retrofit foundation	Shear splitting

Shear Keys Level V

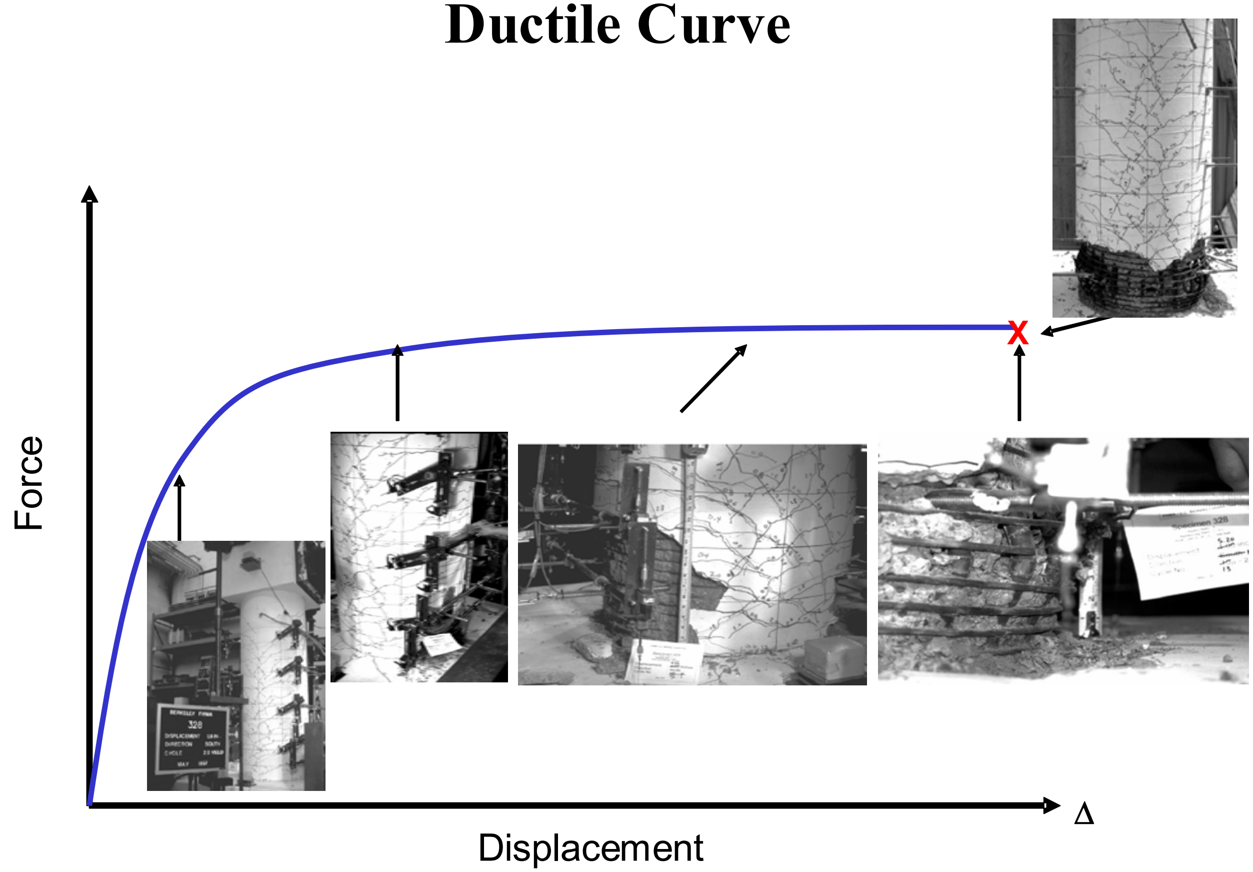
Diagonal Shear crack

Part V

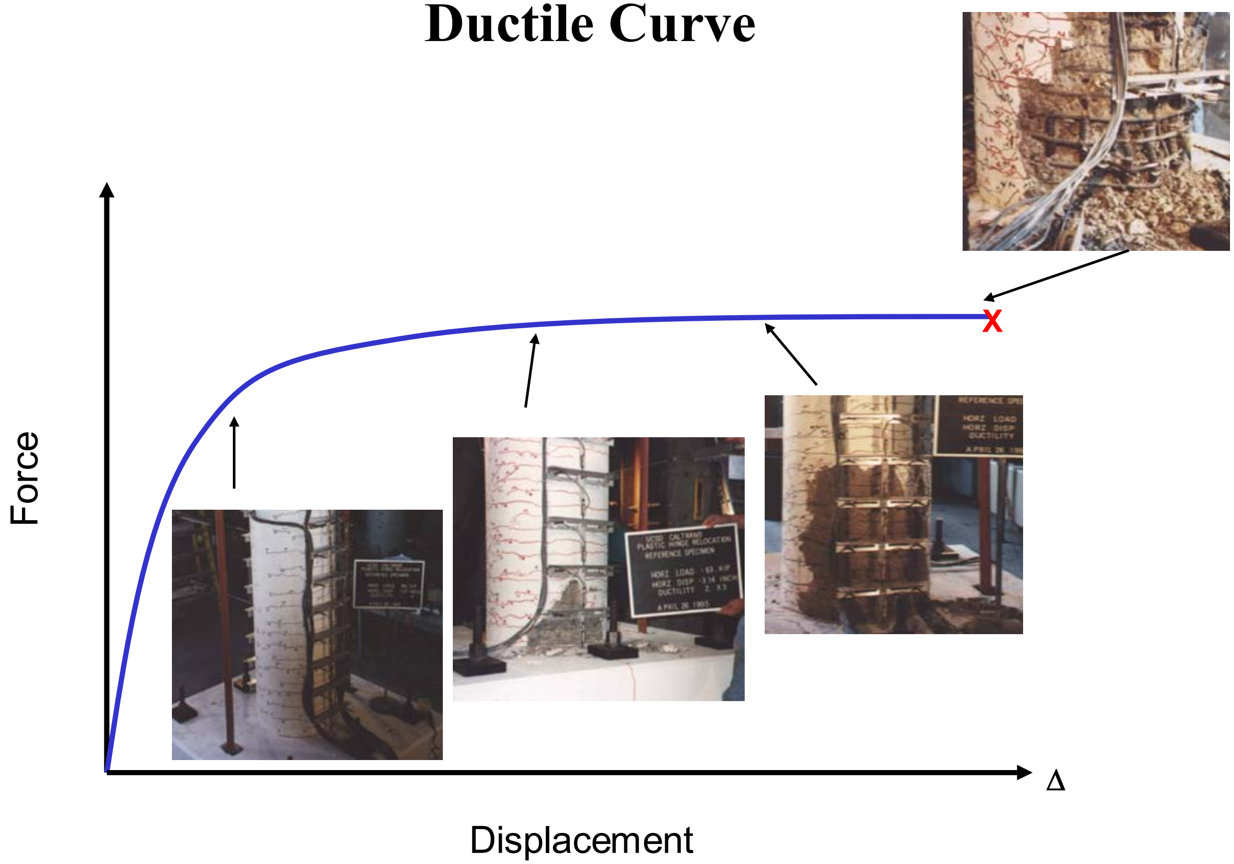
Correlation of lab photos with Performance Curves

Column Performance Curves

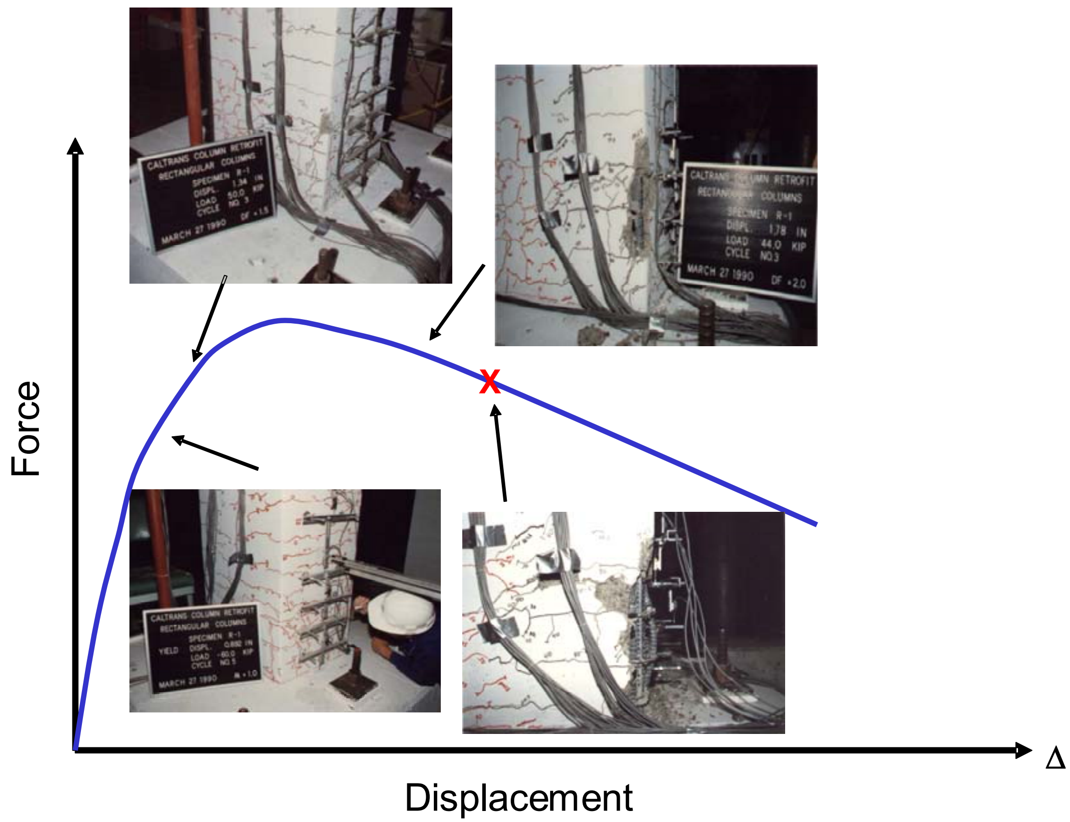
Ductile Curve



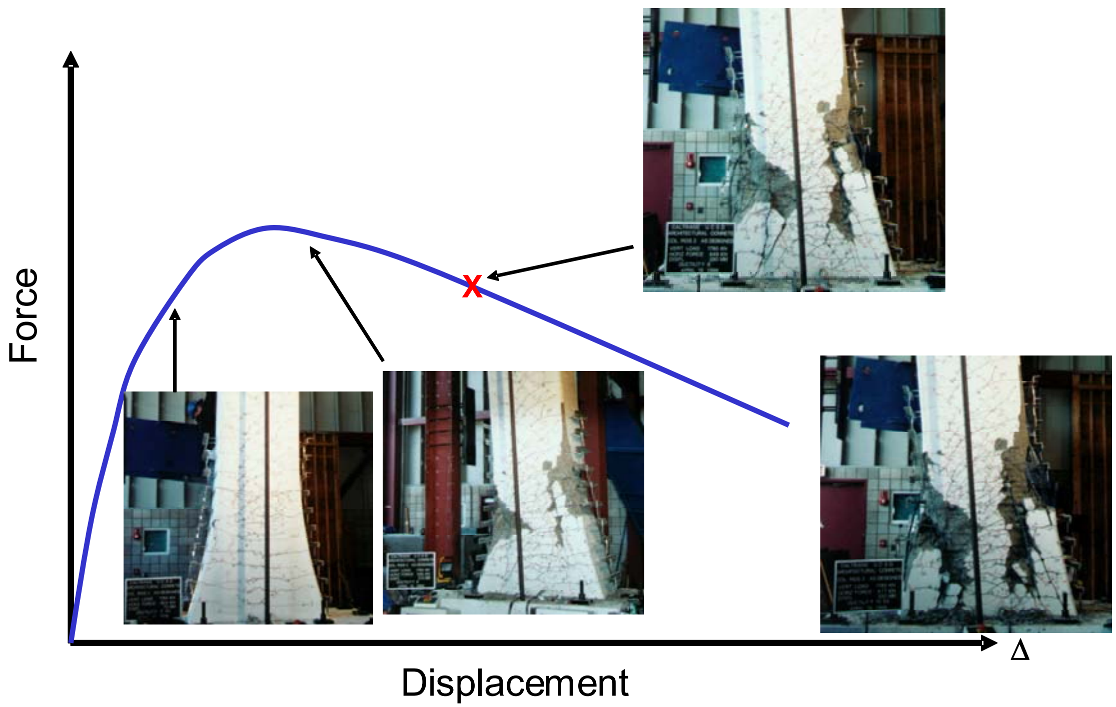
Ductile Curve



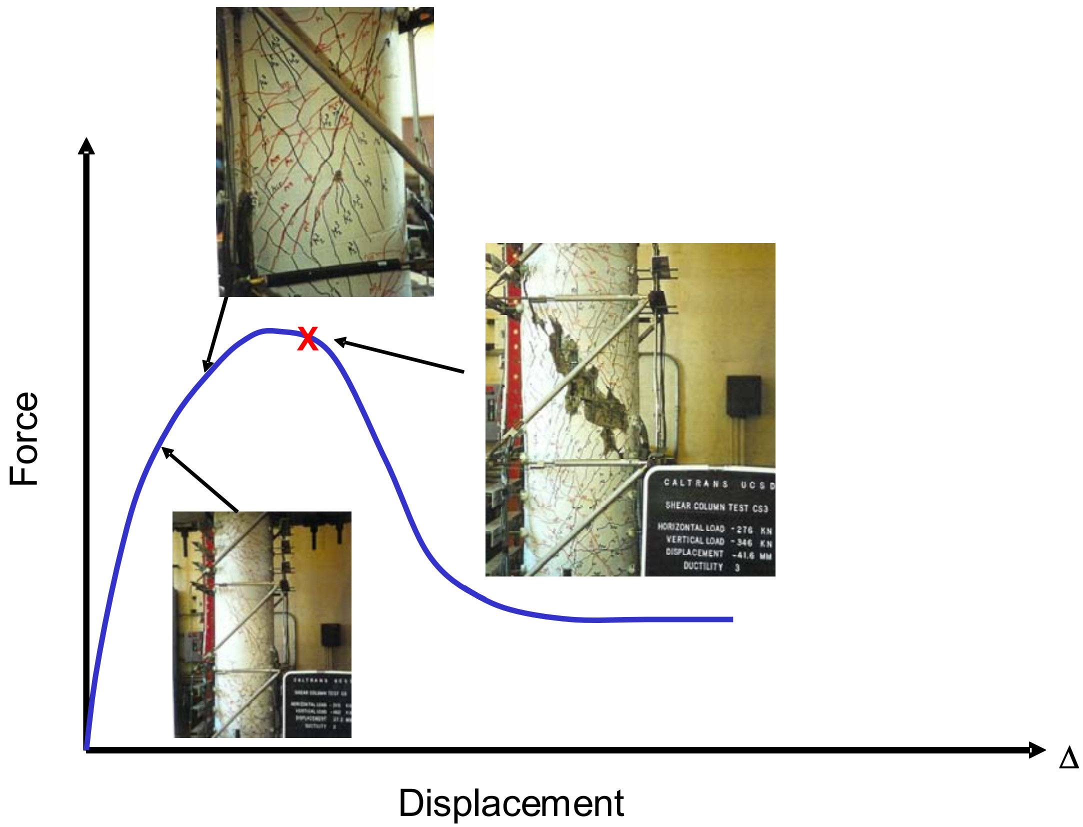
Strength Degrading Curve



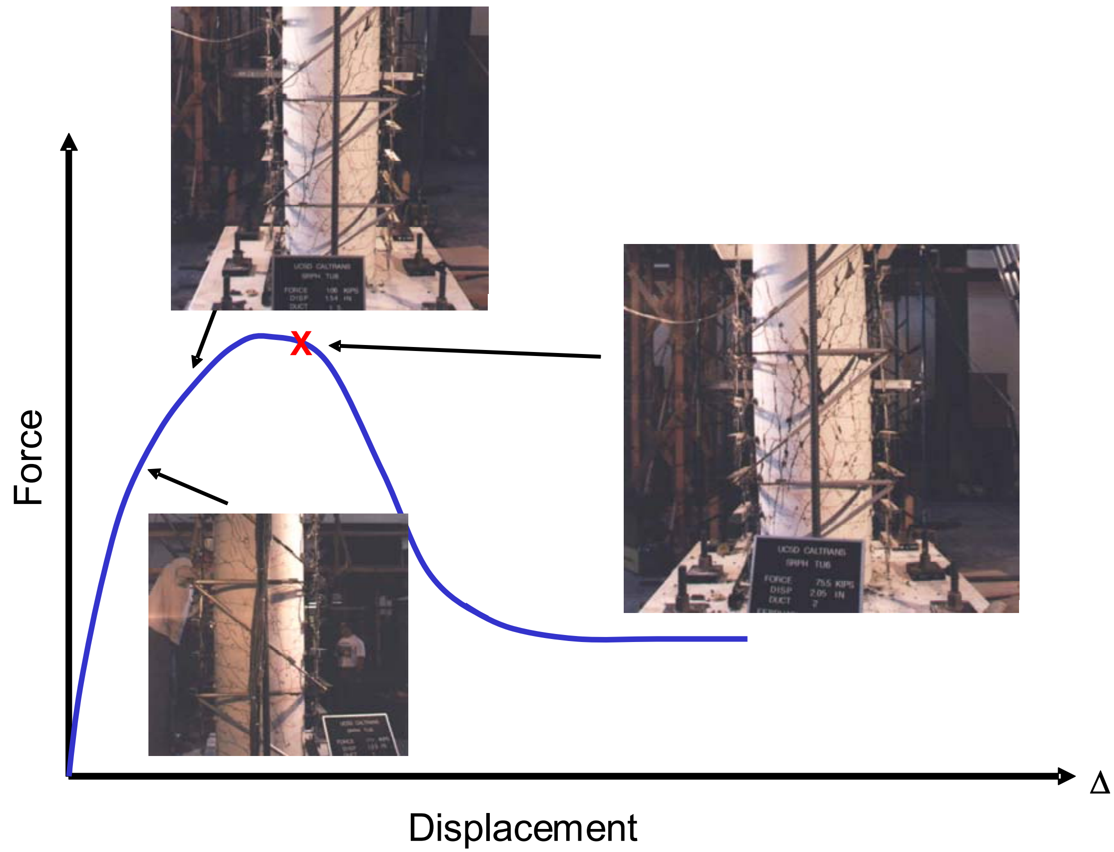
Strength Degrading Curve



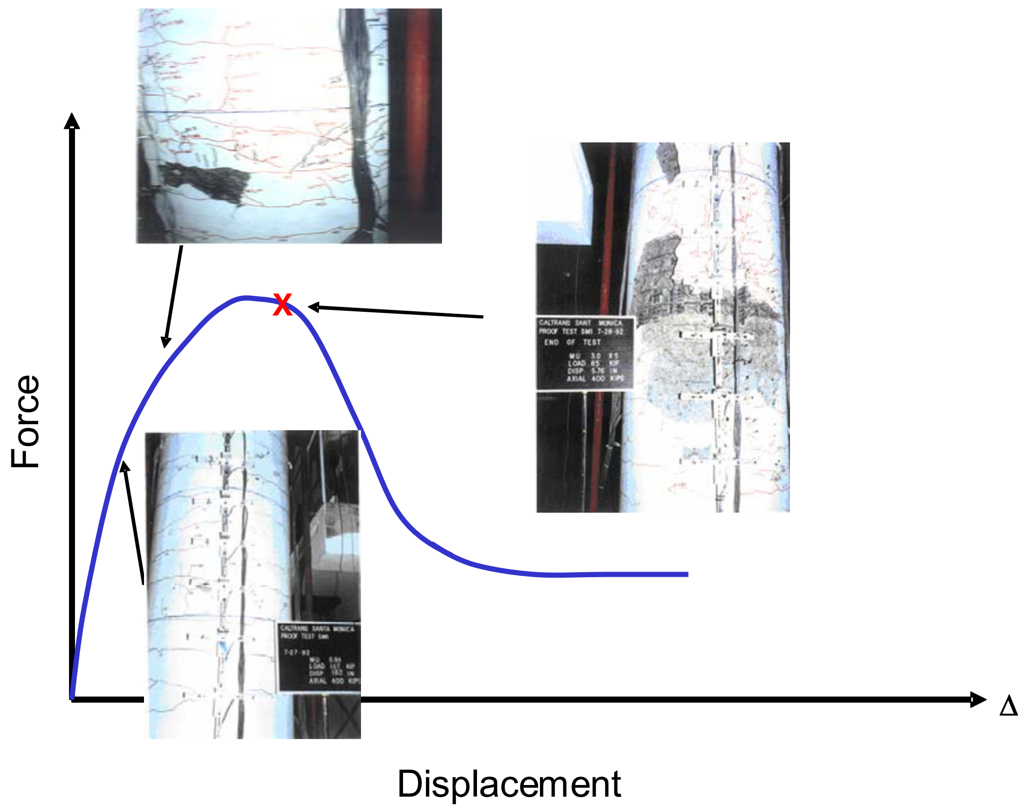
Brittle Curve



Brittle Curve

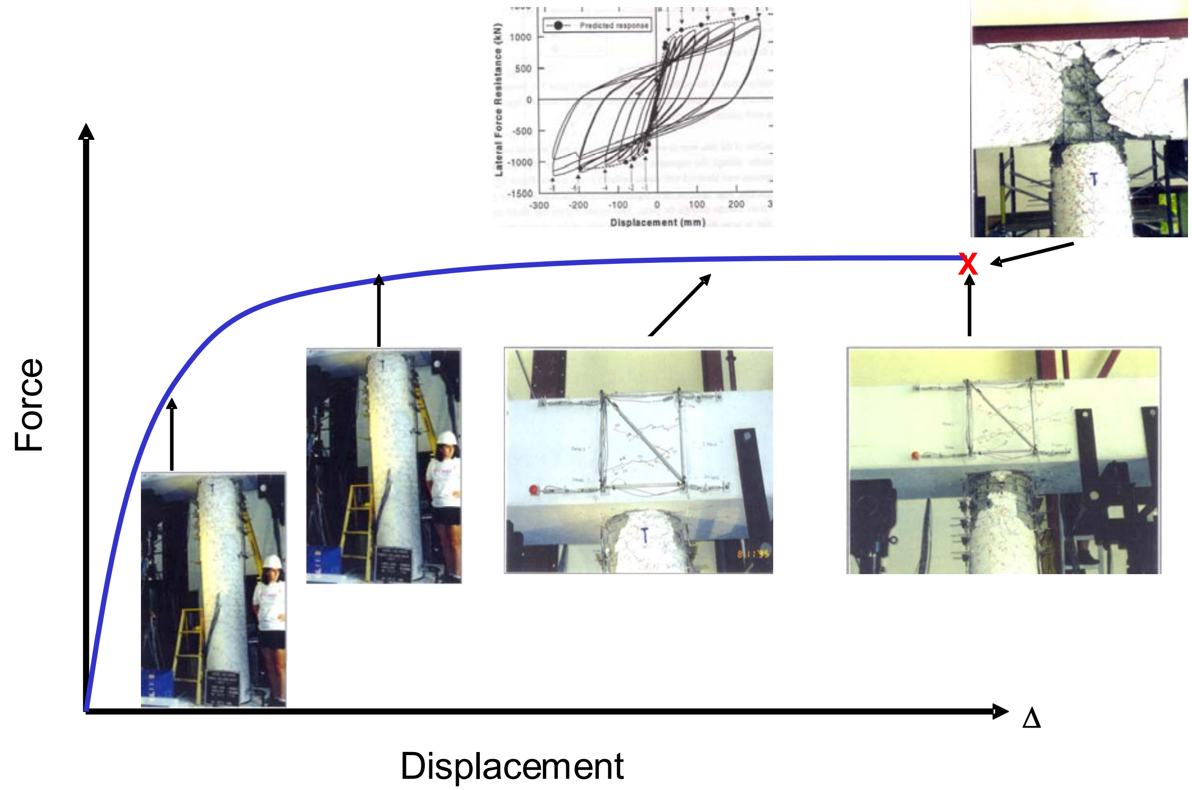


Brittle Curve

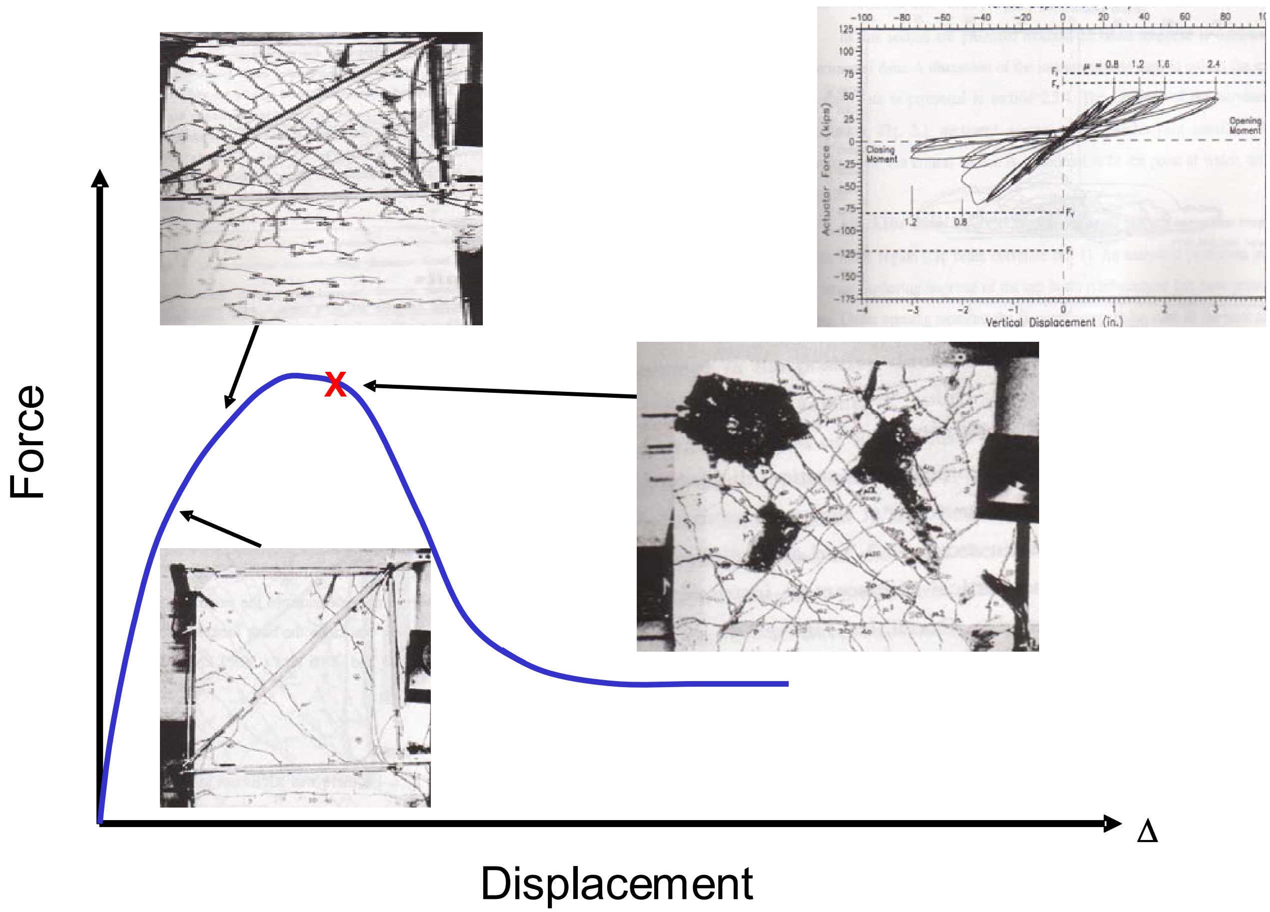


Joint Performance Curves

Ductile Curve (J1)

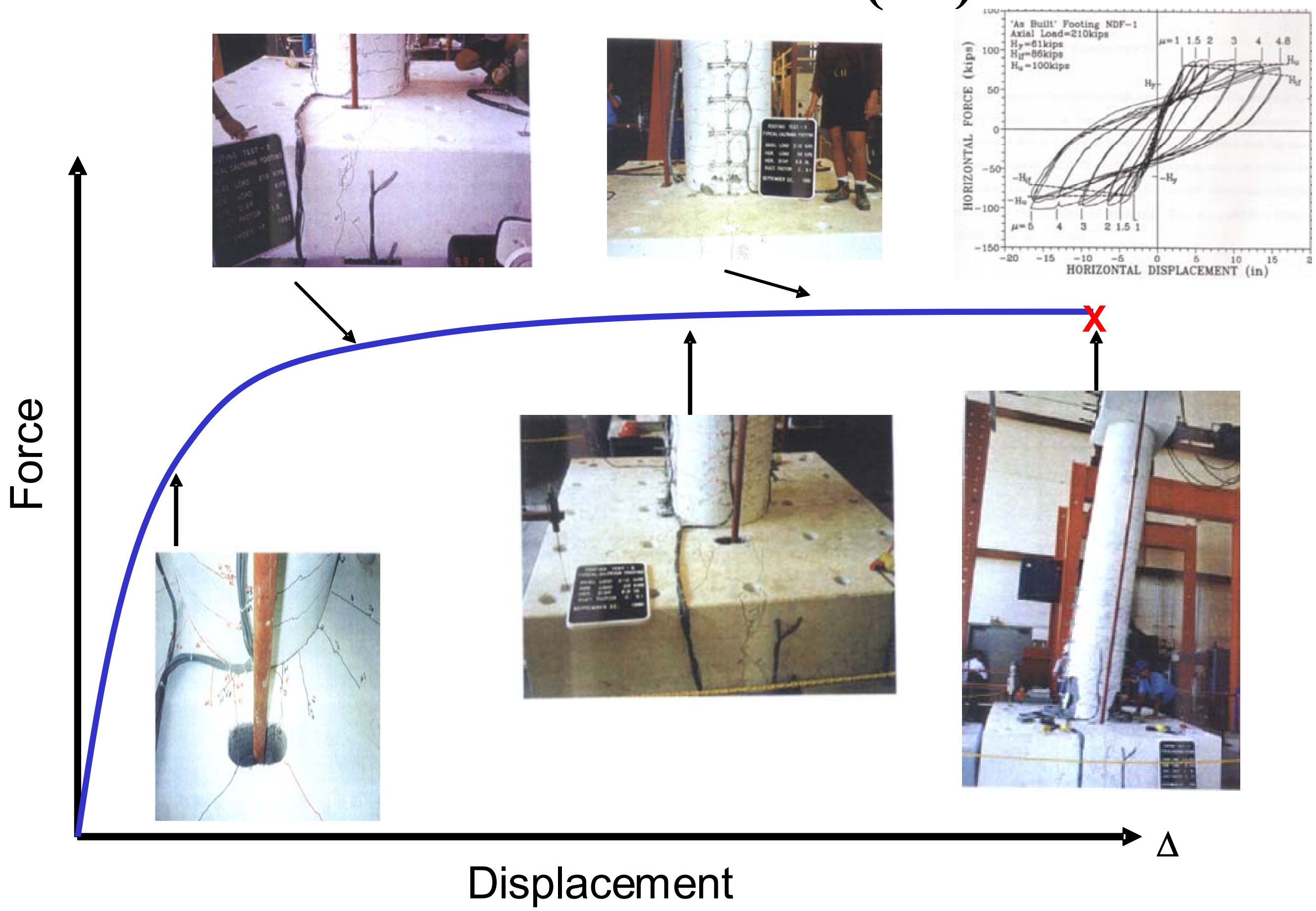


Brittle Curve (J2)

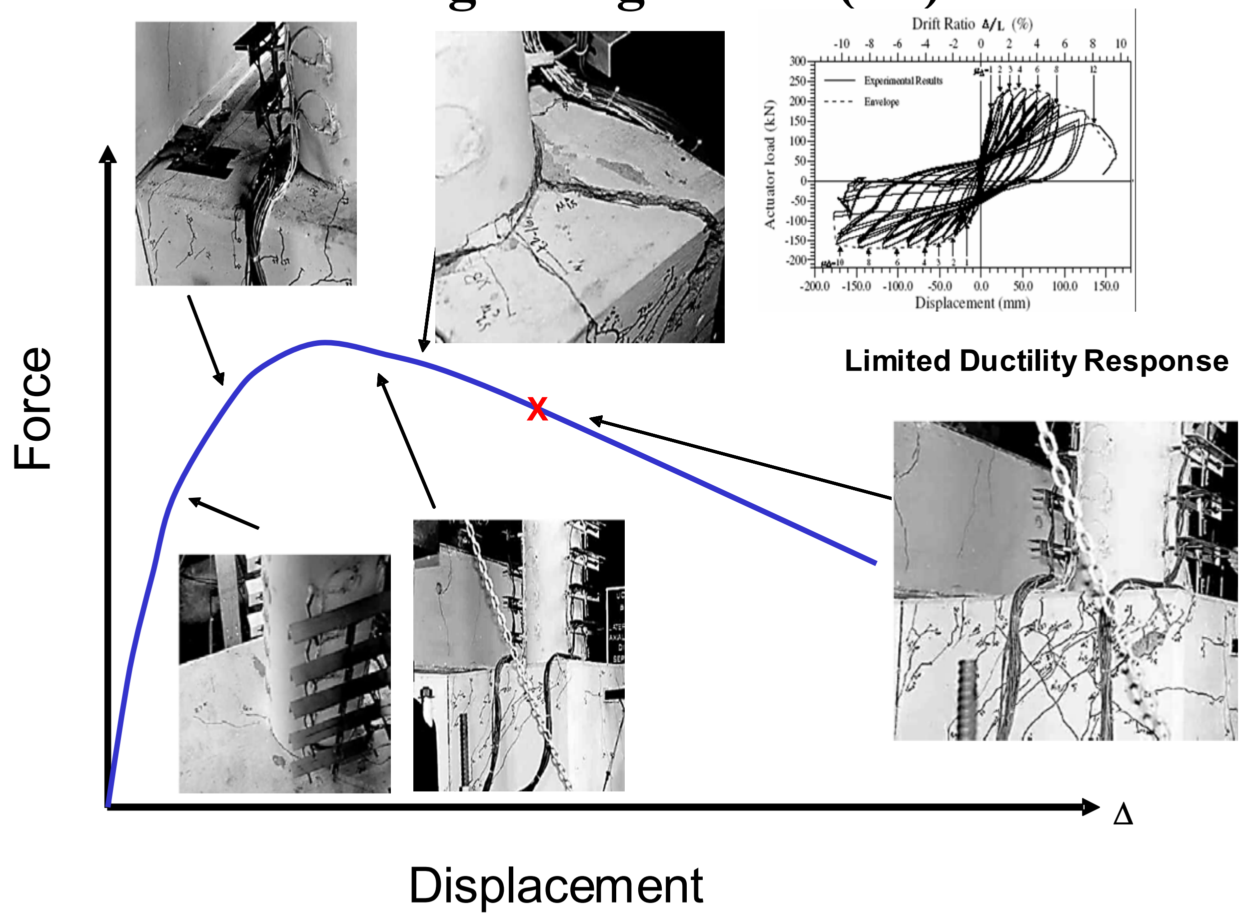


Foundation Performance Curves

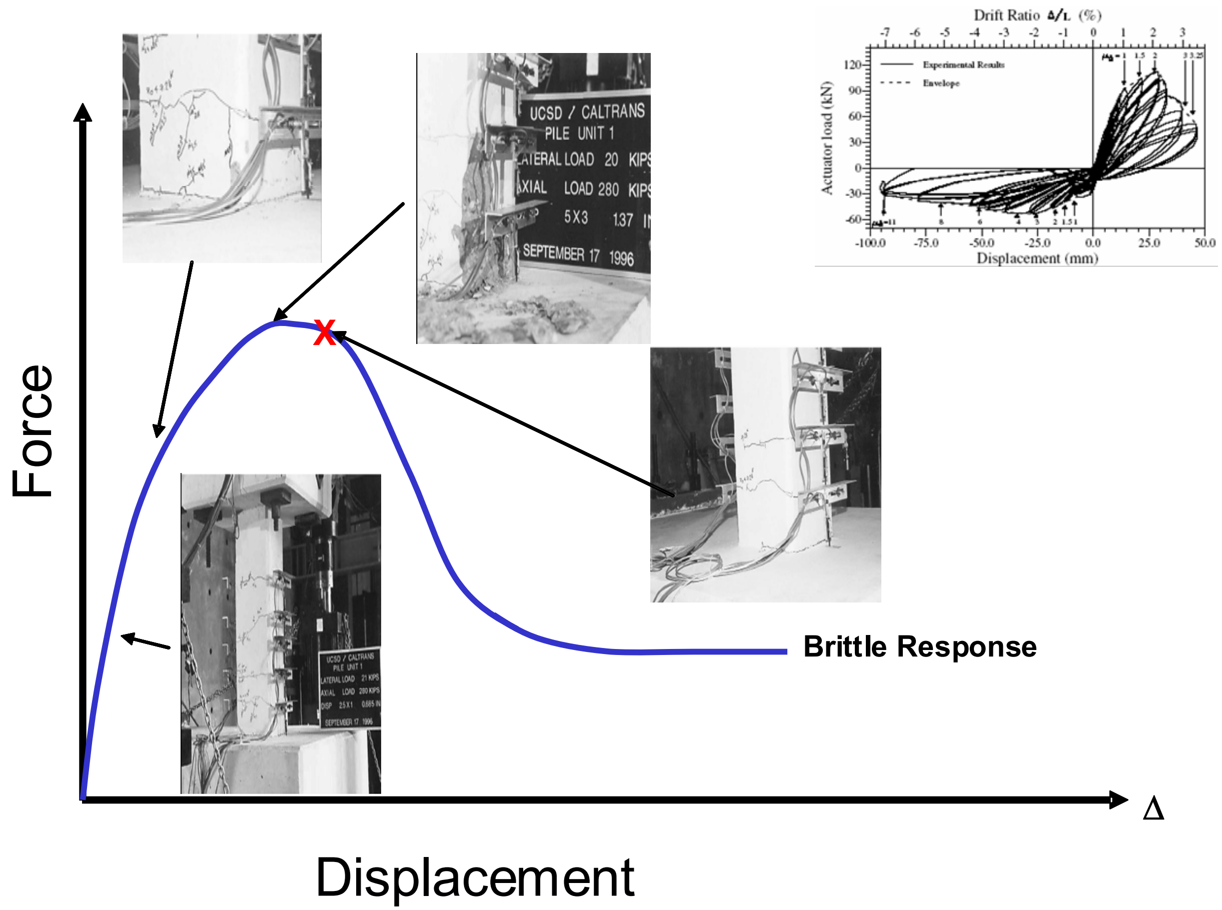
Ductile Curve (F4)



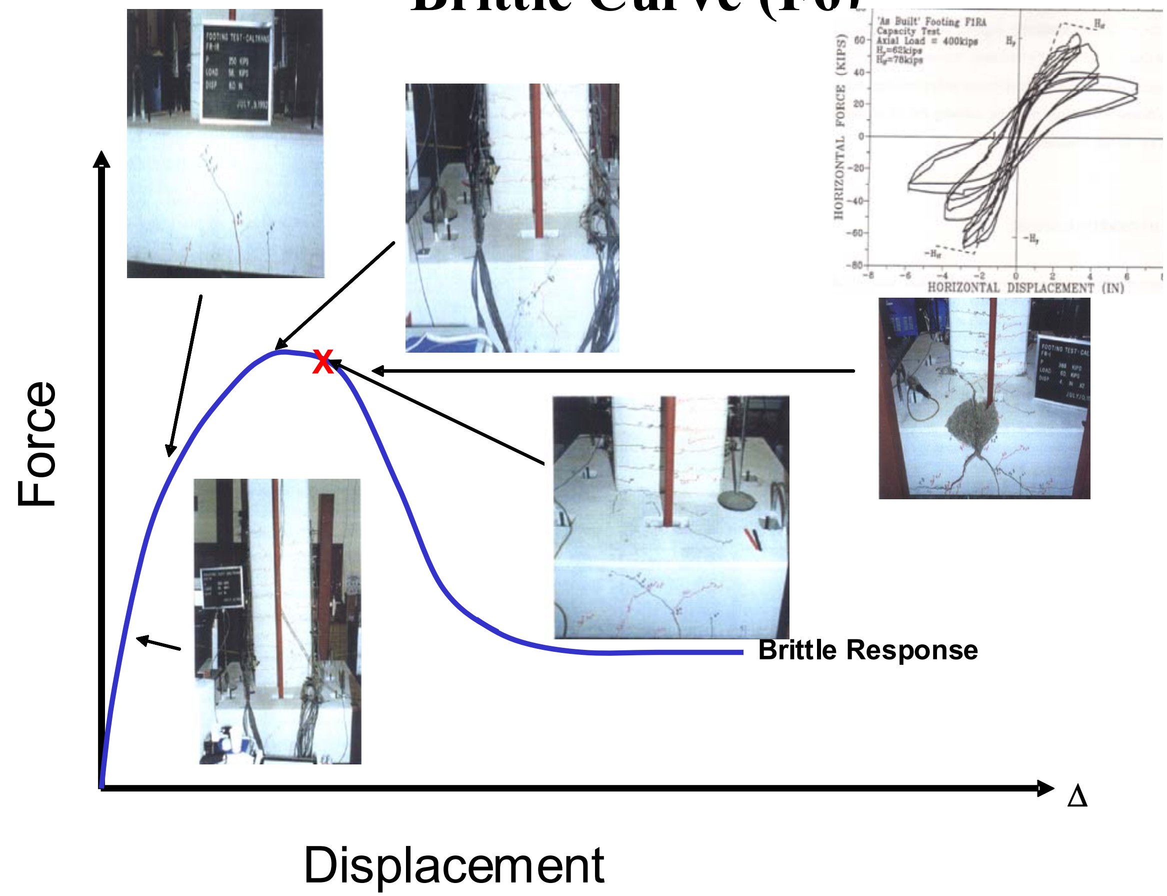
Degrading Curve (F3)



Brittle Curve (F1)

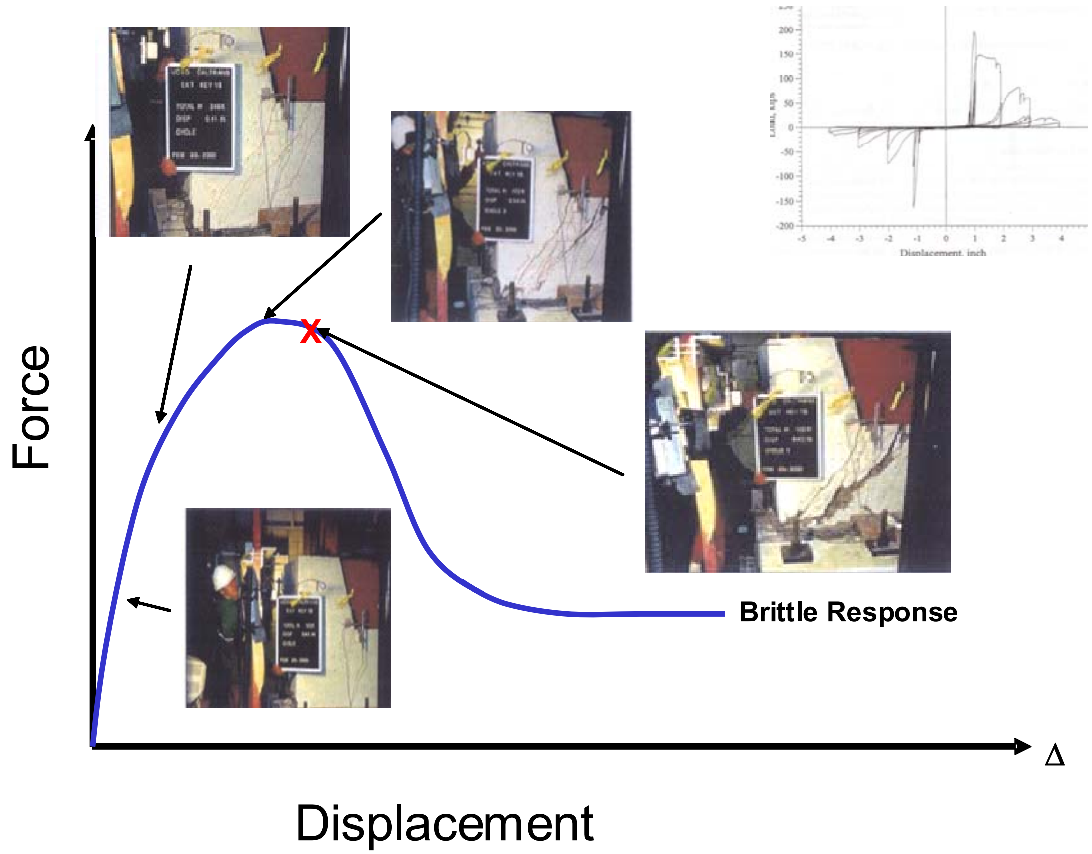


Brittle Curve (F6)



Abutment Performance Curves

Brittle Curve (SK5)



Appendix

References by Catalog Number

Catalog #	Reference	Test Unit
F1	Calderone, Anthony J., Lehman, Dawn E., Moehle, Jack P., Behavior of Reinforced Concrete Bridge Columns Having Varying Aspect Ratios and Varying Lengths of Confinement, Pacific Earthquake Engineering Research Center PEER – 2000/08, University of California, Berkeley, Berkeley, CA, January 2001.	328
F2	Calderone, Anthony J., Lehman, Dawn E., Moehle, Jack P., Behavior of Reinforced Concrete Bridge Columns Having Varying Aspect Ratios and Varying Lengths of Confinement, Pacific Earthquake Engineering Research Center PEER – 2000/08, University of California, Berkeley, Berkeley, CA, January 2001.	328-T
F3	Calderone, Anthony J., Lehman, Dawn E., Moehle, Jack P., Behavior of Reinforced Concrete Bridge Columns Having Varying Aspect Ratios and Varying Lengths of Confinement, Pacific Earthquake Engineering Research Center PEER – 2000/08, University of California, Berkeley, Berkeley, CA, January 2001.	828
F4	Calderone, Anthony J., Lehman, Dawn E., Moehle, Jack P., Behavior of Reinforced Concrete Bridge Columns Having Varying Aspect Ratios and Varying Lengths of Confinement, Pacific Earthquake Engineering Research Center PEER – 2000/08, University of California, Berkeley, Berkeley, CA, January 2001.	1028
F5	Lehman, Dawn E., Moehle, Jack P., Seismic Performance of Well-Confined Concrete Bridge Columns, Pacific Earthquake Engineering Research Center PEER – 1998/01, University of California, Berkeley, Berkeley, CA, December 2000.	415
F6	Lehman, Dawn E., Moehle, Jack P., Seismic Performance of Well-Confined Concrete Bridge Columns, Pacific Earthquake Engineering Research Center PEER – 1998/01, University of California, Berkeley, Berkeley, CA, December 2000.	430
F7	Lehman, Dawn E., Moehle, Jack P., Seismic Performance of Well-Confined Concrete Bridge Columns, Pacific Earthquake Engineering Research Center PEER – 1998/01, University of California, Berkeley, Berkeley, CA, December 2000.	815
F8	Lehman, Dawn E., Moehle, Jack P., Seismic Performance of Well-Confined Concrete Bridge Columns, Pacific Earthquake Engineering Research Center PEER – 1998/01, University of California, Berkeley, Berkeley, CA, December 2000.	1015

F9	Hose, Y., Seible, F., Priestley, N., Strategic Relocation of Plastic Hinges in Bridge Columns, Structural Systems Research Project SSRP – 97/05, University of California, San Diego, La Jolla, CA, August 1997	SRPH-1
F10	Hose, Y., Seible, F., Priestley, N., Strategic Relocation of Plastic Hinges in Bridge Columns, Structural Systems Research Project SSRP – 97/05, University of California, San Diego, La Jolla, CA, August 1997	SRPH-2
F11	Hose, Y., Seible, F., Priestley, N., Strategic Relocation of Plastic Hinges in Bridge Columns, Structural Systems Research Project SSRP – 97/05, University of California, San Diego, La Jolla, CA, August 1997	SRPH-3
F12	Hose, Y., Seible, F., Priestley, N., Strategic Relocation of Plastic Hinges in Bridge Columns, Structural Systems Research Project SSRP – 97/05, University of California, San Diego, La Jolla, CA, August 1997	SRPH-4
F13	Gibson, N., Filiatrault, A., and Ashford, S., Performance of Bridge Joints Subjected to a Large Velocity Pulse, Structural Systems Research Project SSRP – 2001/10, University of California, San Diego, La Jolla, CA, August 2001.	
F14	Esmaeily-Gh, Asadollah, Xiao, Yan, Seismic Behavior of Bridge Columns Subjected to Various Loading Patterns, Pacific Earthquake Engineering Research Center PEER – 2002/15, University of California, Berkeley, Berkeley, CA, December 2002	1
F15	Esmaeily-Gh, Asadollah, Xiao, Yan, Seismic Behavior of Bridge Columns Subjected to Various Loading Patterns, Pacific Earthquake Engineering Research Center PEER – 2002/15, University of California, Berkeley, Berkeley, CA, December 2002	2
F15	Esmaeily-Gh, Asadollah, Xiao, Yan, Seismic Behavior of Bridge Columns Subjected to Various Loading Patterns, Pacific Earthquake Engineering Research Center PEER – 2002/15, University of California, Berkeley, Berkeley, CA, December 2002	5
F16	Esmaeily-Gh, Asadollah, Xiao, Yan, Seismic Behavior of Bridge Columns Subjected to Various Loading Patterns, Pacific Earthquake Engineering Research Center PEER – 2002/15, University of California, Berkeley, Berkeley, CA, December 2002	6
F17	Hose, Y., Seible, F., Priestley, N., Strategic Relocation of Plastic Hinges in Bridge Columns, Structural Systems Research Project SSRP – 97/05, University of California, San Diego, La Jolla, CA, August 1997	SRPH-17

F18	Sun, Z., Seible, F., Priestley, M.J.N., Diagnostics and Retrofit of Rectangular Bridge Columns for Seismic Loads, Structural Systems Research Project SSRP – 93/07, University of California, San Diego, La Jolla, CA, July 1993.	R1
F19	Sun, Z., Seible, F., Priestley, M.J.N., Diagnostics and Retrofit of Rectangular Bridge Columns for Seismic Loads, Structural Systems Research Project SSRP – 93/07, University of California, San Diego, La Jolla, CA, July 1993.	R5
F20	Esmaeily-Gh, Asadollah, Xiao, Yan, Seismic Behavior of Bridge Columns Subjected to Various Loading Patterns, Pacific Earthquake Engineering Research Center PEER – 2002/15, University of California, Berkeley, Berkeley, CA, December 2002	3
F21	Lehman, Dawn E., Moehle, Jack P., Seismic Performance of Well-Confined Concrete Bridge Columns, Pacific Earthquake Engineering Research Center PEER – 1998/01, University of California, Berkeley, Berkeley, CA, December 2000.	407
S1	Priestley, M.J.N., Seible, F., Benzoni, G., Seismic Response of Columns with Low Longitudinal Steel Ratios, Structural Systems Research Project SSRP – 94/08, University of California, San Diego, La Jolla, CA, June 1994.	
S2	Hose, Y., Seible, F., Priestley, N., Strategic Relocation of Plastic Hinges in Bridge Columns, Structural Systems Research Project SSRP – 97/05, University of California, San Diego, La Jolla, CA, August 1997	SRPH-6
S3	Ohtaki, T., Benzoni, G., Priestley, M.J.N., Seismic Performance of a Full Scale Bridge Column-As Built and As Repaired, Structural Systems Research Project SSRP – 96/07, University of California, San Diego, La Jolla, CA, November 1996.	L1
S4	Benzoni, G., Ohtaki, T., Priestley, M.J.N., Seible, F., Seismic Performance of Circular Reinforced Concrete Columns under Varying Axial Load, Structural Systems Research Project SSRP – 96/04, University of California, San Diego, La Jolla, CA, August 1996.	
S5	Benzoni, G., Ohtaki, T., Priestley, M.J.N., Seible, F., Seismic Performance of Circular Reinforced Concrete Columns under Varying Axial Load, Structural Systems Research Project SSRP – 96/04, University of California, San Diego, La Jolla, CA, August 1996.	CS3

S6	Benzoni, G., Ohtaki, T., Priestley, M.J.N., Seible, F., Seismic Performance of Circular Reinforced Concrete Columns under Varying Axial Load, Structural Systems Research Project SSRP – 96/04, University of California, San Diego, La Jolla, CA, August 1996.	
S7	Xiao, Y., Priestley, M.J.N., Seible, F., Steel Jacket Retrofit for Enhancing Shear Strength of Short Rectang. Reinforced Concrete Columns, Structural Systems Research Project SSRP – 92/07, University of California, San Diego, La Jolla, CA, July 1993.	R1
S8	Xiao, Y., Priestley, M.J.N., Seible, F., Steel Jacket Retrofit for Enhancing Shear Strength of Short Rectang. Reinforced Concrete Columns, Structural Systems Research Project SSRP – 92/07, University of California, San Diego, La Jolla, CA, July 1993.	R3
S9	Xiao, Y., Priestley, M.J.N., Seible, F., Steel Jacket Retrofit for Enhancing Shear Strength of Short Rectang. Reinforced Concrete Columns, Structural Systems Research Project SSRP – 92/07, University of California, San Diego, La Jolla, CA, July 1993.	R5
LS1	Melek, Murat, Wallace, John W., Conte, Joel P., Experimental Assessment of Columns with Short Lap Splices Subjected to Cyclic Loads, Pacific Earthquake Engineering Research Center PEER – 2003/04, University of California, Berkeley, Berkeley, CA, April 2003.	
LS2	Priestley, M.J.N., Seible, F., Chai, Y.H., Wong, R., Santa Monica Viaduct Retrofit - Full-Scale Test on Col. Lap Splice with #11 (35 mm) Reinforcement, Structural Systems Research Project SSRP – 92/08, University of California, San Diego, La Jolla, CA, September 1992.	
SS1	Ranzo, G., Priestley, M.J.N., Seismic Performance of Circular Hollow Columns Subjected to High Shear, Structural Systems Research Project SSRP – 2001/01, University of California, San Diego, La Jolla, CA, March 2001.	HS-1
SS2	Ranzo, G., Priestley, M.J.N., Seismic Performance of Circular Hollow Columns Subjected to High Shear, Structural Systems Research Project SSRP – 2001/01, University of California, San Diego, La Jolla, CA, March 2001.	HS-2
SS3	Ranzo, G., Priestley, M.J.N., Seismic Performance of Circular Hollow Columns Subjected to High Shear, Structural Systems Research Project SSRP – 2001/01, University of California, San Diego, La Jolla, CA, March 2001.	HS-3
SS4	Hines, E.M., Dazio, A., Seible, F., Structural Testing of the San Francisco-Oakland Bay Bridge East Span Skyway Piers, Structural Systems Research Project SSRP – 2002/01, University of California, San Diego, La Jolla, CA, August 2002.	

SS5	Dazio, A., Seible, F., Structural Testing of the San Francisco-Oakland Bay Bridge East Spans Pier W2, Structural Systems Research Project SSRP – 2002/11, University of California, San Diego, La Jolla, CA, May 2003.	
SS6	Sanchez, A., Seible, F., Priestley, M.J.N., Seismic Performance of Flared Bridge Columns, Structural Systems Research Project SSRP – 97/06, University of California, San Diego, La Jolla, CA, October 1997.	RDS1
SS7	Sanchez, A., Seible, F., Priestley, M.J.N., Seismic Performance of Flared Bridge Columns, Structural Systems Research Project SSRP – 97/06, University of California, San Diego, La Jolla, CA, October 1997.	RDS2
SS8	Sanchez, A., Seible, F., Priestley, M.J.N., Seismic Performance of Flared Bridge Columns, Structural Systems Research Project SSRP – 97/06, University of California, San Diego, La Jolla, CA, October 1997.	RDS6
SM1	Kowalsky, M.J., Priestley, M.J.N., Seible, F., Flexural Behavior of Lightweight Concrete Columns under Seismic Conditions, Structural Systems Research Project SSRP – 96/08, University of California, San Diego, La Jolla, CA, December 1996.	FL1
SM1	Kowalsky, M.J., Priestley, M.J.N., Seible, F., Flexural Behavior of Lightweight Concrete Columns under Seismic Conditions, Structural Systems Research Project SSRP – 96/08, University of California, San Diego, La Jolla, CA, December 1996.	
SM2	Kowalsky, M.J., Priestley, M.J.N., Seible, F., Flexural Behavior of Lightweight Concrete Columns under Seismic Conditions, Structural Systems Research Project SSRP – 96/08, University of California, San Diego, La Jolla, CA, December 1996.	FL3
SM3	Kowalsky, M.J., Priestley, M.J.N., Seible, F., Shear Behavior of Lightweight Concrete Columns under Seismic Conditions, Structural Systems Research Project SSRP – 95/10, University of California, San Diego, La Jolla, CA, July 1995.	
SM4	Stephan, B., Restrepo, J., Seible F., Seismic Behavior of Bridge Columns Built Incorporating MMFX Steel, Structural Systems Research Project SSRP – 2003/09, University of California, San Diego, La Jolla, CA, October 2003.	Unit 1
SM5	Stephan, B., Restrepo, J., Seible F., Seismic Behavior of Bridge Columns Built Incorporating MMFX Steel, Structural Systems Research Project SSRP – 2003/09, University of California, San Diego, La Jolla, CA, October 2003.	Unit 2

SM6	Holombo, J., MacRae, G., Priestley, M.J.N., Seible, F., Steel Column Prooftests of the Bayshore and Central Viaducts, Structural Systems Research Project SSRP – 95/05, University of California, San Diego, La Jolla, CA, April 1995.	
SM7	Holombo, J., MacRae, G., Priestley, M.J.N., Seible, F., Steel Column Prooftests of the Bayshore and Central Viaducts, Structural Systems Research Project SSRP – 95/05, University of California, San Diego, La Jolla, CA, April 1995.	Retro
J1	Sritharan, S., Priestley, M.J.N., Seible, F., Seismic Design And Performance Of Concrete Multi-Column Bents For Bridges, Structural Systems Research Project SSRP – 97/03, University of California, San Diego, La Jolla, CA, June 1997.	MCB1
J2	Sritharan, S., Priestley, M.J.N., Seible, F., Seismic Design And Performance Of Concrete Multi-Column Bents For Bridges, Structural Systems Research Project SSRP – 97/03, University of California, San Diego, La Jolla, CA, June 1997.	MCB1
J3	Ingham, J., Priestley, M.J.N., Seible, F., Seismic Performance of Bridge Knee Joints - Vol. I, Structural Systems Research Project SSRP – 94/12, University of California, San Diego, La Jolla, CA, June 1994.	Unit 1
J4	Ingham, J., Priestley, M.J.N., Seible, F., Seismic Performance of Bridge Knee Joints - Vol. I, Structural Systems Research Project SSRP – 94/12, University of California, San Diego, La Jolla, CA, June 1994.	Unit 2
J5	Ingham, J., Priestley, M.J.N., Seible, F., Seismic Performance of Bridge Knee Joints - Vol. I, Structural Systems Research Project SSRP – 94/12, University of California, San Diego, La Jolla, CA, June 1994.	Unit 5
J6	Ingham, J., Priestley, M.J.N., Seible, F., Seismic Performance of Bridge Knee Joints - Vol. I, Structural Systems Research Project SSRP – 94/12, University of California, San Diego, La Jolla, CA, June 1994.	Unit 7
SP1	Megally, S. H., Garg, M., Seible, F., Dowell, Robert K., Seismic Performance of Precast Segmental Bridge Superstructures, Structural Systems Research Project SSRP – 2001/24, University of California, San Diego, La Jolla, CA, May 2002.	100 INT Phase I
SP2	Megally, S. H., Garg, M., Seible, F., Dowell, Robert K., Seismic Performance of Precast Segmental Bridge Superstructures, Structural Systems Research Project SSRP – 2001/24, University of California, San Diego, La Jolla, CA, May 2002.	100 INT-CIP Phase I

SP3	Megally, S. H., Garg, M., Seible, F., Dowell, Robert K., Seismic Performance of Precast Segmental Bridge Superstructures, Structural Systems Research Project SSRP – 2001/24, University of California, San Diego, La Jolla, CA, May 2002.	100 EXT Phase I
SP4	Megally, S. H., Garg, M., Seible, F., Dowell, Robert K., Seismic Performance of Precast Segmental Bridge Superstructures, Structural Systems Research Project SSRP – 2001/24, University of California, San Diego, La Jolla, CA, May 2002.	50INT/50EXT Phase I
SP5	Megally, S. H., Garg, M., Seible, F., Dowell, Robert K., Seismic Performance of Precast Segmental Bridge Superstructures, Structural Systems Research Project SSRP – 2001/24, University of California, San Diego, La Jolla, CA, May 2002.	100 INT Phase II
SP6	Megally, S. H., Garg, M., Seible, F., Dowell, Robert K., Seismic Performance of Precast Segmental Bridge Superstructures, Structural Systems Research Project SSRP – 2001/24, University of California, San Diego, La Jolla, CA, May 2002.	100 INT-CIP Phase II
SP7	Megally, S. H., Garg, M., Seible, F., Dowell, Robert K., Seismic Performance of Precast Segmental Bridge Superstructures, Structural Systems Research Project SSRP – 2001/24, University of California, San Diego, La Jolla, CA, May 2002.	100 EXT Phase II
SP8	Megally, S. H., Garg, M., Seible, F., Dowell, Robert K., Seismic Performance of Precast Segmental Bridge Superstructures, Structural Systems Research Project SSRP – 2001/24, University of California, San Diego, La Jolla, CA, May 2002.	50INT/50EXT Phase II
F1	Silva, P., Seible, F., Priestley, M.J.N., Response of Standard Caltrans Pile-To-Pile Cap Connections Under Simulated Seismic Loads, Structural Systems Research Project SSRP – 97/09, University of California, San Diego, La Jolla, CA, November 1997.	STD 1
F2	Silva, P., Seible, F., Priestley, M.J.N., Response of Standard Caltrans Pile-To-Pile Cap Connections Under Simulated Seismic Loads, Structural Systems Research Project SSRP – 97/09, University of California, San Diego, La Jolla, CA, November 1997.	STD 2
F3	Silva, P., Seible, F., Priestley, M.J.N., Response of Standard Caltrans Pile-To-Pile Cap Connections Under Simulated Seismic Loads, Structural Systems Research Project SSRP – 97/09, University of California, San Diego, La Jolla, CA, November 1997.	STD 3
F4	Xiao, Y., Priestley, M.J.N., Seible, F., Experimental Evaluation of a Typical Bridge Column Footing Designed to Current Caltrans Standards, Structural Systems Research Project SSRP – 95/08, University of California, San Diego, La Jolla, CA, March 1995.	

F5	Xiao, Y., Priestley, M.J.N., Seible, F., Hamada, N., Seismic Assessment and Retrofit of Bridge Footings, Structural Systems Research Project SSRP – 94/11, University of California, San Diego, La Jolla, CA, May 1994.	Retrofit F2CR
F6	Xiao, Y., Priestley, M.J.N., Seible, F., Hamada, N., Seismic Assessment and Retrofit of Bridge Footings, Structural Systems Research Project SSRP – 94/11, University of California, San Diego, La Jolla, CA, May 1994.	F1RA
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SM5	Patty, J., Seible, F., Uang, C-M., Seismic Response of Integral Bridge Connections, Structural Systems Research Project SSRP – 2000/16, University of California, San Diego, La Jolla, CA, October 2002.	Specimen 1 (CR-NS)
SM6	Patty, J., Seible, F., Uang, C-M., Seismic Response of Integral Bridge Connections, Structural Systems Research Project SSRP – 2000/16, University of California, San Diego, La Jolla, CA, October 2002.	Specimen 2 (CR-S)
SM7	Patty, J., Seible, F., Uang, C-M., Seismic Response of Integral Bridge Connections, Structural Systems Research Project SSRP – 2000/16, University of California, San Diego, La Jolla, CA, October 2002.	Specimen 3 (PT-NS)
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SM13	Holombo, J., Priestley, M.J.N., Seible, F., Longitudinal Seismic Response of Precast Spliced-Girder Bridges, Structural Systems Research Project SSRP – 98/05, University of California, San Diego, La Jolla, CA, April 1998.	Bath Tub
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SM15	Holombo, J., Priestley, M.J.N., Seible, F., Longitudinal Seismic Response of Precast Spliced-Girder Bridges, Structural Systems Research Project SSRP – 98/05, University of California, San Diego, La Jolla, CA, April 1998.	Bath Tub Super

Visual Inspection & Capacity Assessment of Earthquake Damaged Reinforced Concrete Bridge Elements.

Final Report

Appendices

Summary of Related Resources Available by Request through SM&I

A: Research Deployment Products (Developed Collaboratively by UCSD and SM&I)

B: Resources Used in Caltrans Emergency Response Training (Developed by SM&I)

Appendix A: Research Deployment Products
(Developed Collaboratively by UCSD and SM&I)

1) Reinforced Concrete Bridge Capacity Assessment Training Manual

This manual is the primary teaching resource from the project that describes fundamental concepts required for RC bridge capacity assessment. It includes discussion of seismic design concepts, the performance of RC bridge components, post earthquake evaluation, and lessons learned.

2) Post-Earthquake Inspection Manual for Reinforced Concrete Bridge Columns

This manual identifies a step-by-step procedure to guide maintenance and inspection engineers in the determination of the remaining capacity of damaged reinforced concrete bridge columns.

3) Training Slide Sets for RC Bridge Capacity Assessment

These slide sets present key concepts from the Reinforced Concrete Bridge Capacity Assessment Training Manual and the Post Earthquake Inspection Manual for Reinforced Concrete Columns. There are four modules:

Lecture 1: California Seismic Design Concepts (43 slides)

Concepts presented include response and plastic mechanisms, capacity design, material properties, construction techniques, and typical design provisions from pre-1971, 1971-'94, and post 1994.

Lecture 2: Performance of Bridge Components (26 slides)

Illustrates typical columns, flexural failure, shear failure, lap splice failure, hollow column, flared column, lightweight concrete column, connections/joint, superstructure, foundations, abutments/shear keys, bearings and restrainers.

Lecture 3: Post-Earthquake Column Evaluation and Lessons Learned (35 slides)

Addresses damage evaluation, performance curves, failure mechanisms, performance curve determinations, serviceability guidelines, flexure vs. shear, design era, shear vs. lap splice, abutments, and connections.

Lecture 4: Post-Earthquake Column Typing (56 slides)

Provides detailed steps following a flow chart to determine 'type' of column being inspected for use by office engineers and possibly field personnel.

Appendix B: Resources Used in Caltrans Emergency Response Training
(Developed by SM&I)

1) Caltrans SM&I Emergency Response Plan

This plan outlines roles and responsibilities of, and provides a list of actions to be taken by, Structures Maintenance and Investigations (SM&I) staff after a catastrophic event involving structures on the state highway system. It applies to earthquakes, floods, and any major catastrophe involving state highway structures.

2) SM&I Training Program Slide Sets

These slide sets are used to train SM&I and affiliated staff on emergency response procedures involving Caltrans bridges with emphasis on earthquake disaster response. There are five modules:

Lecture 1: SM&I Emergency Response Plan (106 slides)

Reviews SM&I's emergency response procedures as detailed in the Caltrans SM&I Emergency Response Plan. The objective is to assure that the trainee understands the Department's duties as well as their own duties.

Lecture 2: California Seismic Retrofits (31 slides)

Illustrates California bridge seismic retrofit strategies and elements in more detail.

Lecture 3: Field Investigation (88 slides)

Describes what to expect and what elements to inspect after an earthquake. Provides examples of actual damaged elements, and lists available inspection tools and techniques for post earthquake inspection.

Lecture 4: Analyze/Recommendations/Repairs and Reports (41 slides)

Outlines process of making field decisions, conducting post-investigation analyses, and providing damage reporting and work recommendations needed to assess either the closing of a structure or the opening of a structure with shoring and/or emergency repairs.

Lecture 5: ABME Combined 1-4 Post Earthquake Column Typing (102 slides)

An overview compilation of the more detailed four-part training slide sets for Post Earthquake Inspection and RC Column Capacity Assessment training that was developed with University of California San Diego (see Appendix A-3).