California Department of Transportation
Structure Maintenance and Investigations

Visual Catalog of Reinforced Concrete Bridge Damage

© Copywrite 2006 California Department of Transportation
All Rights Reserved

Date: June 20, 2006

Acknowledgements

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.

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
Table of Contents

Table of Contents ……... i

Introduction

Organization …..……..1

Damage Levels ……..……. 2

Seismic Design Provisions ……. 2

Discussion of Bridge Component Behavior…… 5

References …..……7

Part I - Laboratory Tests Photos

Components

Columns

Ordinary Columns

Flexural…..... 13

Shear..... 35

Lap Splice..... 46

Special Sections

Hollow…… 50

Boundary elements..... 54

Flared 58

Special Material

Lightweight …… 63

MMX Steel …… 67

Steel Column ……. 70

Joints 73

Superstructure ……. 80

Foundations ..... ……... 89

Abutments/Shear Keys 97

Retrofit 105

Sub-Assemblages – Systems

Column Superstructure Sub-Assemblages 119

Column Foundation Sub-Assemblages 129

Double Deck Viaduct 131

Precast 134

Part II - Field Photos from Historic Earthquakes

Classification According to Earthquake

San Fernando, USA 1971 141

Imperial Valley, USA 1979 144

Whittier Narrows 1987 146

Loma Prieta 1989 150

Erzincan, Turkey 1992 158

Northridge, USA 1994 160

Morgan Hill, USA 1994 178

Kobe, Japan 1995 180

Adana-Ceyhan 1998 187

Izmit, Turkey 1999 189

Duzce, Turkey 1999 193

Chi-Chi, Taiwan 1999 195

Kocaeli, Turkey 1999 208

Mid Niigata Prefecture Earthquake, Japan 2004 211

Classification According to Type of Damage

Columns

Flexural 217

Shear 222

Retrofit 241

Joint Damage 243

Superstructure

Deck 249

Cap beams/Girder 256

Span Collapse ……. 259
Movement…….. 264
Foundations/Soil Damage …… 268
Abutments/Shear Keys …… 271
Bearing Damage …….. 280
Total Collapse ……...…… 283

Part III - Correlation

Correlation of Field Photos with Laboratory Database

Flexural …….……. 288
Shear …….……...…….. 292
Joints …….…….……...……. 295
Cap Beam – Column ……..... 298
Abutments/Shear Keys ……... 300
Superstructure ……... 305
Foundation ……..……...…… 307
Other cases …….…….…….…. 309

Part IV – Details

Details of Extreme Damage Levels

Flexural Level V 312
Shear Level V 313
Lap Splice …..... 314
Retrofit – Level IV 315
Retrofit – Level V 316
Joints - Level V 317
Foundation - Level V 318
Shear Key – Level V 319

Part V – Performance Curves

Correlation of Damage Level with Performance Curves

Columns …….……321
Joints ……... 329

Foundations …….332
Abutments ……... 337

Appendix

References by Catalog Number……... 339

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

REFERENCES

1. 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.
2. 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.
3. Chai, Y., Priestley, M.J.N., Seible, F., Flexural Retrofit of Circular Reinf. Concrete Bridge Columns by Steel Jacketing-Experimental Studies, Structural Systems Research Project SSRP – 91/06, University of California, San Diego, La Jolla, CA, October 1991.
4. 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.
5. Dowell, R., Burgueño, R., Seible, F., Priestley, M.J.N., Mari, A., The Terminal Separation Replacement Structure Prooftest and Retrofit Test, Structural Systems Research Project SSRP – 94/15, University of California, San Diego, La Jolla, CA, October 1994.
6. 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

7. 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.

8. Hewes, J., Priestley, M.J.N., Seismic Design and Performance of Precast Concrete Segmental Bridge Columns, Structural Systems Research Project SSRP – 2001/25, University of California, San Diego, La Jolla, CA, June 2002.

9. 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.

10. 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.

11. 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.

12. 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

13. 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.

14. Innamorato, D, Seible, F., Hegemier, G., Priestley, M.J.N., Ho, F., Full Scale Test of a Two Column Bridge Bent with Carbon Fiber Jacket Retrofit, Advanced Composite Technology Transfer ACTT-96/10, University of California, San Diego, La Jolla, CA, August 1996.

15. 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.

16. 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.

17. 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.

18. MacGregor J.G., Wight J.K. "Reinforced Concrete : Mechanics And Design", 4th Ed., Upper Saddle River, New Jersey: Pearson Education, Inc., 2005.

19. 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.

20. Megally, S. H., Silva, P.F., Seible, F., Seismic Response of Sacrificial Shear Keys in Bridge Abutments, Structural Systems Research Project SSRP – 2001/23, University of California, San Diego, La Jolla, CA, May 2002.

21. 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.

22. Moehle et al, "Highway Bridges and Traffic Management", *Earthquake Spectra*, Vol. 11, Supplement C, Chapter 6, April, 1995

23. National Information Service for Earthquake Engineering. http://nisee.berkeley.edu/northridge/highway_bridges.html (accessed Dec 2004)

24. 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.

25. 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.

26. Priestley, M.J.N., Seible F., Calvi G.M., "Seismic Design And Retrofit of Bridges", 1st Ed., New York, New York : John Wiley And Sons, Inc., 1996.

27. Priestley, M.J.N., Seible, F., Anderson, D., Proof Test of a Retrofit Concept for the San Francisco Double-Deck Viaducts, Structural Systems Research Project SSRP – 92/03, University of California, San Diego, La Jolla, CA, July 1992.

28. 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.

29. 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.

30. 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.

31. Roberts, J.E., "Caltrans Structural Control for Bridges in High-Seismic Zones", *Earthquake Engineering and Structural Dynamics*, 2005, Vol. 34, pages 449-470.

32. 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.

33. Schoettler, M., Restrepo, J., Seible, F., BART Aerial Guideway Bent Proof Test, Structural Systems Research Project SSRP – 2002/13, University of California, San Diego, La Jolla, CA, October 2002.

34. Seible, F., Priestley, M.J.N., Latham, C., Silva, P., Full-Scale Bridge Column/Superstructure Connection Tests under Simulated Longitudinal Seismic Loads, Structural Systems Research Project SSRP – 94/14, University of California, San Diego, La Jolla, CA, June 1994.

35. Seible, F., Priestley, M.J.N., Sun, Z.L., San Francisco Flexural Retrofit Validation Tests on Rectangular Columns, Structural Systems Research Project SSRP – 90/07, University of California, San Diego, La Jolla, CA, December 1990.

36. Shmoldas, A., Shleifer, G., Seible, F., Innamorato, D., Carbon Fiber Retrofit of the Arroyo Seco Spandrel Column, Structural Systems Research Project SSRP – 97/13, University of California, San Diego, La Jolla, CA, October 1997.

37. 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.

38. Silva, P.F., Sritharan, S., Seible, F., Priestley, M.J.N., Full-Scale Test of the Alaska Cast-In-Place Steel Shell Three Column Bridge Bent, Structural Systems Research Project SSRP – 98/13, University of California, San Diego, La Jolla, CA, February 1999.

39. 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.

40. Sritharan, S., Priestley, M.J.N., Seible, F., Seismic Response of Column/Cap Beam Tee Connections w/Cap Beam Prestressing, Structural Systems Research Project SSRP – 96/09, University of California, San Diego, La Jolla, CA, December 1996.

41. 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.

42. 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.

43. 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.

44. 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.

45. 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.

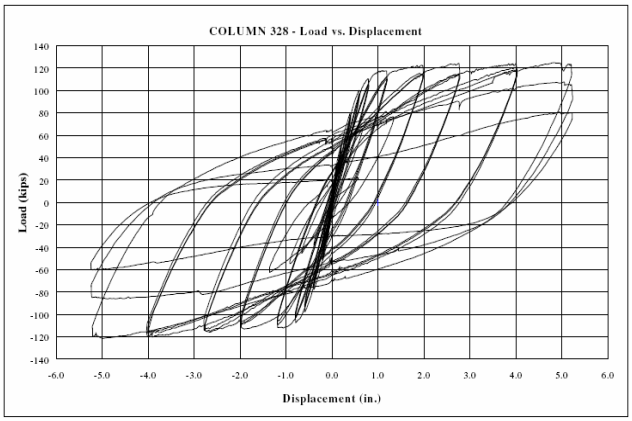
Part I

Laboratory tests photos

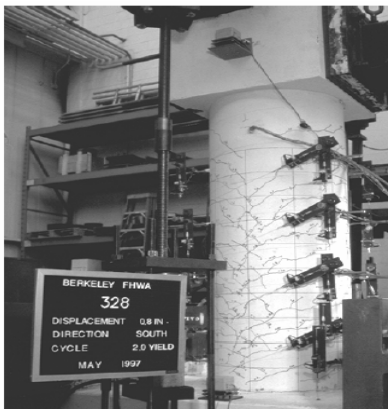
Ordinary Columns

Flexural

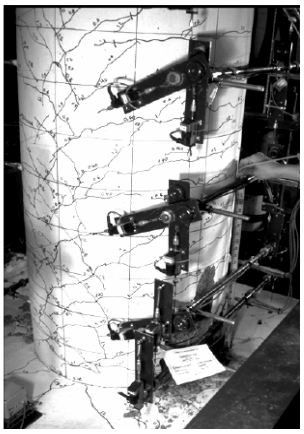
F1 – Flexural - Ductile



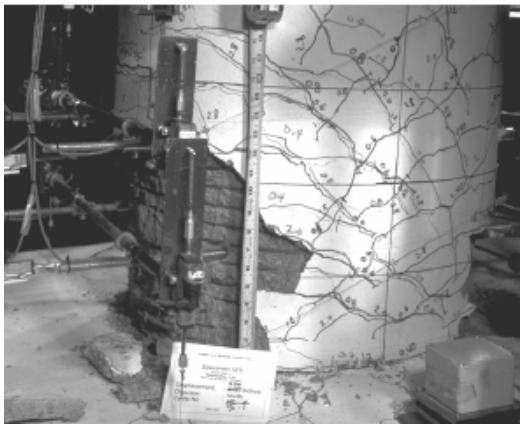
F-d Graph



Level II

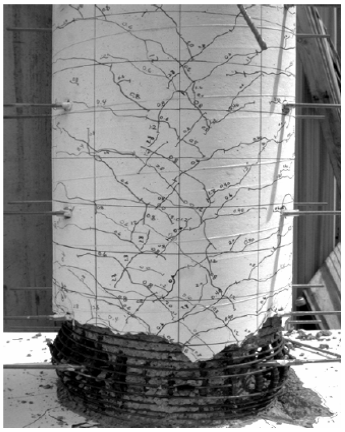


Level III



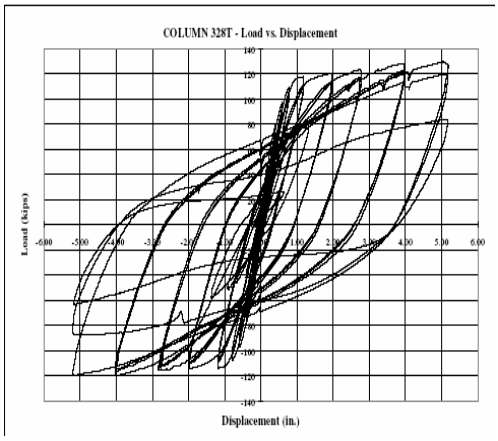
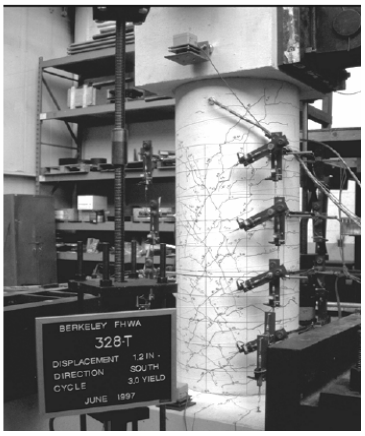
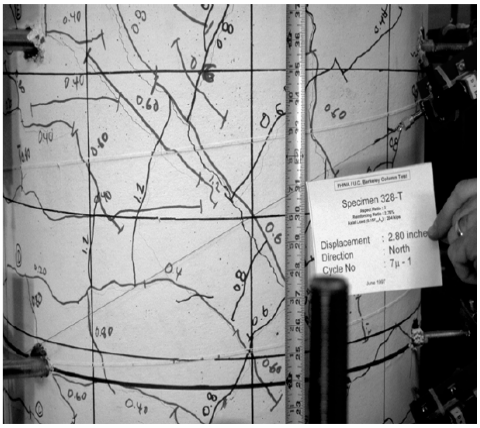
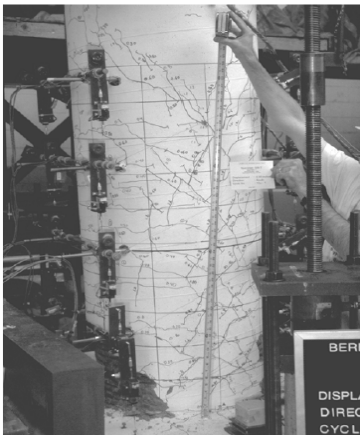
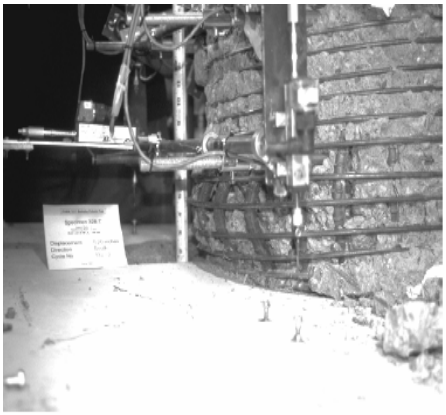
Level IV

Level V (buckling of long. bars)

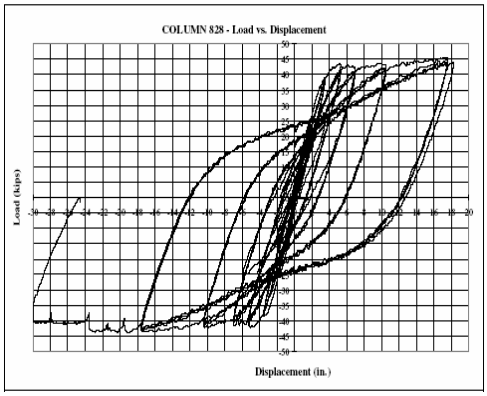


Level V

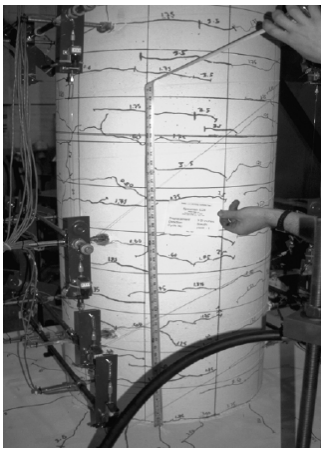
F2- Flexural - Ductile

	
F-d Graph	Level II
	
Level II	Level IV
	
Level V cycle 1 (buckling of long. bars)	

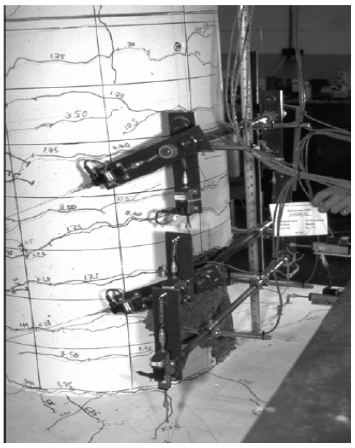
F3 – Flexural - Ductile



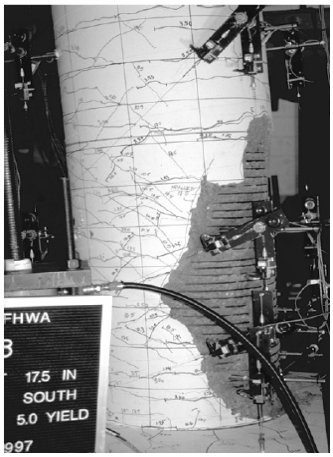
F-d Graph



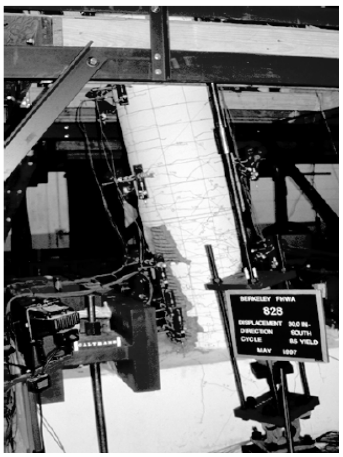
Level II



Level III

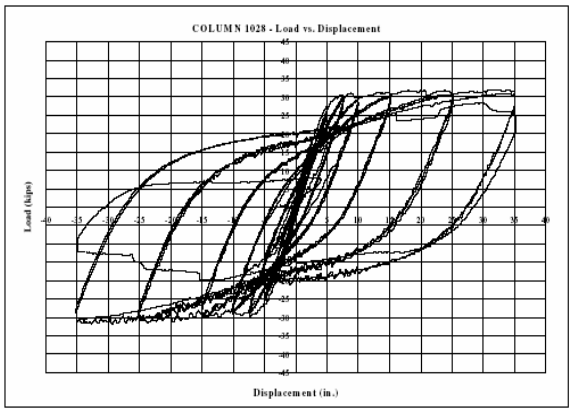


Level IV

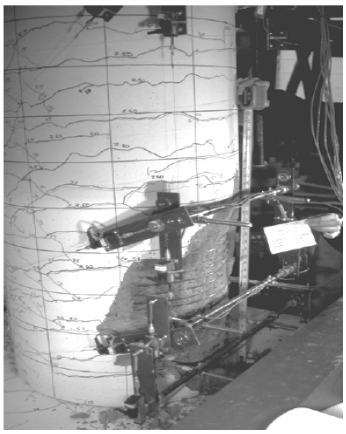


Level V (permanent deformation)

F4 – Flexural - Ductile



F-d Graph



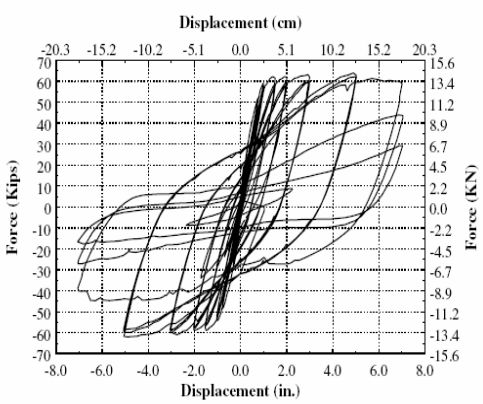
Level IV

Level V

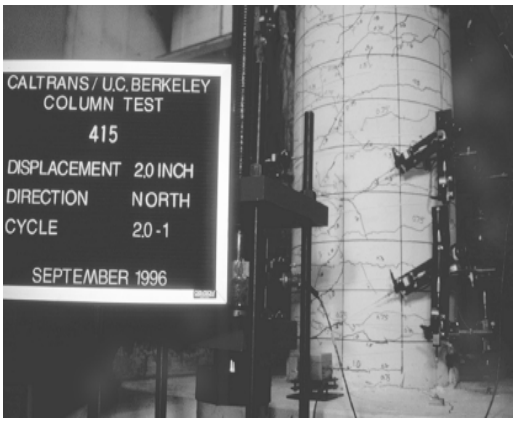
Level V -(buckling of bars)

Level V

F5 – Flexural - Ductile

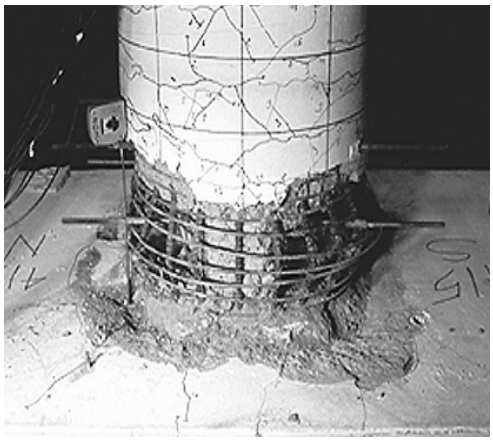


F-d Graph



Level II

Level IV



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

F6 – Flexural - Ductile

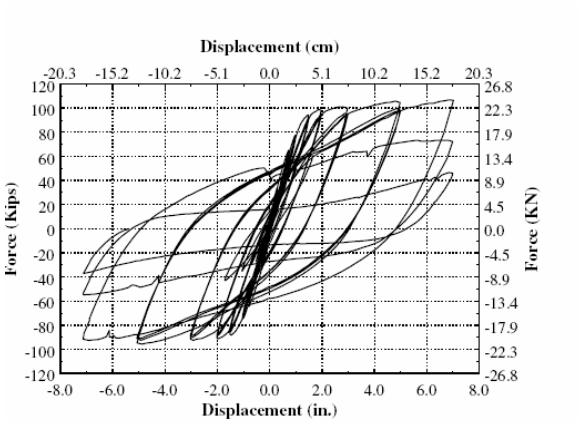
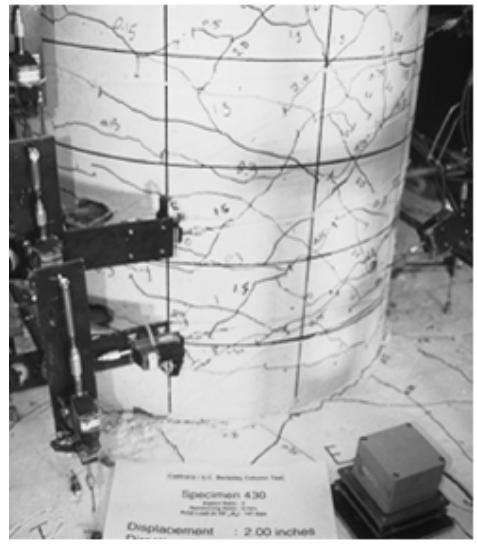
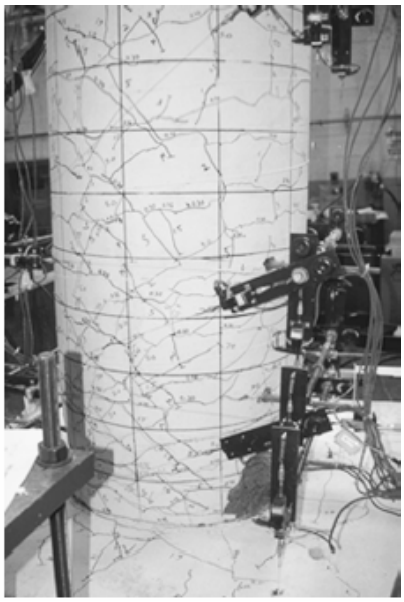


Figure 3.24: Column 430 Force-Displacement Response

F-d Graph



Level II



Level III

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

F7 – Flexural - Ductile

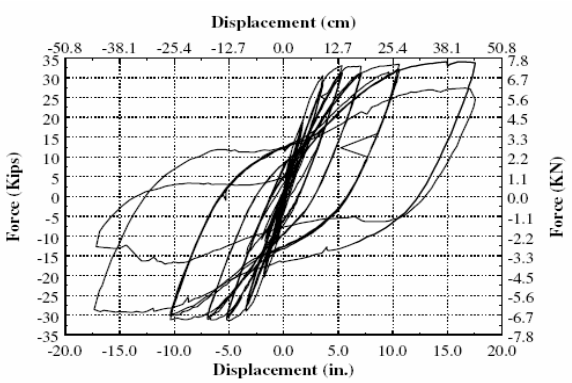
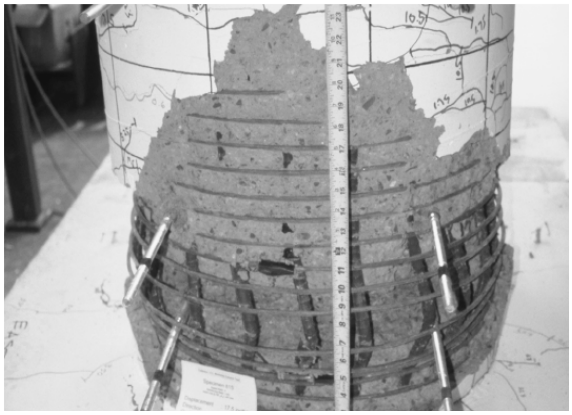


Figure 3.33: Column 815 Force-Displacement Response

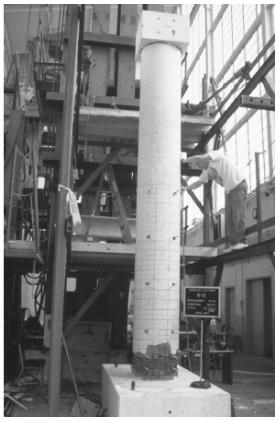
F-d Graph

Level II

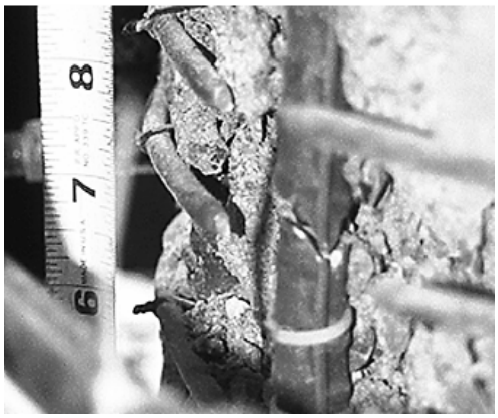
Level IV



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

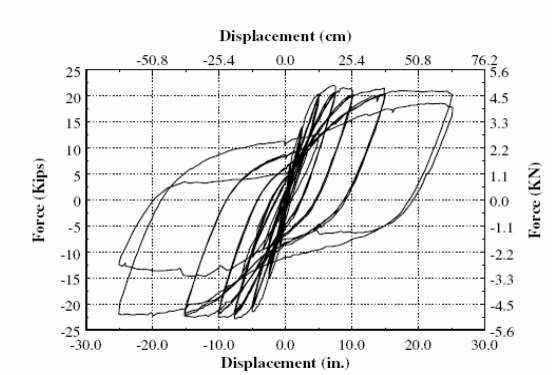


Level V

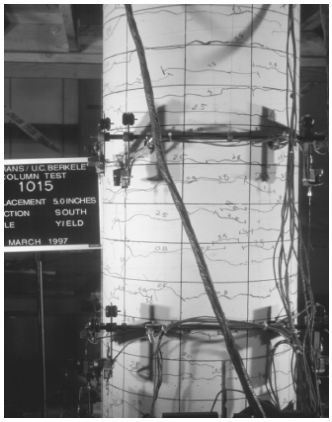


Level V cycle 2 (fracture of long. bars)

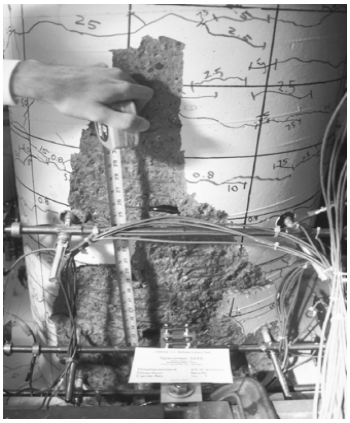
F8 – Flexural - Ductile



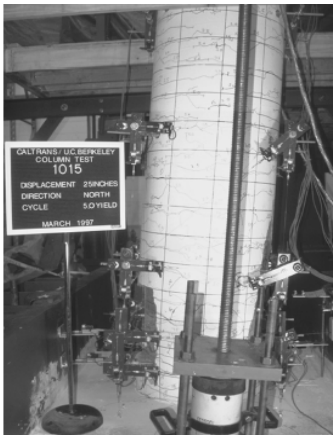
F-d Graph



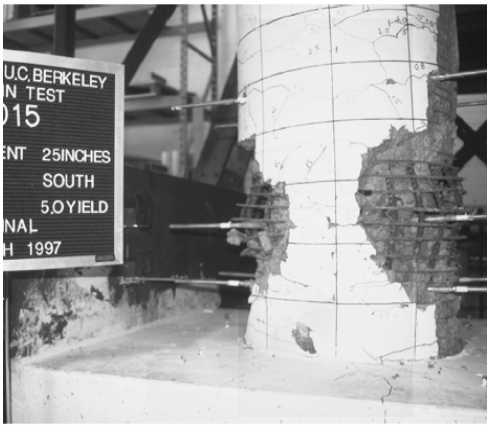
Level II



Level III

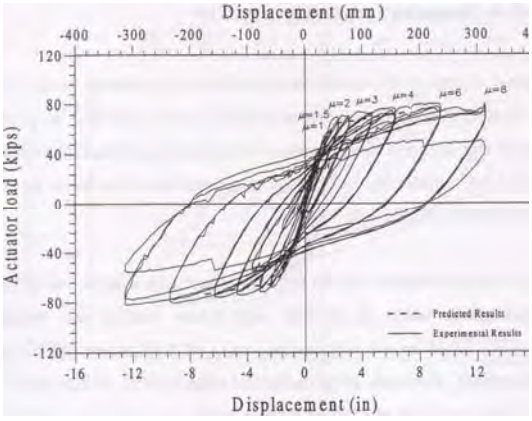


Level V (permanent deformation)

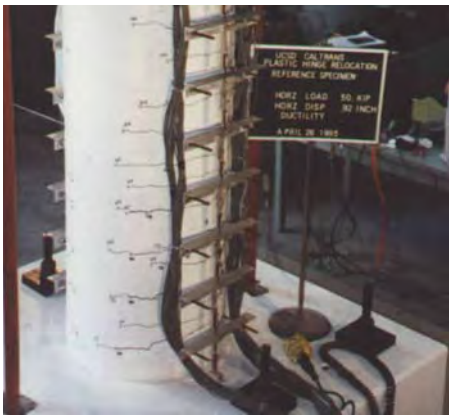


Level V (buckling of long. bars)

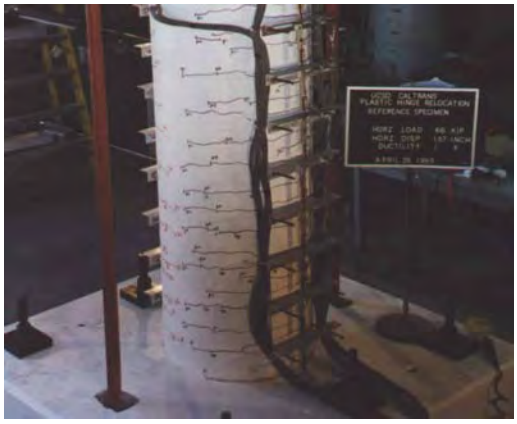
F9 – Flexural - Ductile



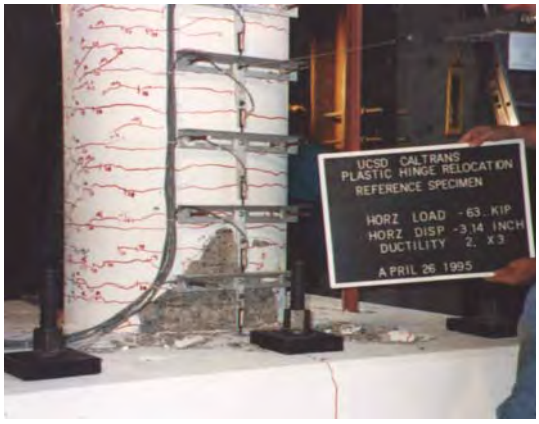
F-d Graph



Level I

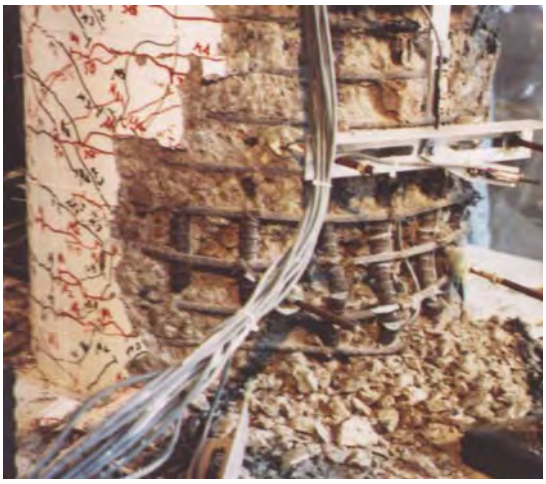


Level II



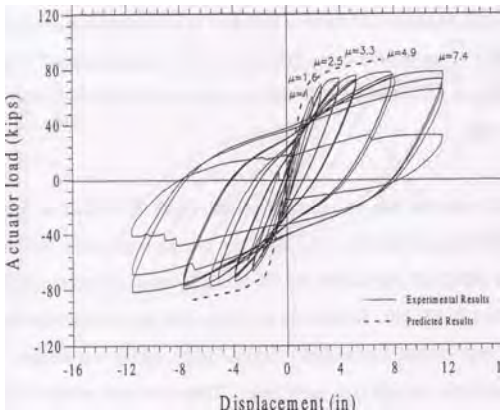
Level III

Level IV



Level V (buckling of long. bars)

F10 – Flexural - Ductile



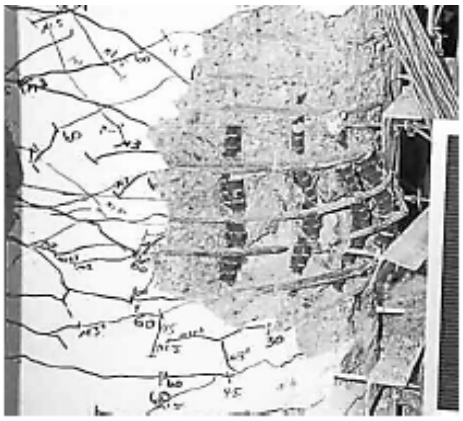
F-d Graph

Level I

Level II

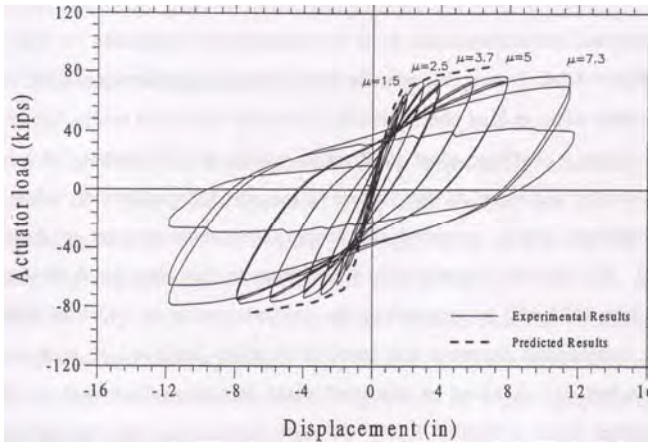
Level III

Level IV

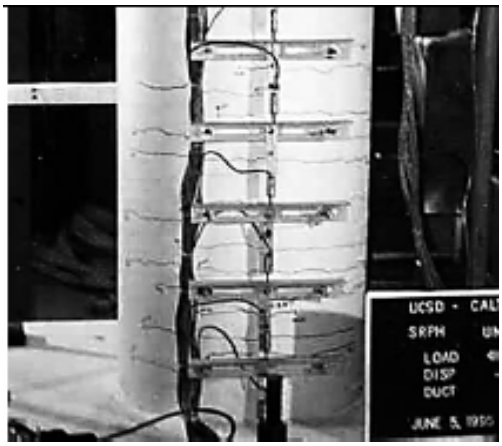


Level V (buckling of long bars)

F11 – Flexural - Ductile



F-d Graph



Level I

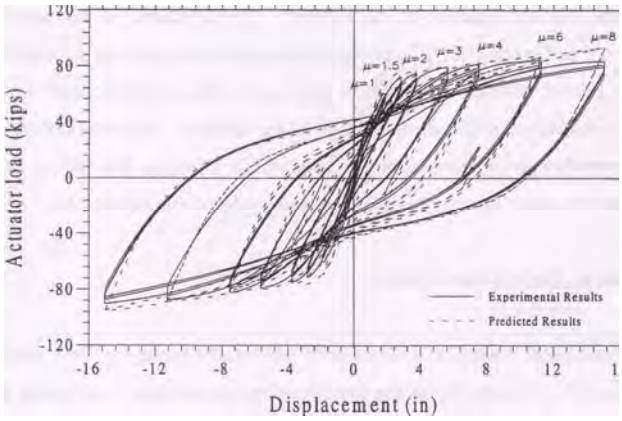
Level II

Level III

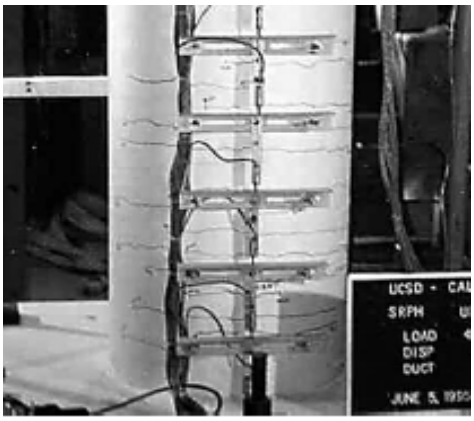
Level IV

Level V (buckling of long. bars)

F12 – Flexural – Ductile

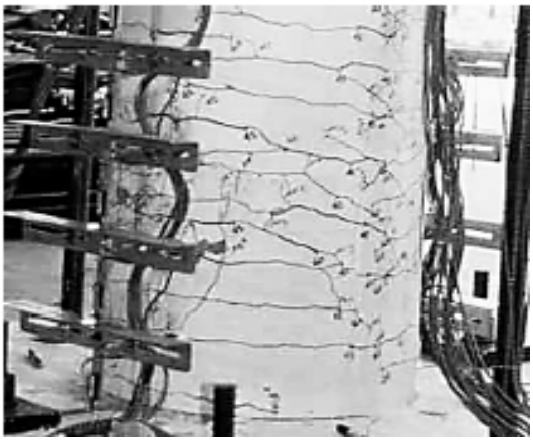


F-d Graph

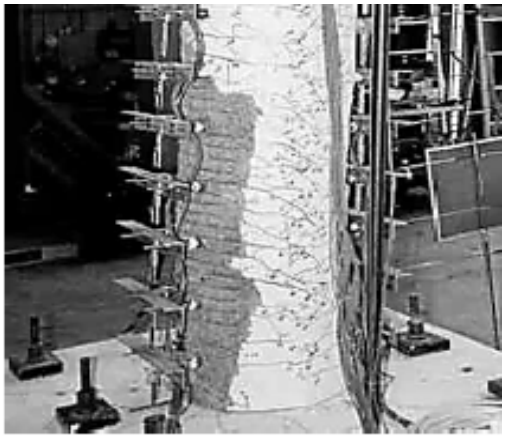


Level I

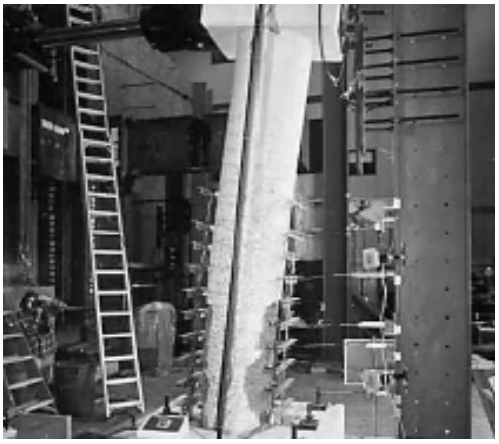
Level II



Level III

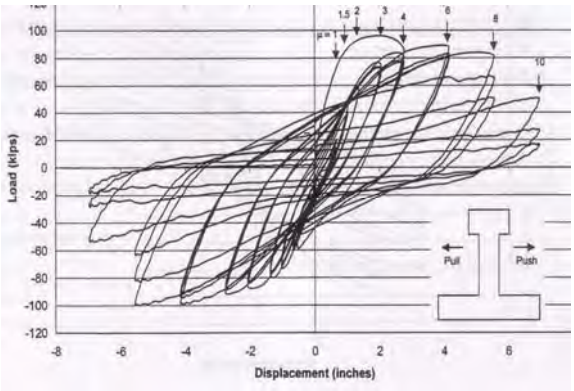


Level IV

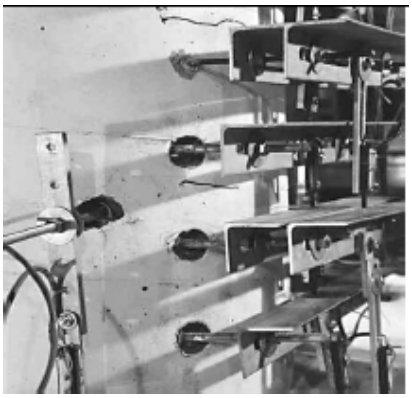


Level V (permanent deformation)

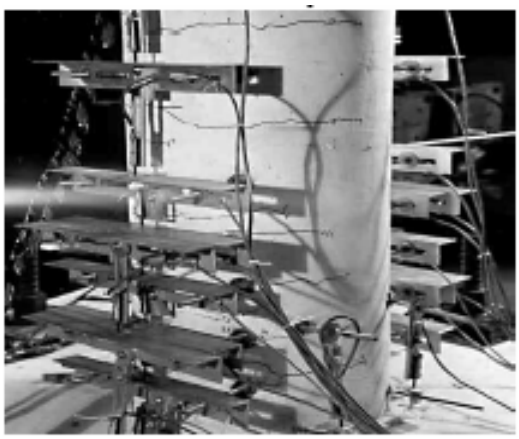
F13 – Flexural – Ductile



F-d Graph



Level I



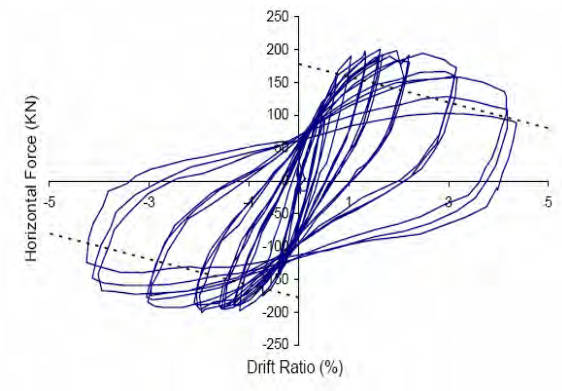
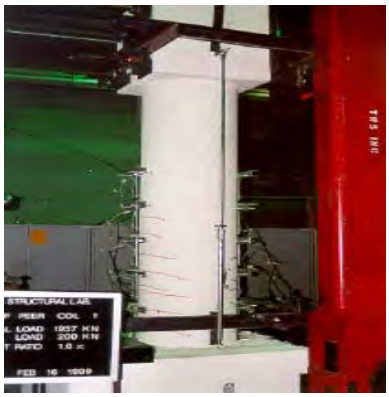
Level II

Level III

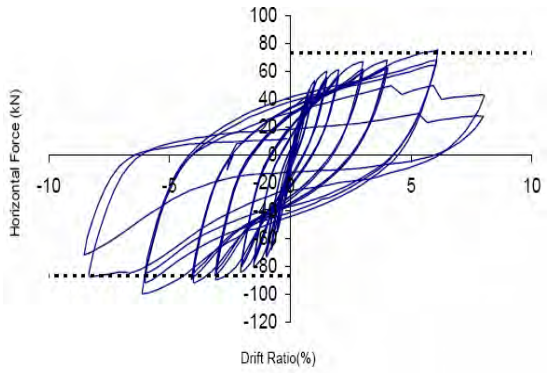
Level IV

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

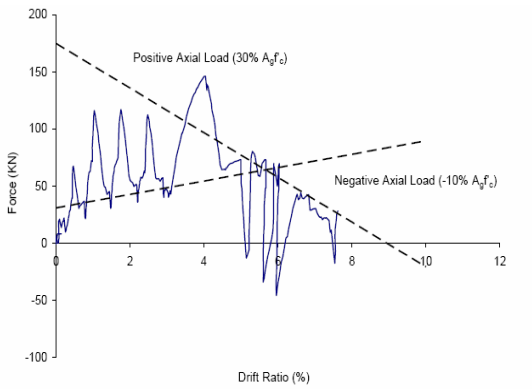
Level III

Level IV

Level V

Level V

F16 – Flexural – Ductile



F-d Graph

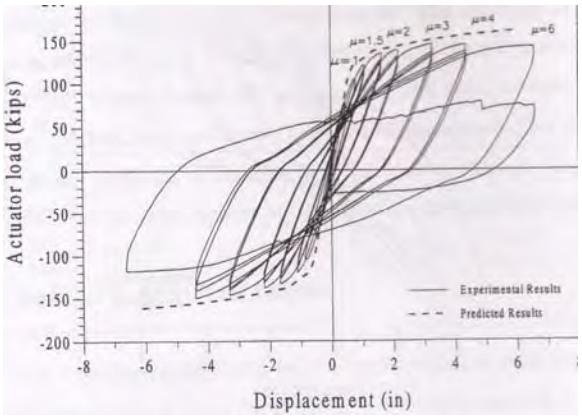
Level II

Level III

Level IV

Level IV

F17 – Flexural/Shear – Ductile



F-d Graph

Level I

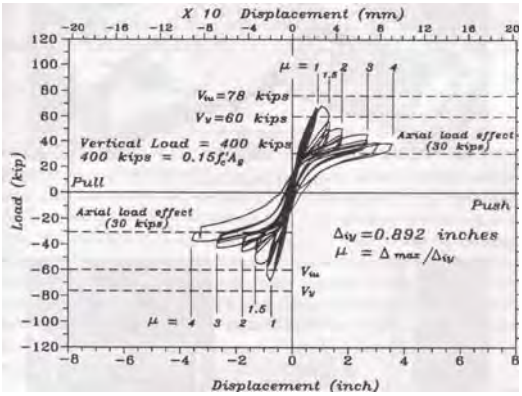
Level II

Level III

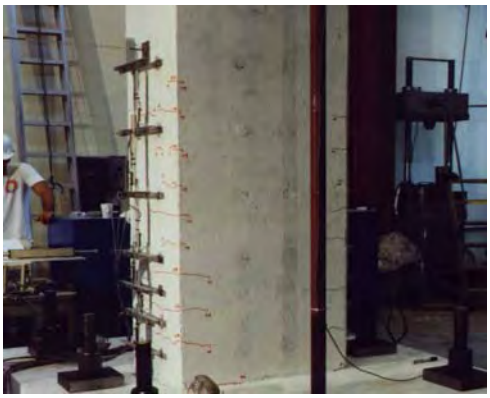
Level IV

Level V

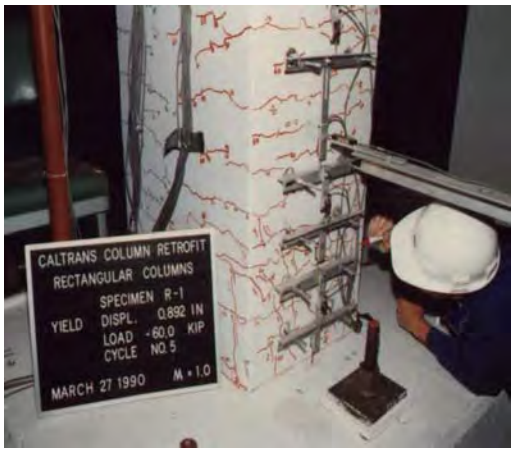
F18 – Flexural – Brittle



F-d Graph



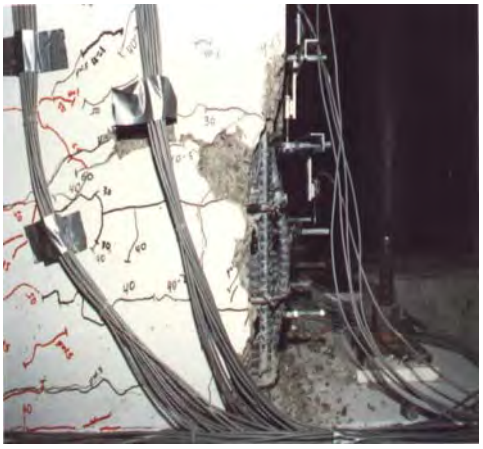
Level I



Level II

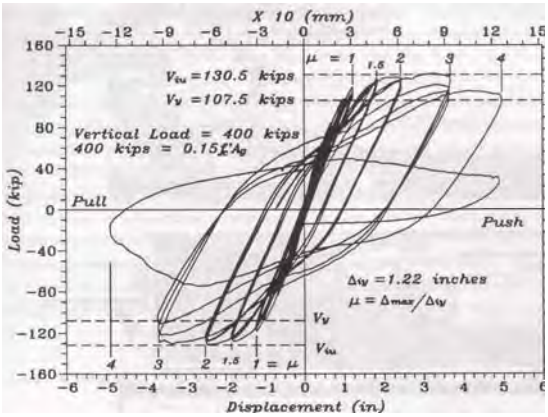
Level III

Level IV



Level V - (buckling of long. bars)

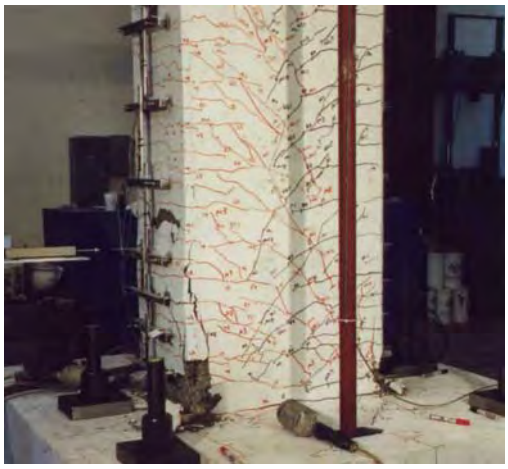
F19 – Flexural – Ductile



Level I

Level II

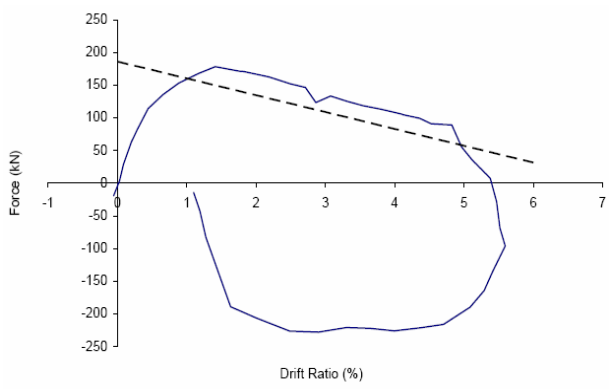
Level III



Level IV

Level V - (buckling of long. bars)

F20 – Flexural – Strength Degrading



F-d Graph

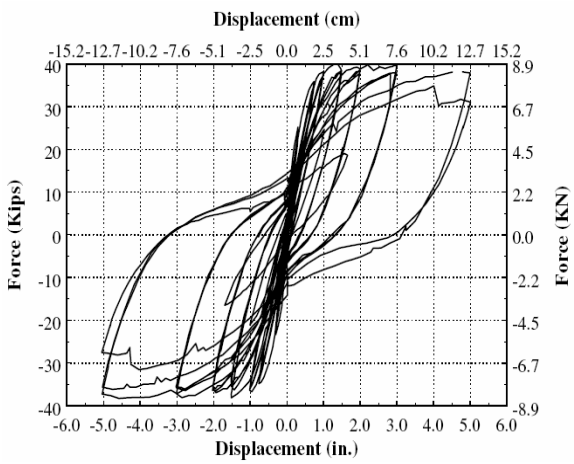
Level III

Level V

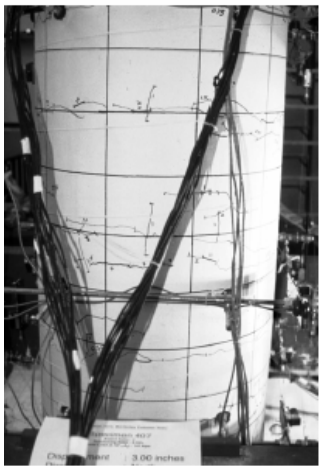
Level V

Level V fracture stirrup, buckling bars

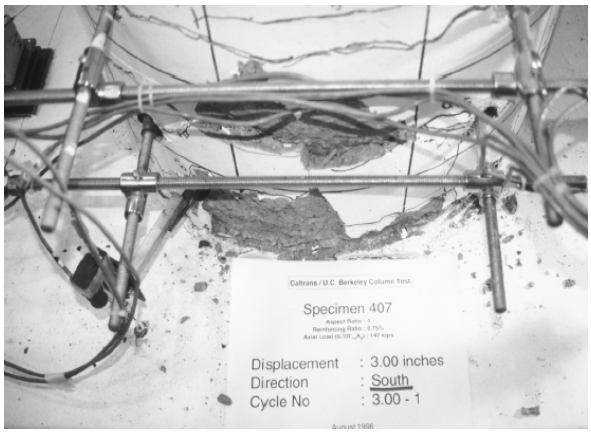
F21 – Flexural – Ductile



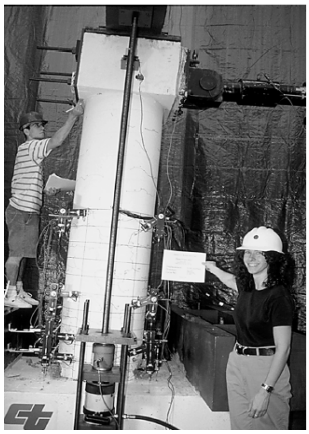
F-d Graph



Level I



Level III



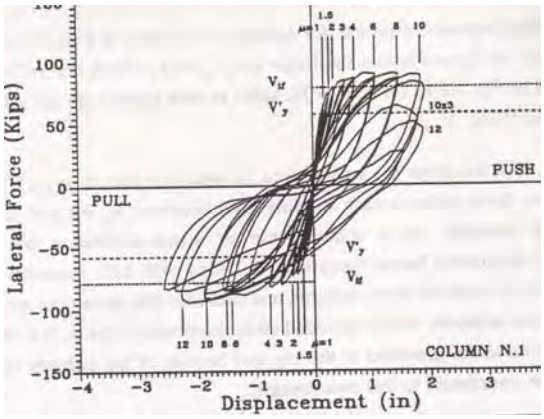
Level V (permanent deformation)

Level V cycle 1 (buckling of bars)

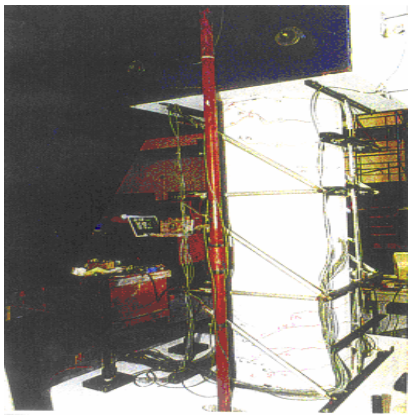
Level V cycle 2 (fracture of bars)

Shear

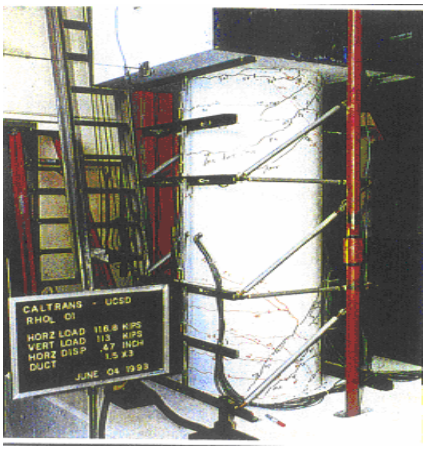
S1 – Shear – Ductile



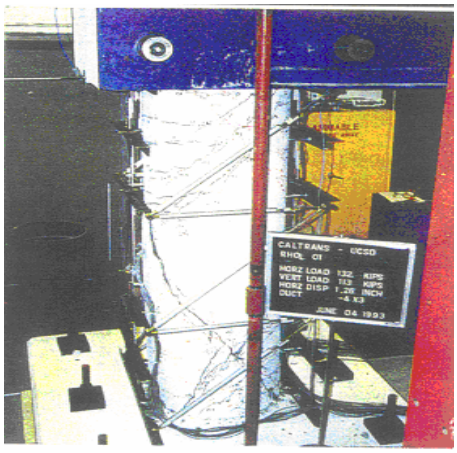
F-d Graph



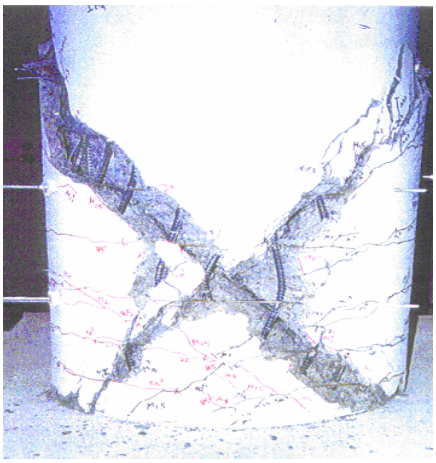
Level II



Level III

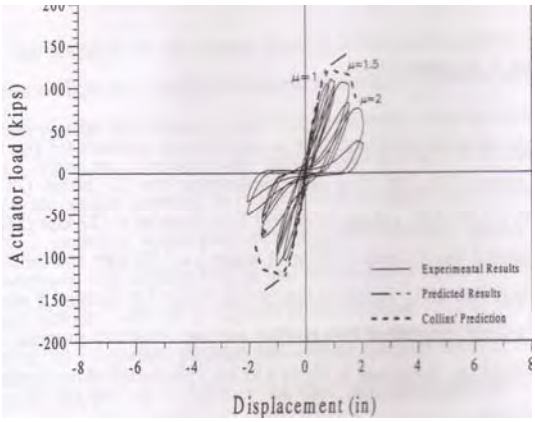


Level IV

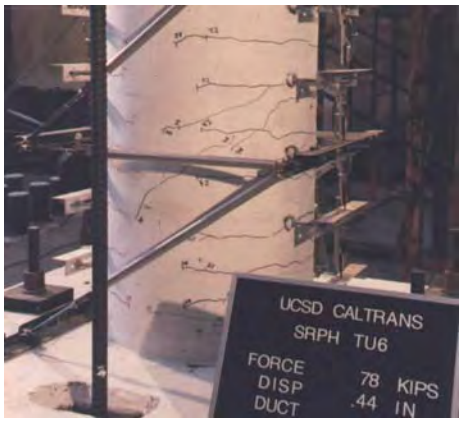


Level V

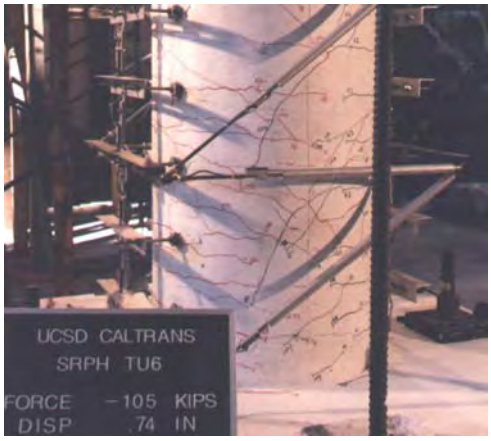
S2 – Shear – Brittle



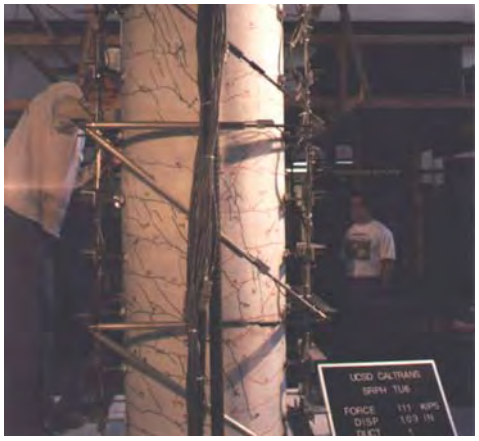
F-d Graph



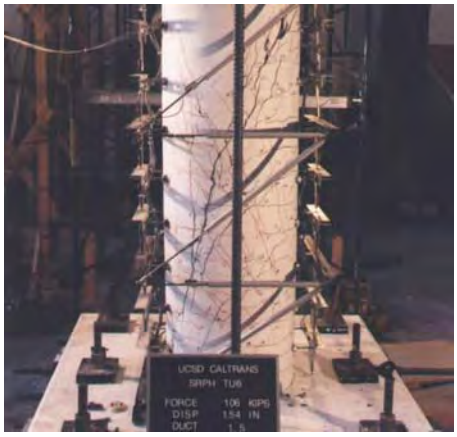
Level I



Level II



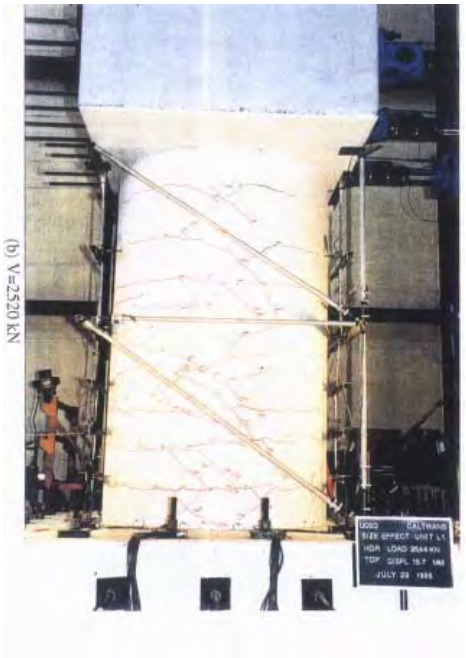
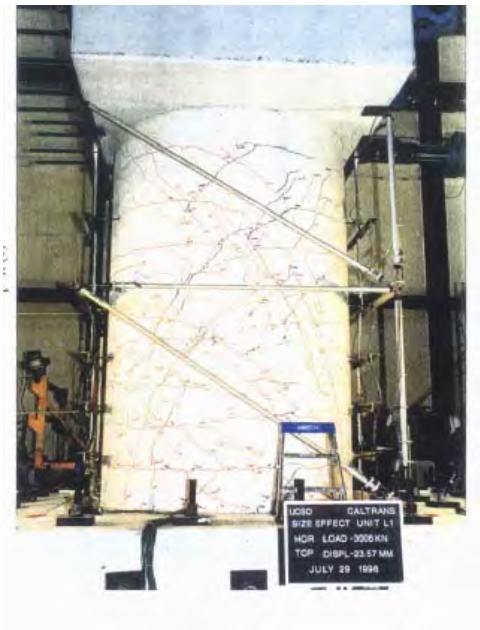
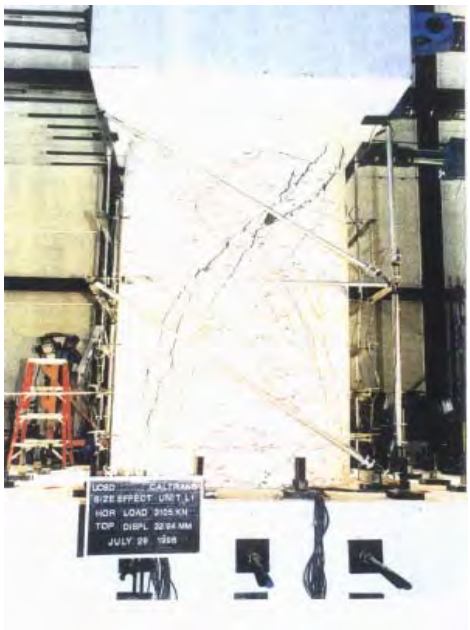
Level III



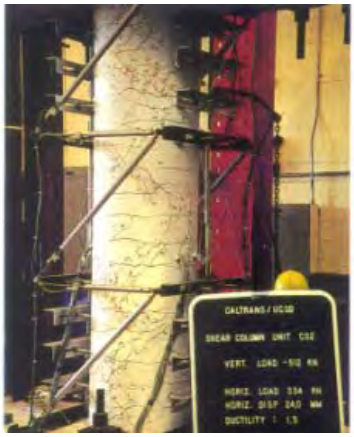
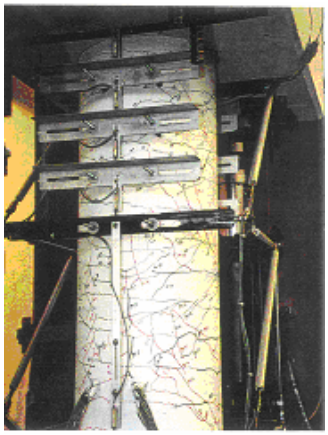
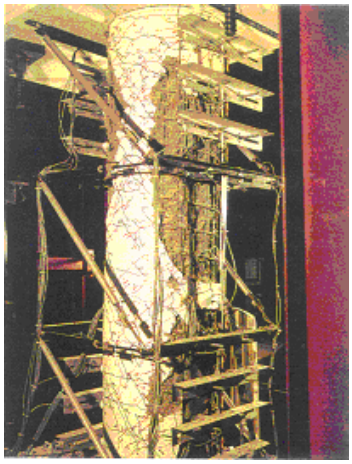
Level IV

Level V

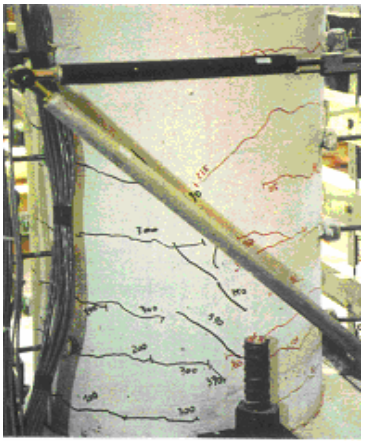
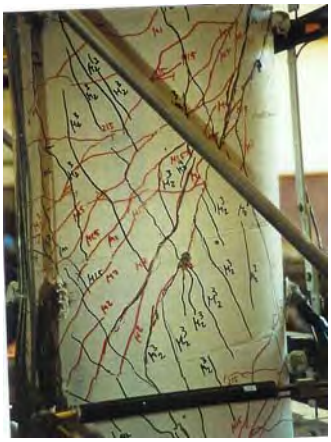
S3 – Shear – Brittle

	
Level II	Level III
	
Level IV	Level V

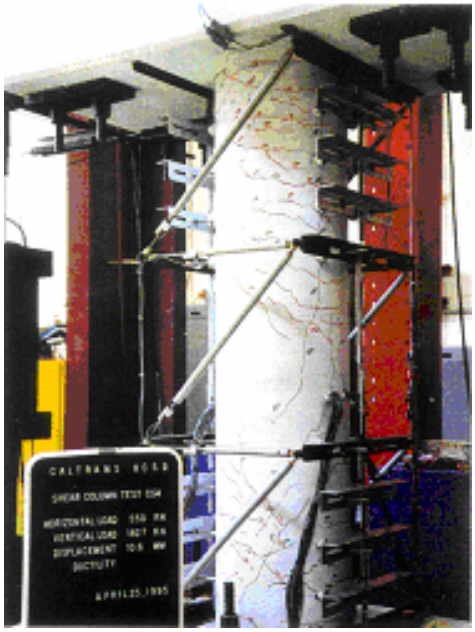
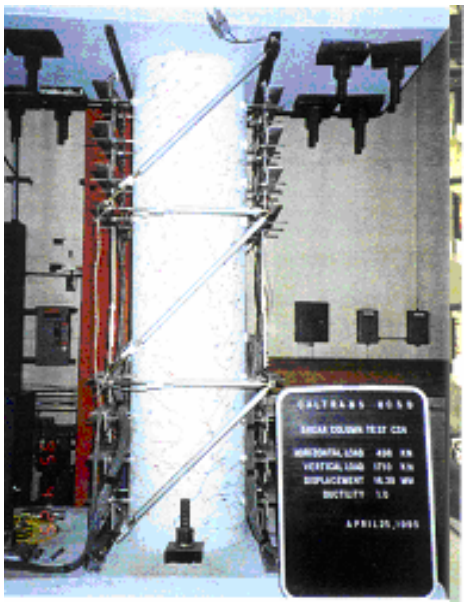
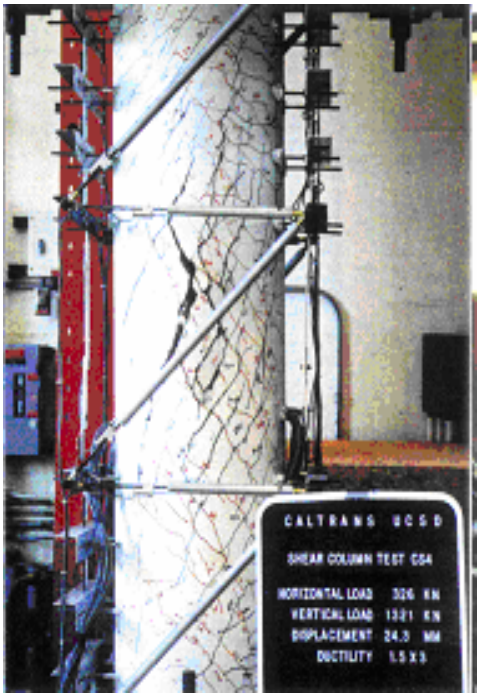
S4 – Shear – Brittle

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

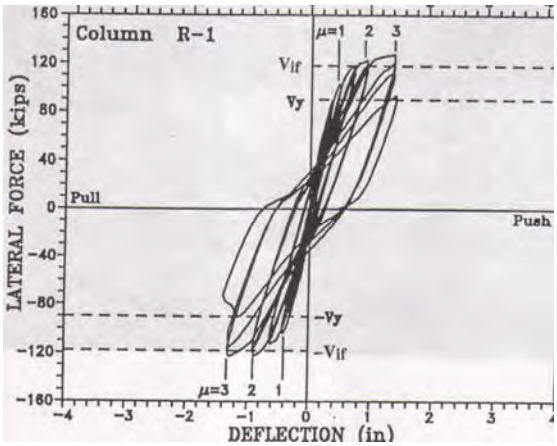
S5 – Shear – Brittle

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

S6 – Shear – Brittle

	
Level III	Level IV
	
Level V	Level V

S7 – Shear – Brittle



F-d graph

Level II

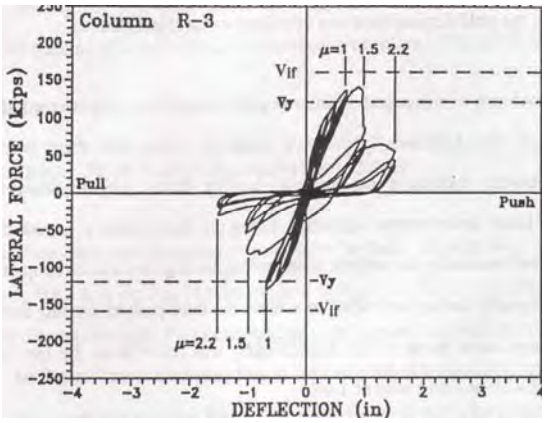
Level III

Level IV

Level V

Level V

S8 – Shear – Brittle



F-d graph

Level II

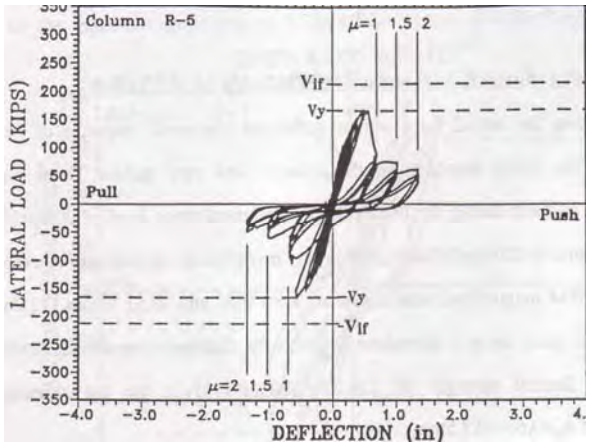
Level III

Level IV

Level V

Level V

S9 – Shear – Brittle



F-d graph

Level II

Level III

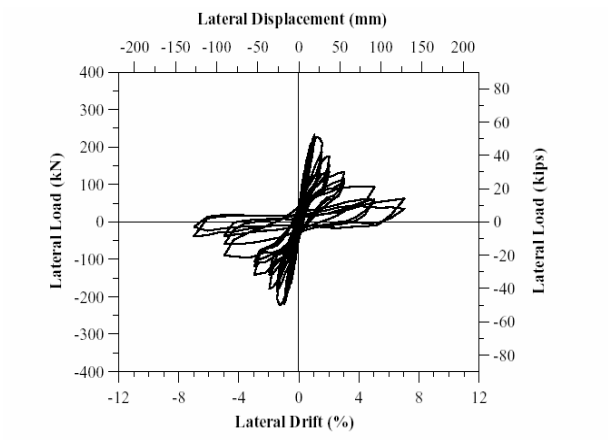
Level IV

Level V

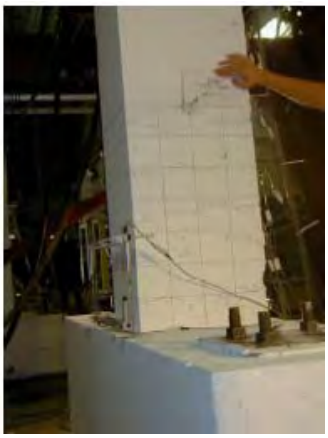
Level V

Lap Splice

LS1 – Lap Splice – Brittle



F-d Graph



Level II

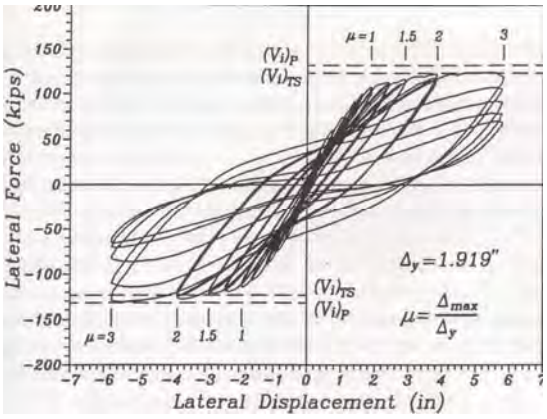
Level III

Level IV

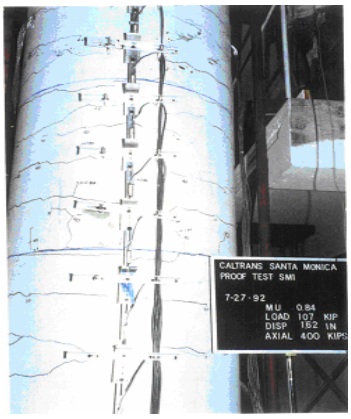
Level V

Level V

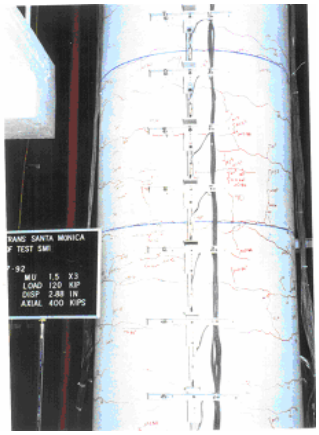
LS2 – Lap Splice - Ductile



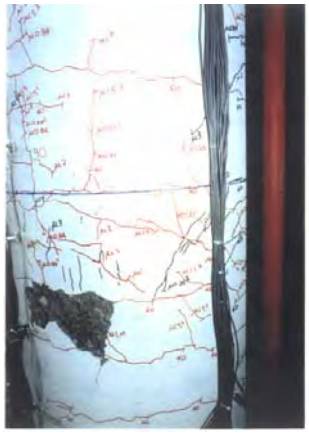
F-d Graph



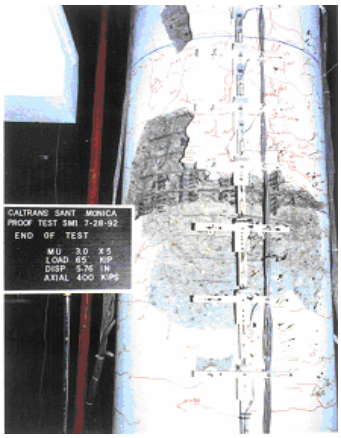
Level II



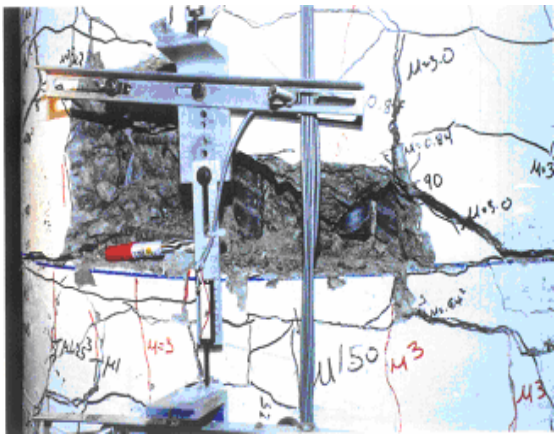
Level III



Level IV (inclination of cracks at splice)



Level V –well confined region below lap splice

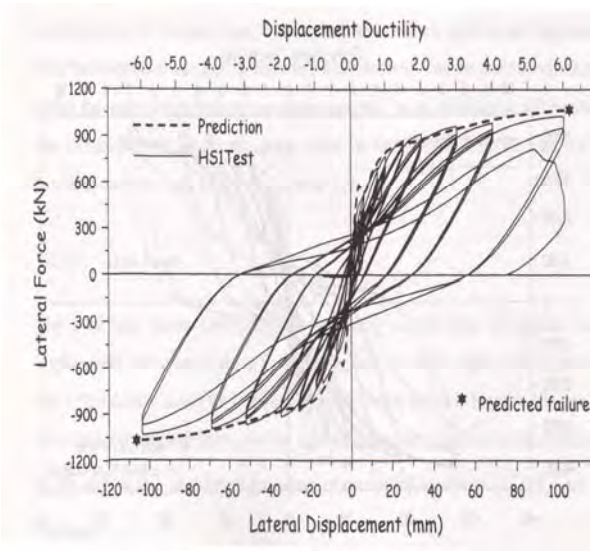


Level V - bond slip – space of bars

Special Sections

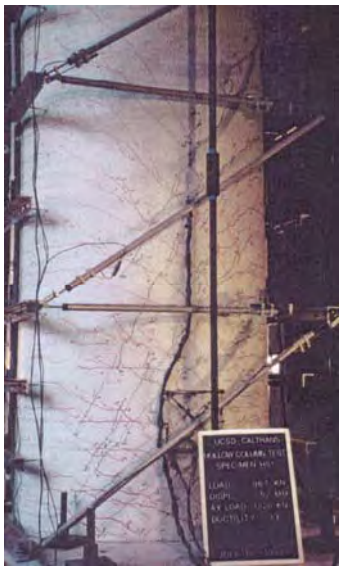
Hollow

SS1 – Flexural – Ductile



F-d Graph

Level II

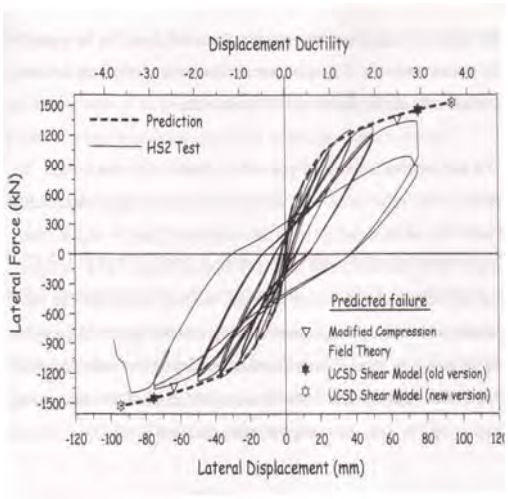


Level III

Level V

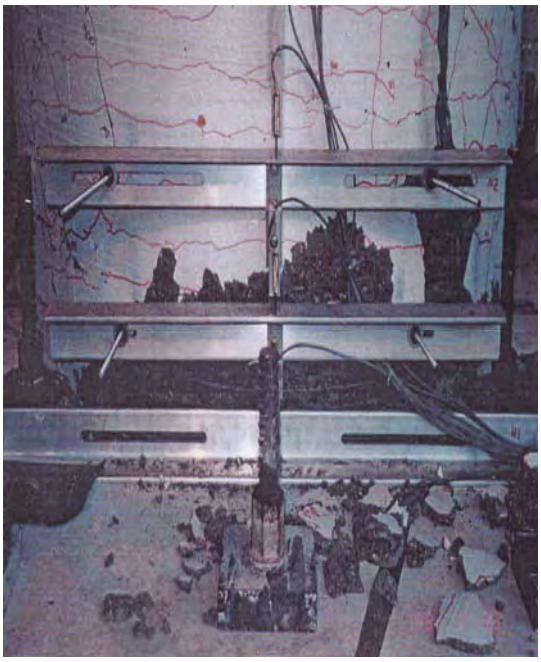
Ref: SSRP 2001/01, HS-1

SS2 – Flexural – Ductile

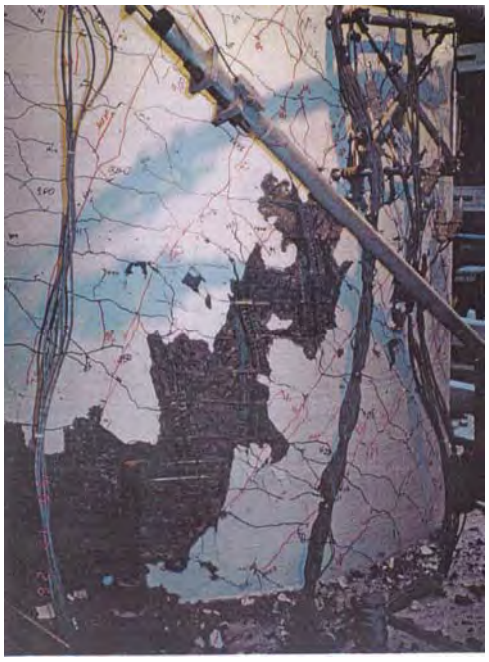


F-d Graph

Level III

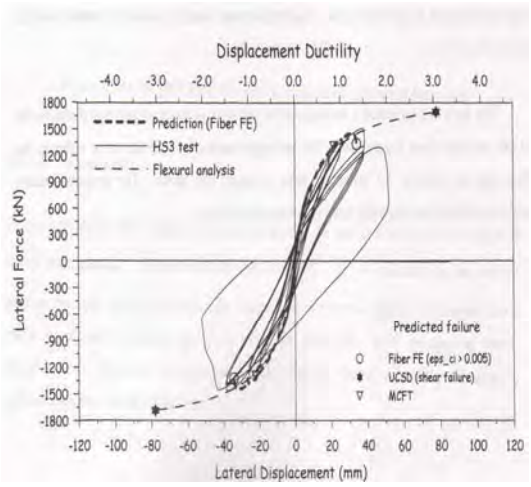


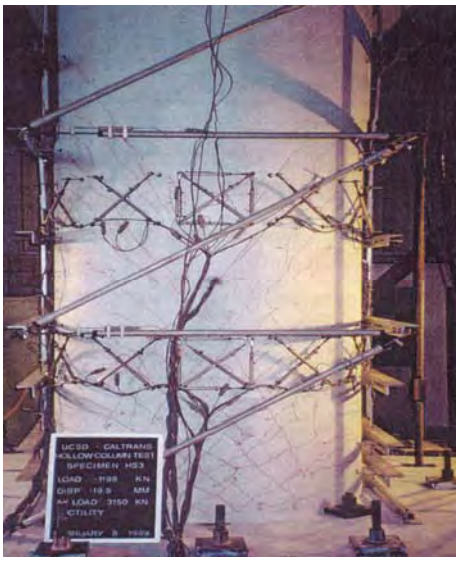
Level IV



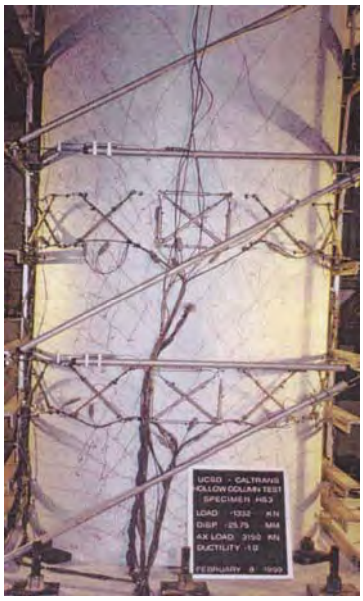
Level V

SS3 – Shear – Brittle





Level II

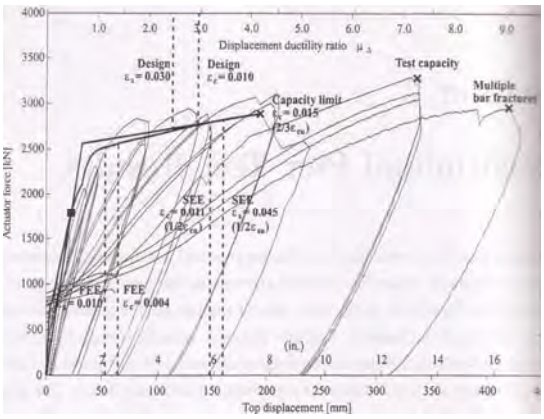


Level IV

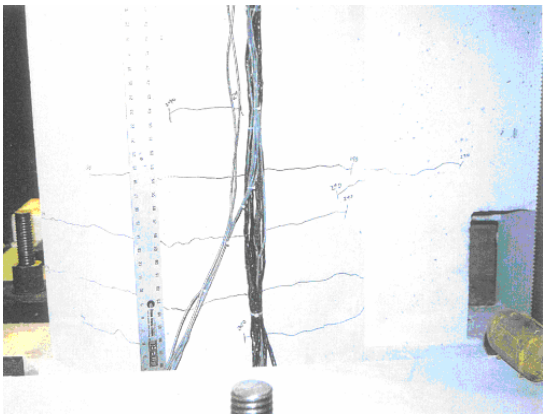
Level V

Columns with Boundary Elements

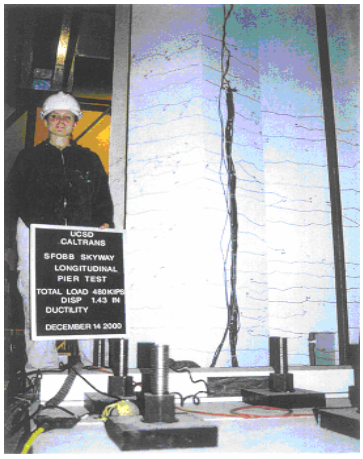
SS4 – Flexural – Ductile



F-d Graph



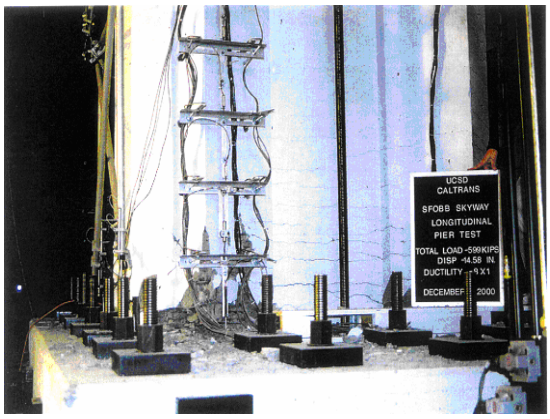
Level II



Level III

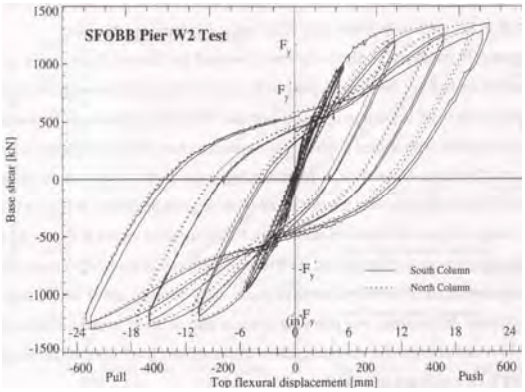
Level IV

Level III



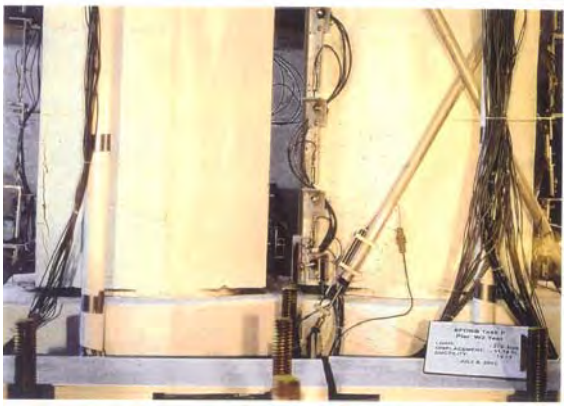
Level V

SS5 – Flexural – Ductile

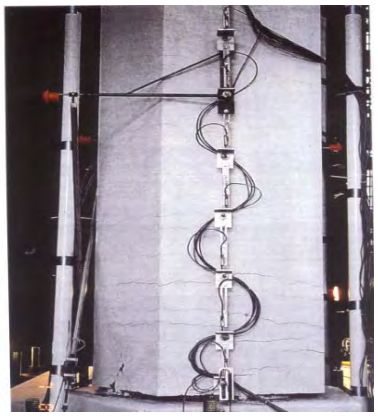


F-d graph

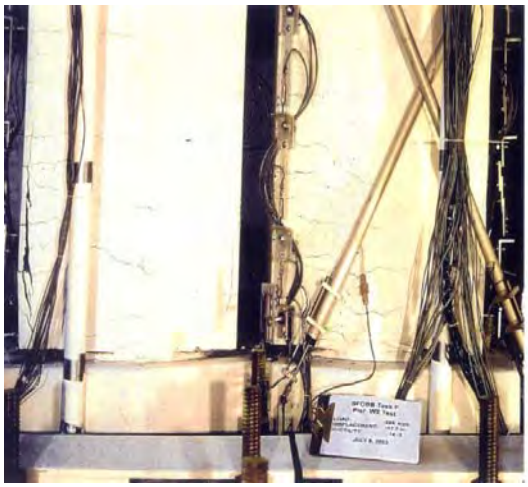
Level II



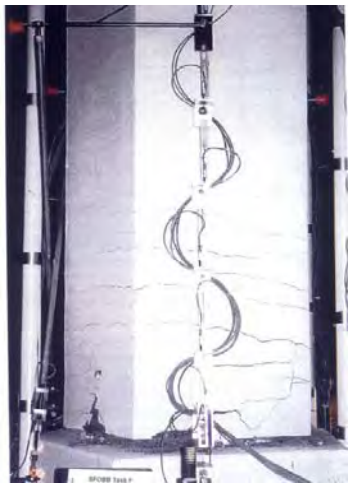
Level II



Level II tension side

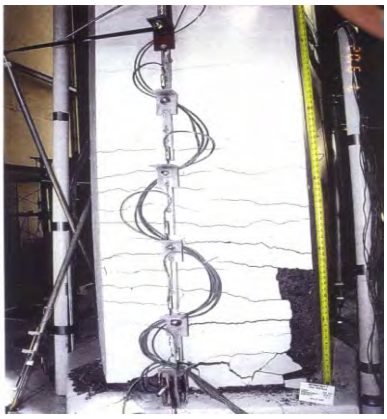
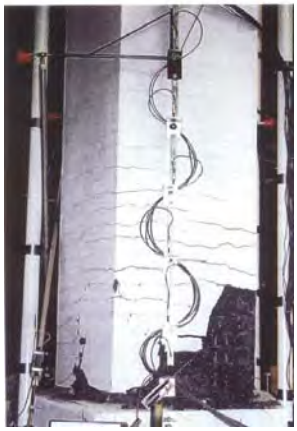
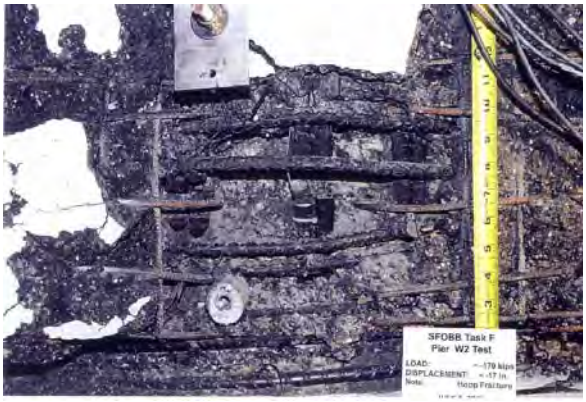


Level III



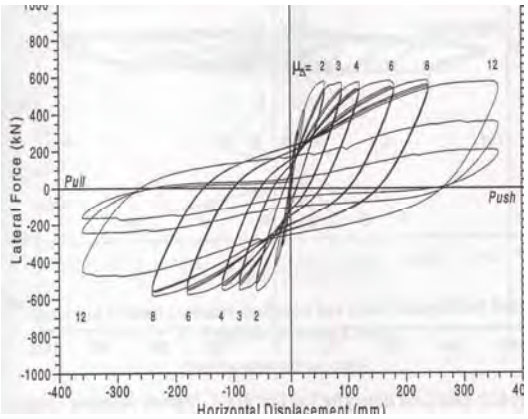
Level III tension side

SS5 – Flexural – Ductile

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

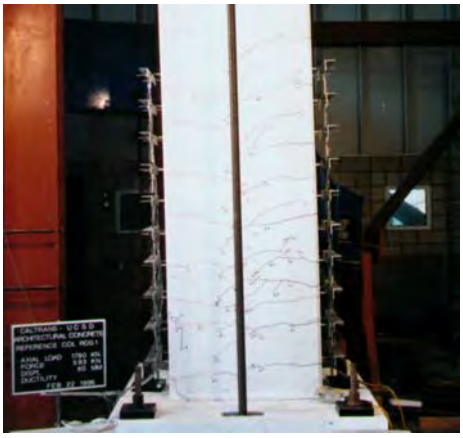
Flared

SS6 – Flexural – Ductile



F-d Graph

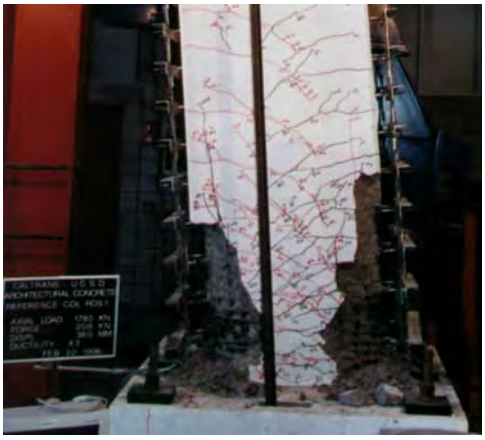
Level I



Level II

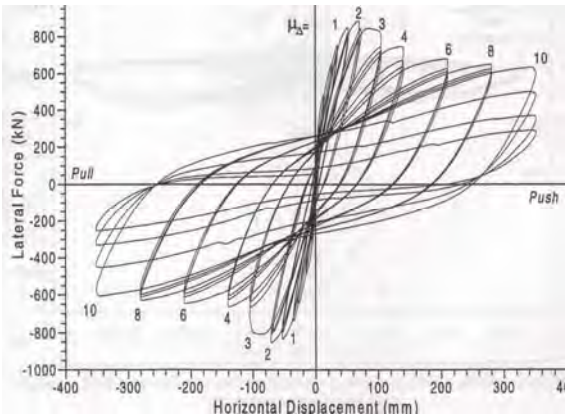
Level III

Level IV

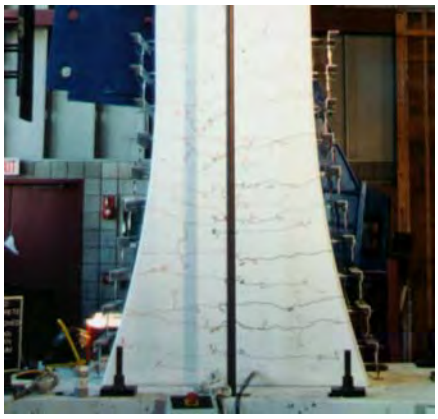


Level V

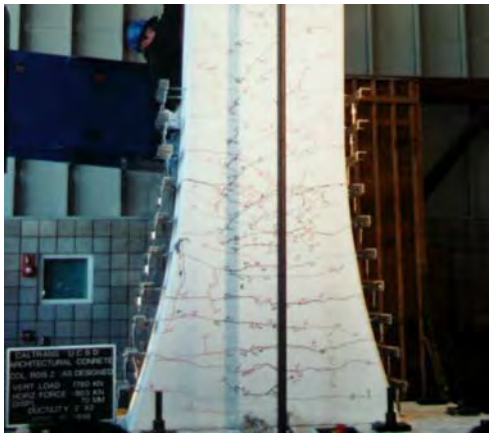
SS7 – Flexural - Ductile



F-d Graph



Level II



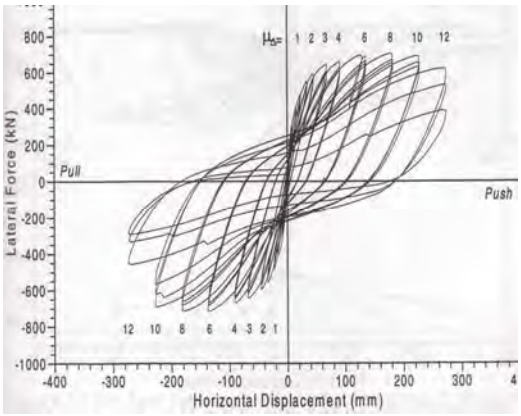
Level III

Level III

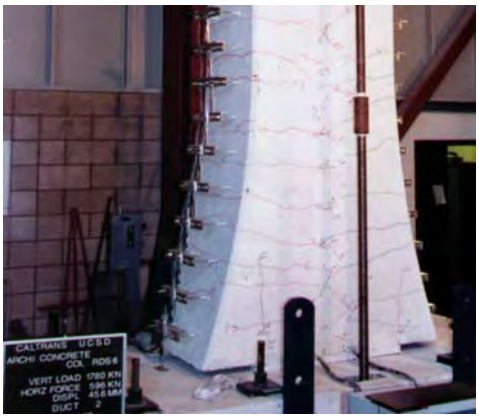
Level IV

Level V

SS8 – Flexural – Ductile



F-d response



Level I

Level II

Level III

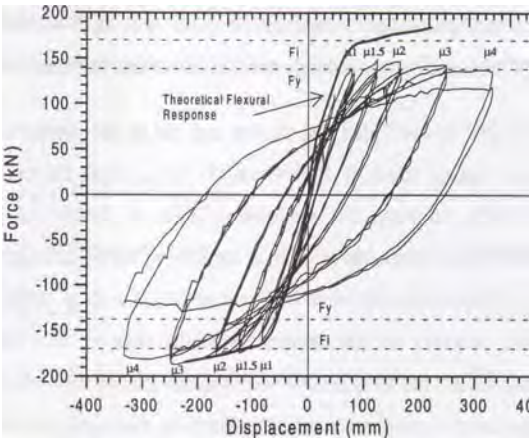
Level IV

Level V

Special Material

Lightweight

SM1 – Flexural – Ductile



F-d Graph

Level III

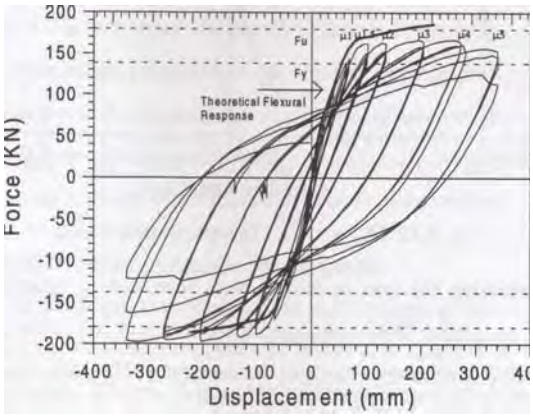
Level IV

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

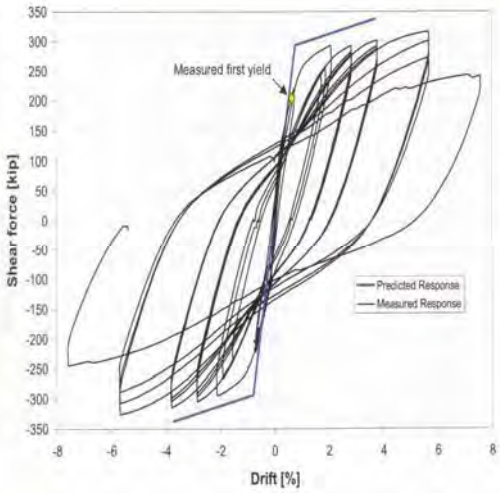
Level III

Level IV

Level V

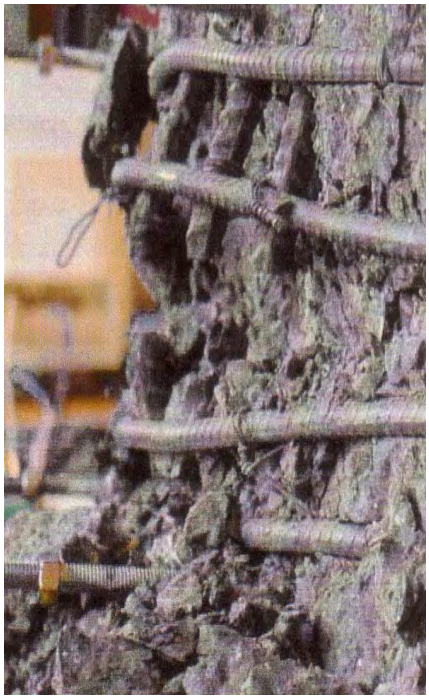
MMX Steel

SM4 – Shear - Brittle



F-d Graph

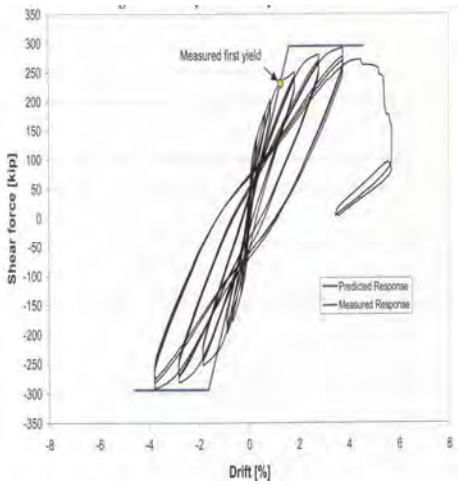
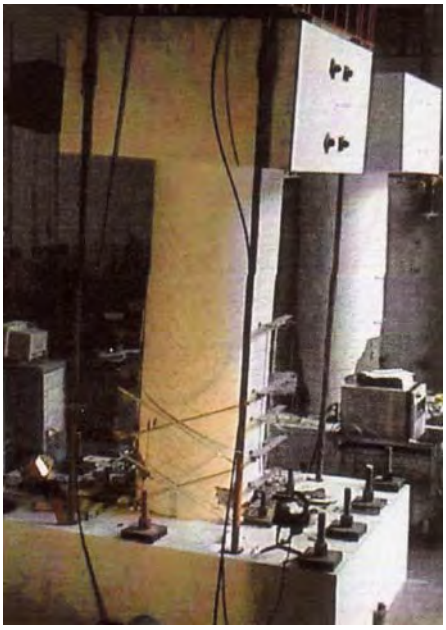
Level V



Level V

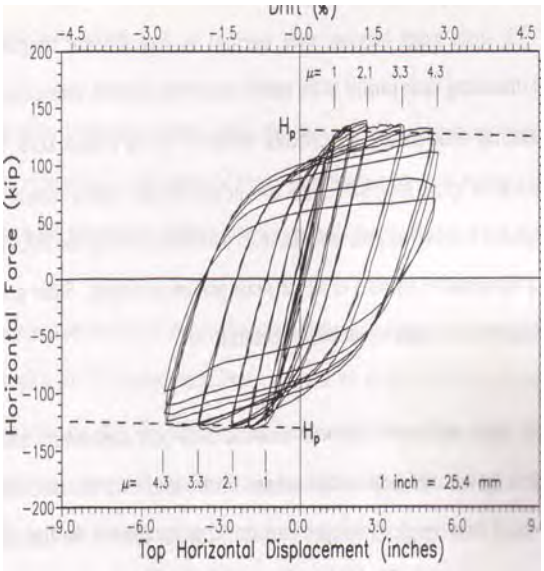
Level V

SM5 – Shear – Brittle

	
F-d Graph	Level V (Hoop fracture)
	
Level V longitudinal bar fracture)	Level V

Steel Columns

SM6 – Shear - Brittle



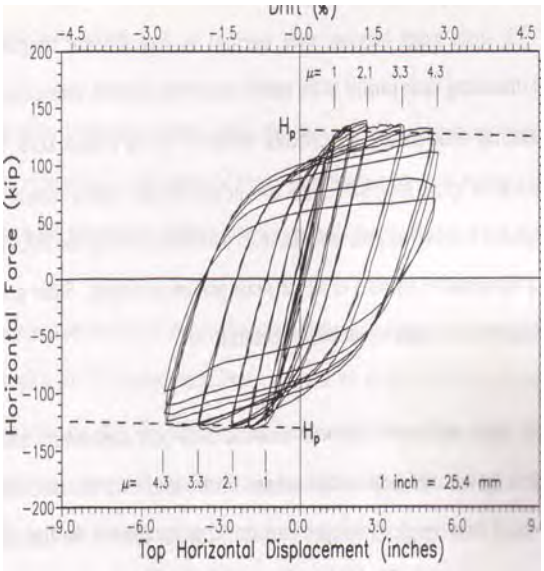
F-d Graph

Level III

Level IV

Level V

SM7 – Shear – Brittle



F-d Graph

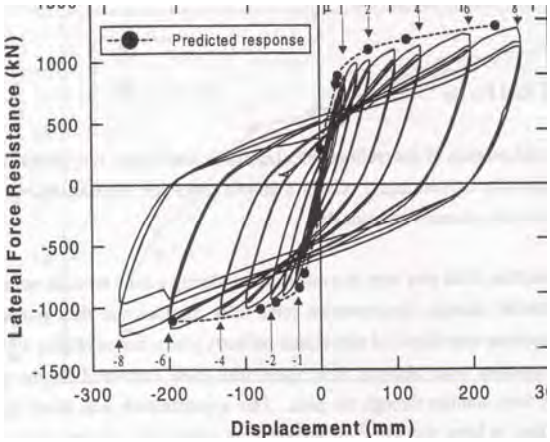
Level III

Level IV

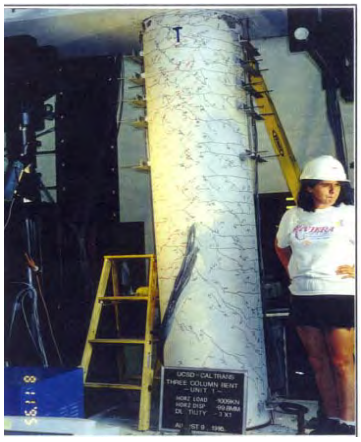
Level V

Joints

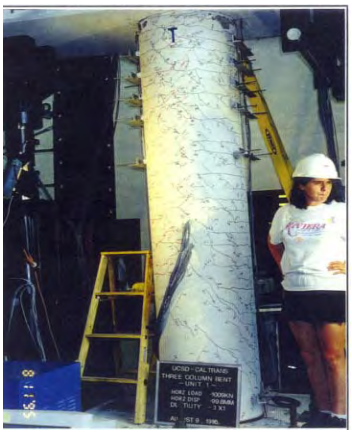
J1 – Flexural – Ductile



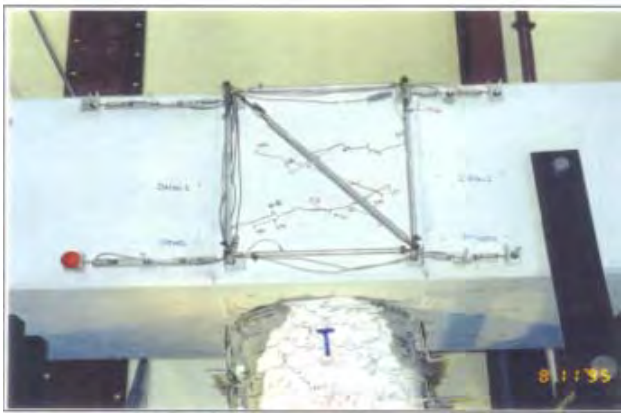
F-d Graph



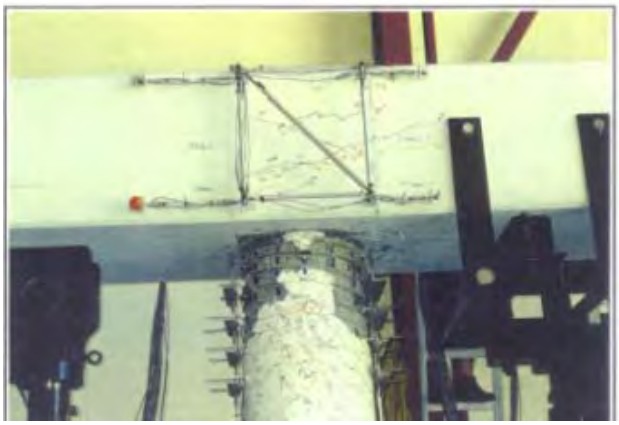
Level II



Level III



Level IV



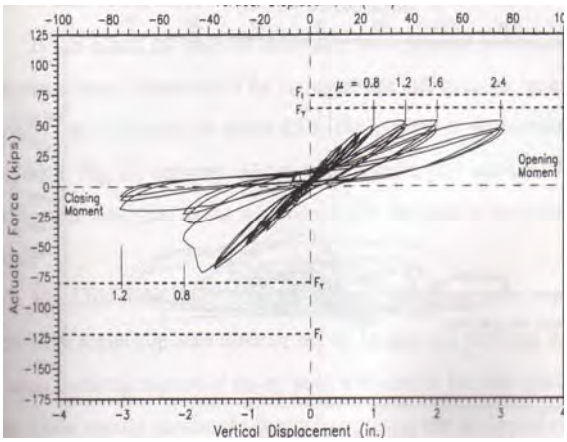
Level V

Level V

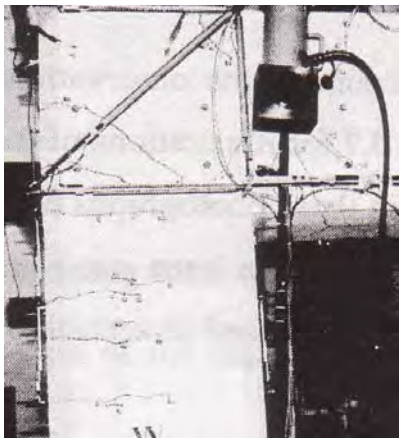
J2

Level III	Level IV
Level IV	Level V

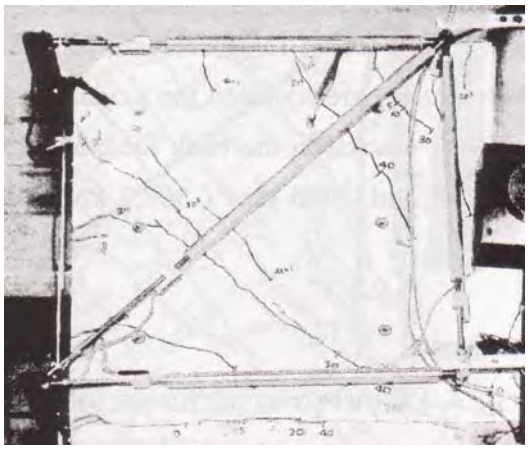
J3 – Shear - Brittle



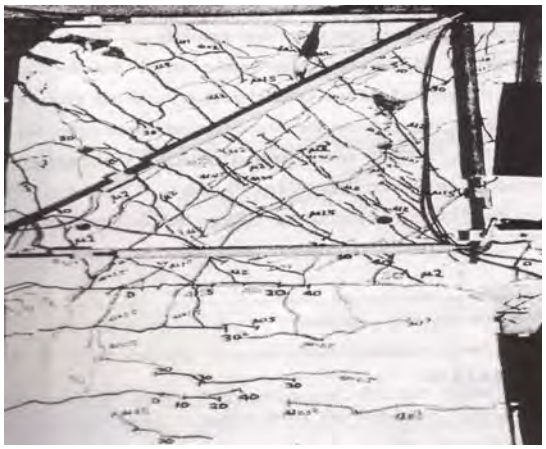
F-d Graph



Level II



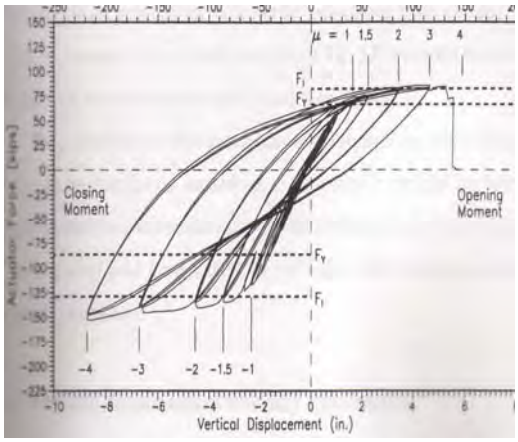
Level III



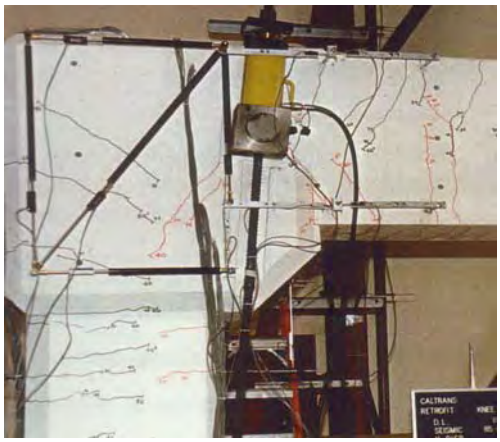
Level IV

Level V

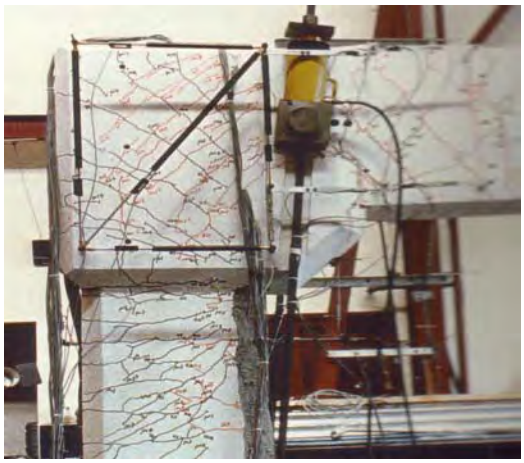
J4 – Shear - Brittle



F-d Graph

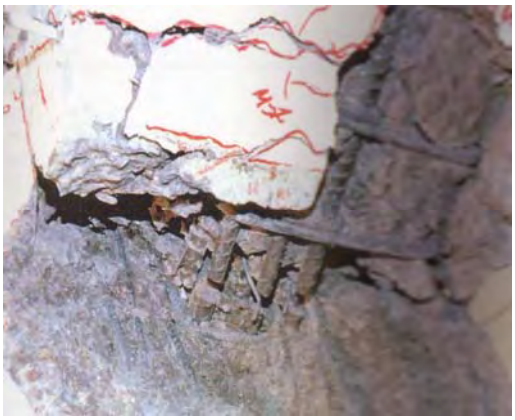


Level III



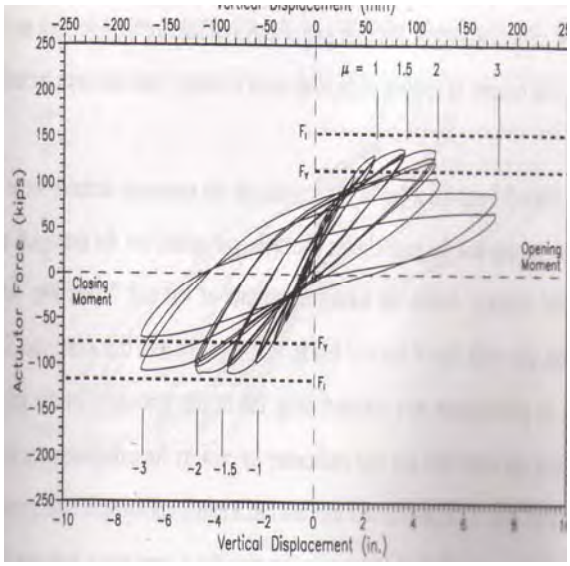
Level IV

Level V

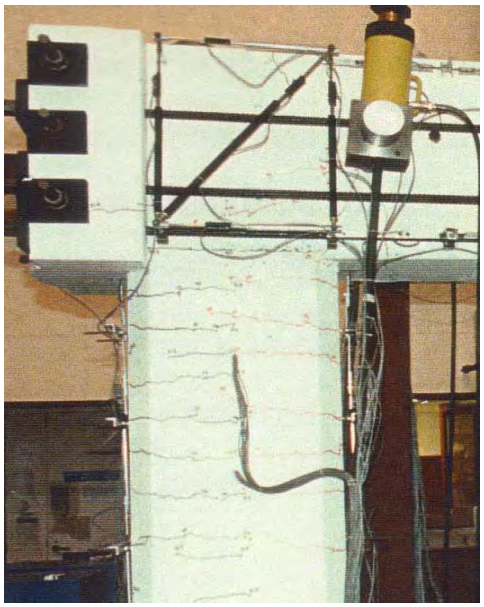


Level V

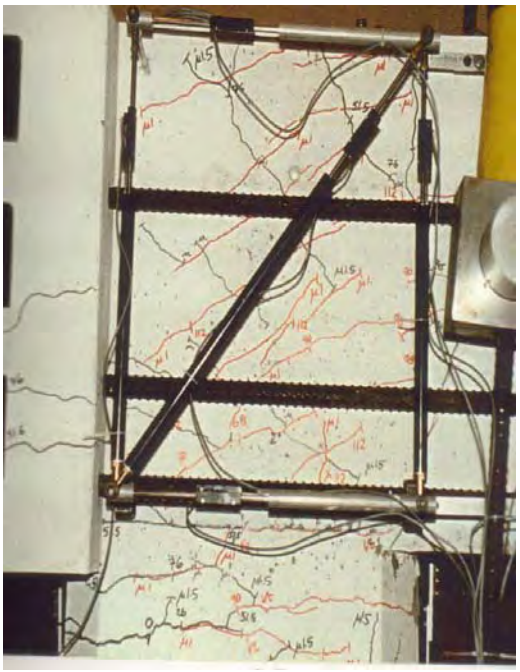
J5 – Shear - Brittle



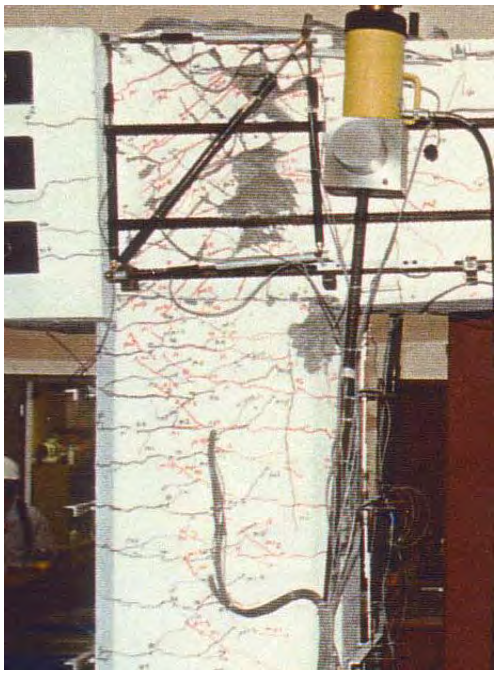
F-d Graph



Level II

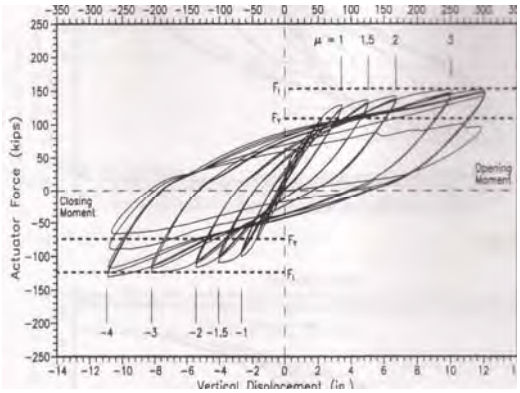
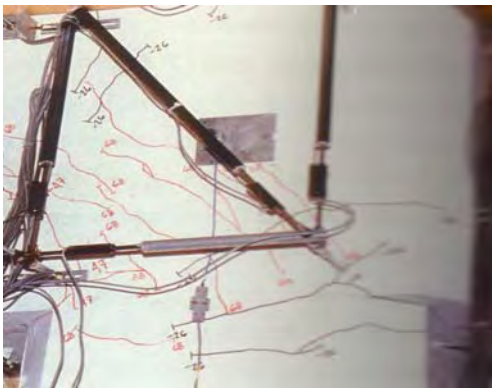
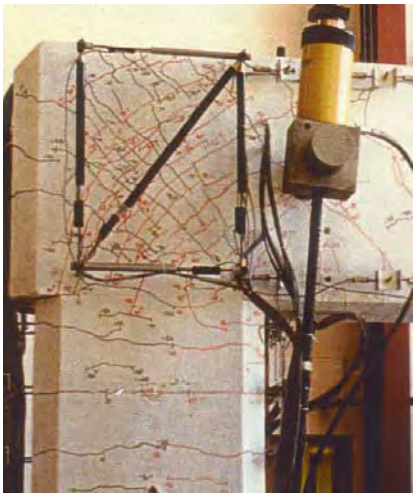
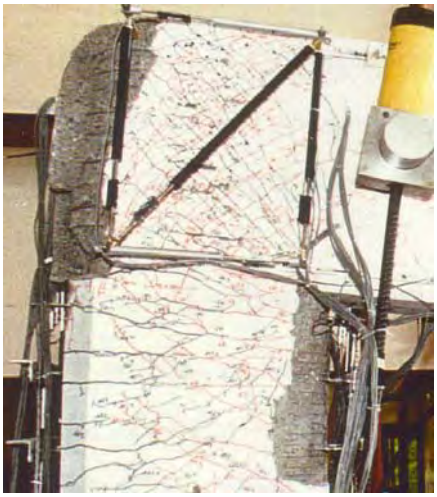
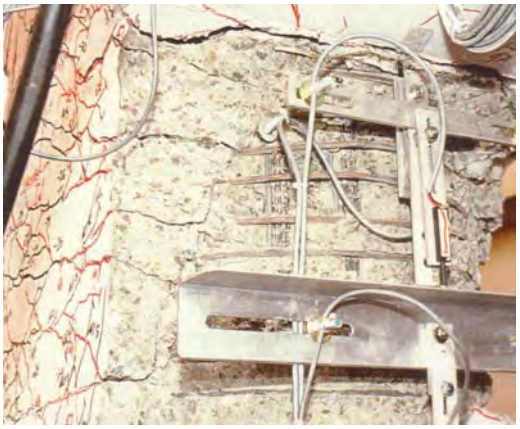


Level III



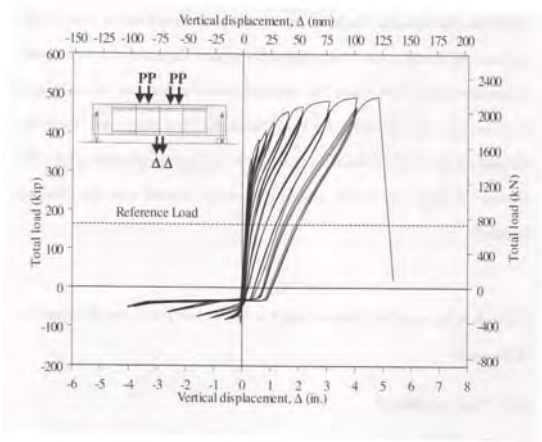
Level IV

J6 – Shear - Brittle

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

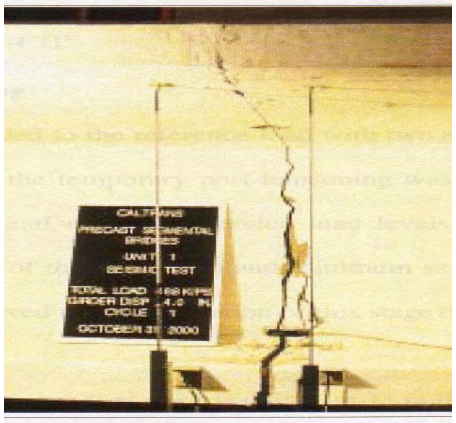
Superstructure

SP1 – Flexural - Brittle

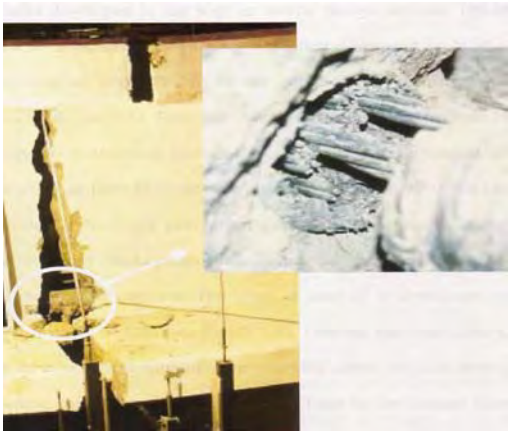


F-d Graph

Level III

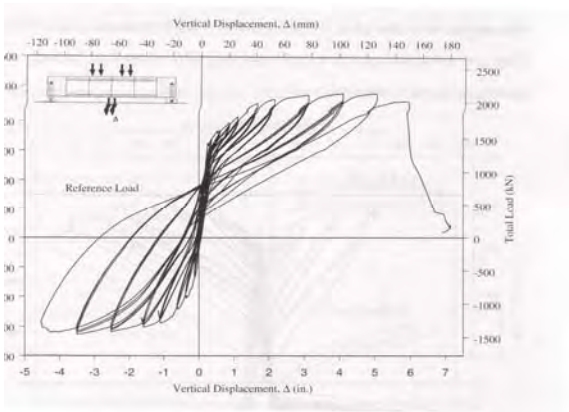


Level IV



Level V

SP2 – Flexural - Ductile

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

SP3 – Flexural - Ductile

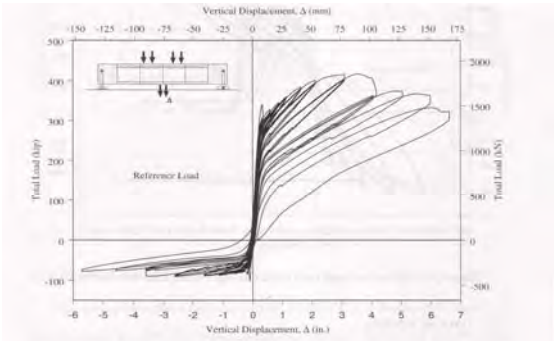
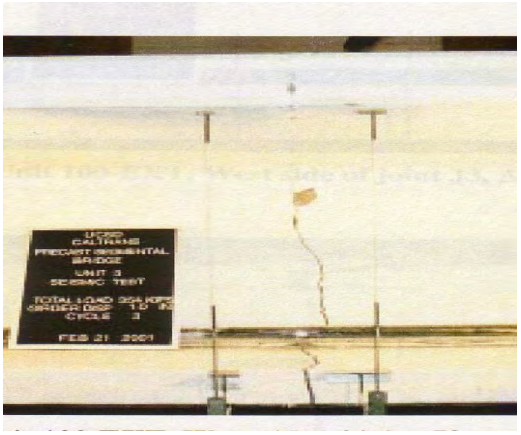
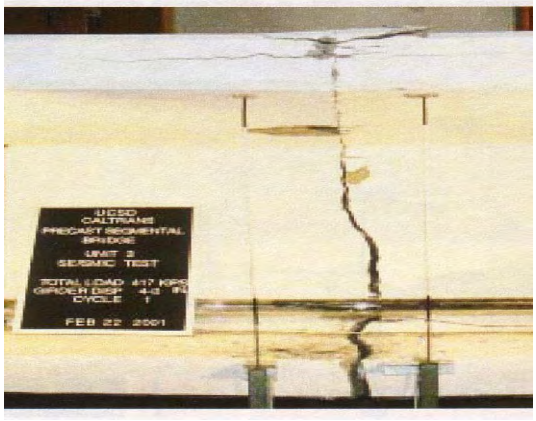


Figure 3-24 History of total load versus displacement, Unit 100-EXT

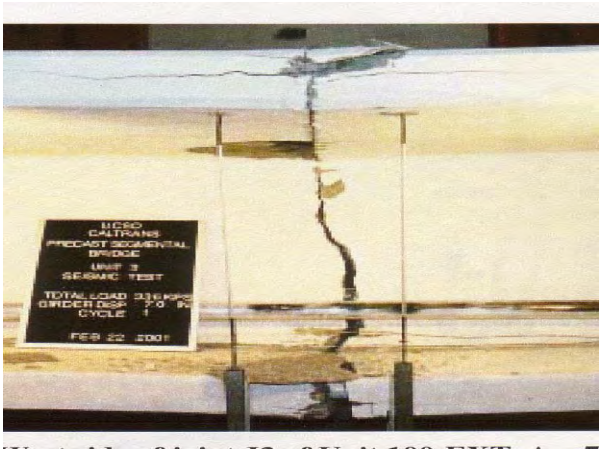
F-d Graph



Level III



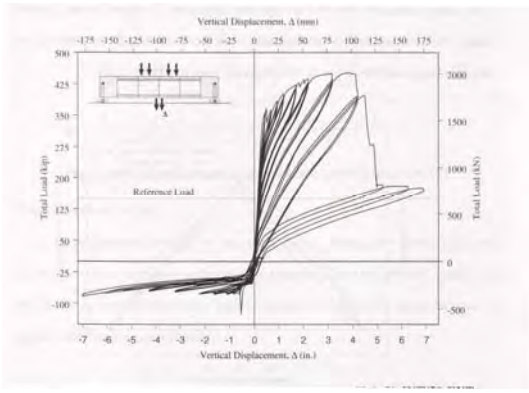
Level IV



Level V

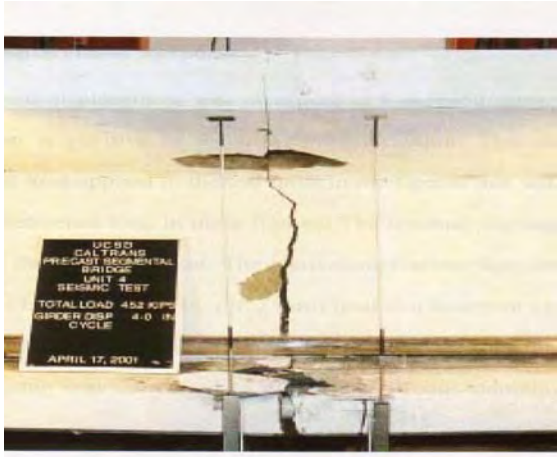
Level V

SP4 – Flexural – Brittle



F-d Graph

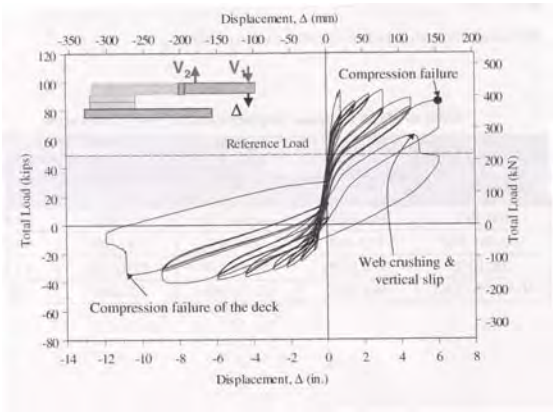
Level IV



Level V

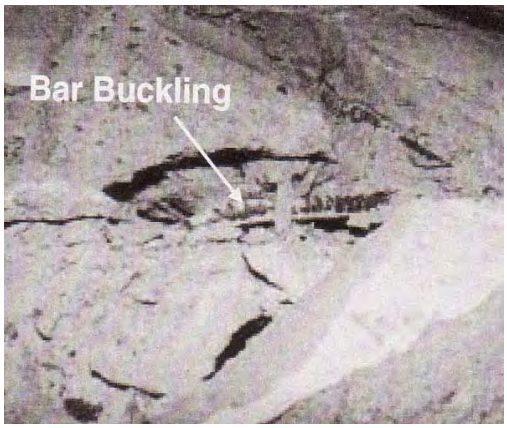
Level V

SP5 – Flexural – Brittle



F-d Graph

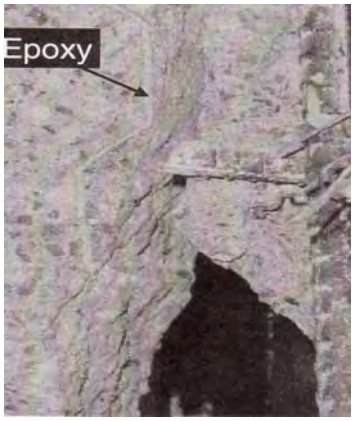
Level II



Level V

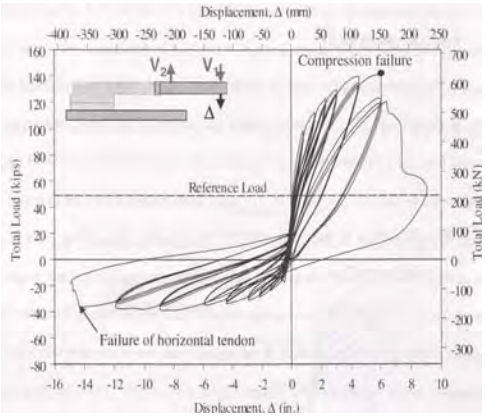
Level V (Compression failure)

Level V (prestress steel failure- lower tendon)

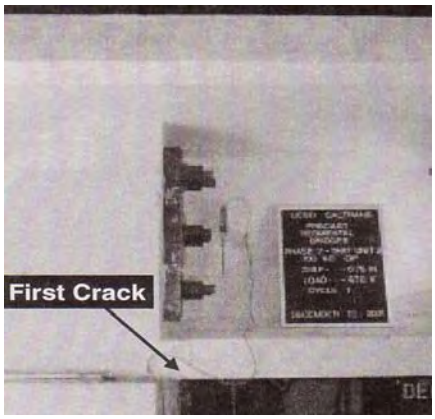


Level V

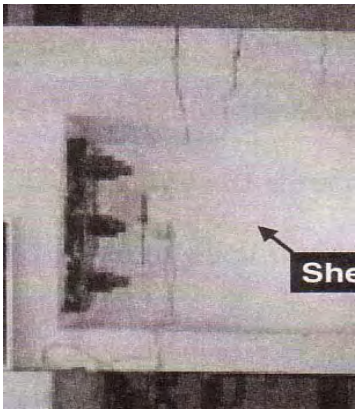
SP6 – Flexural - Brittle



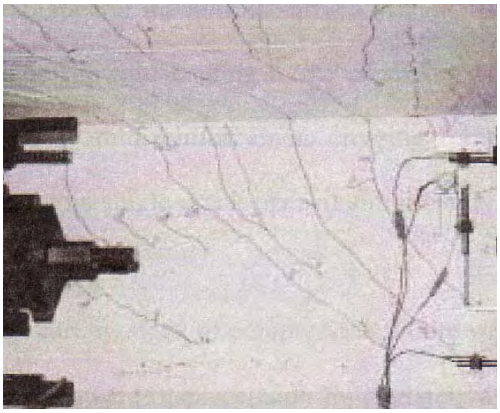
F-d Graph



Level II

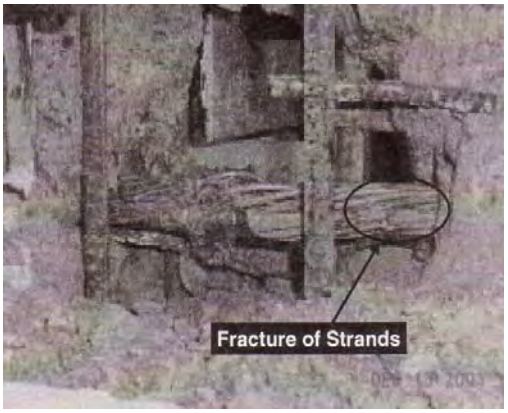


Level IV



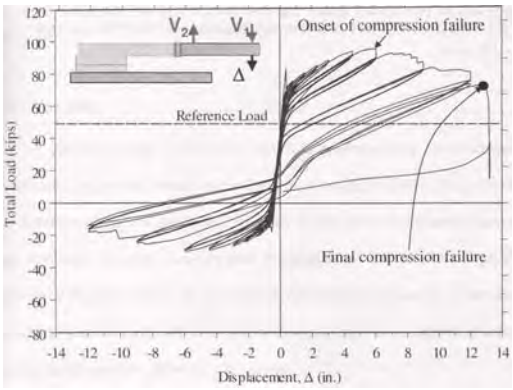
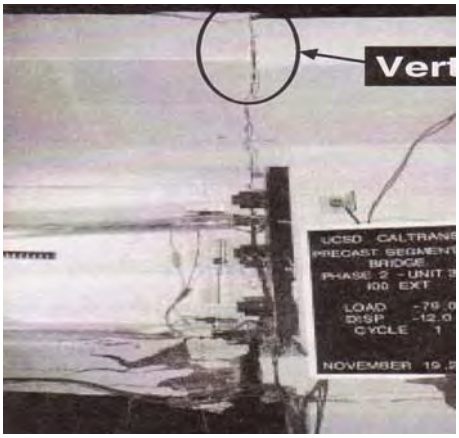
Level IV

Level V

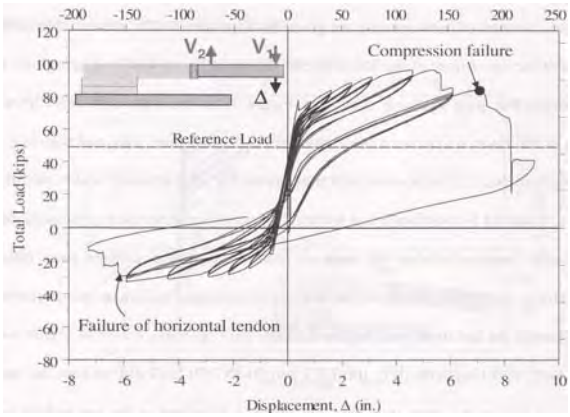


Level V

SP7 – Flexural – Brittle

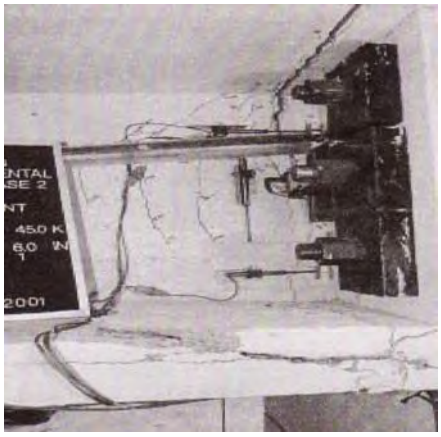
	
F-d Graph	Level I
Level IV	Level V
	
Level V	Level V

SP8 – Flexural – Ductile



F-d Graph

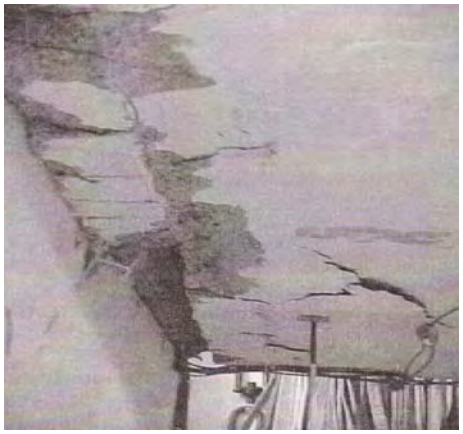
Level II



Level III

Level IV

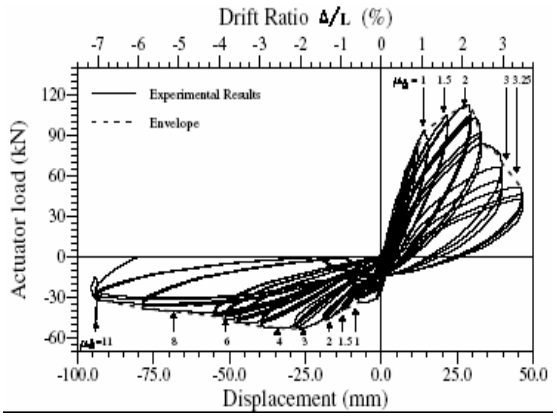
Level V



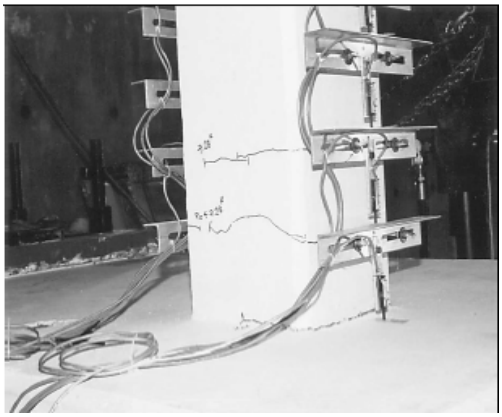
Level V

Foundations

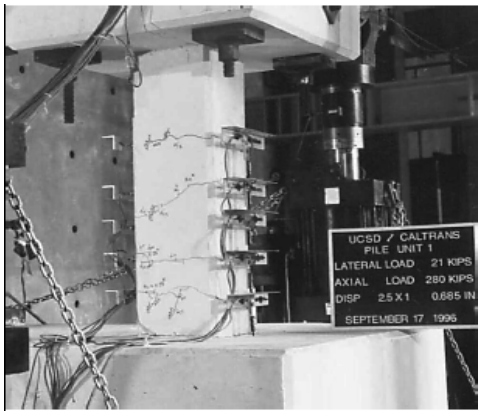
F1 – Shear – Brittle



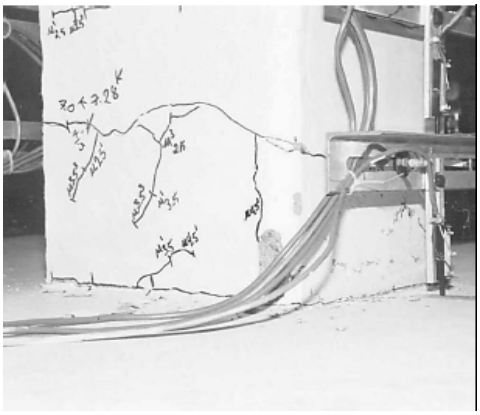
F-d Graph



Level I

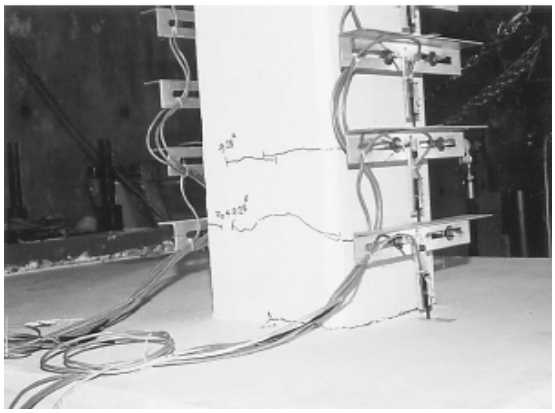


Level II



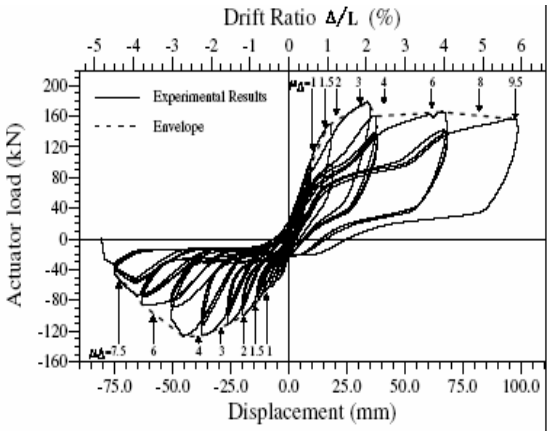
Level III

Level IV



Level V

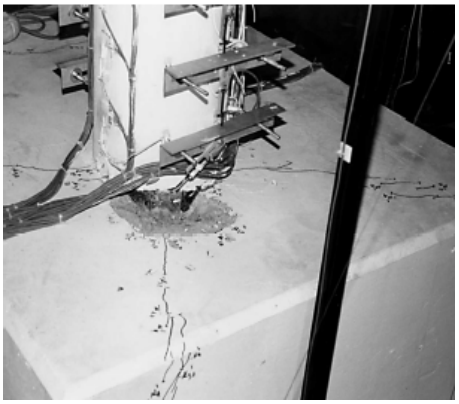
F2 – Degrading - Ductile



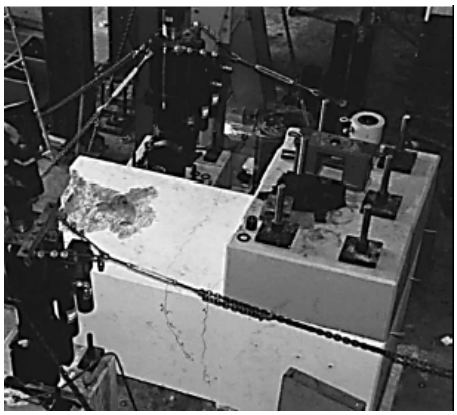
Level I

Level II

Level III

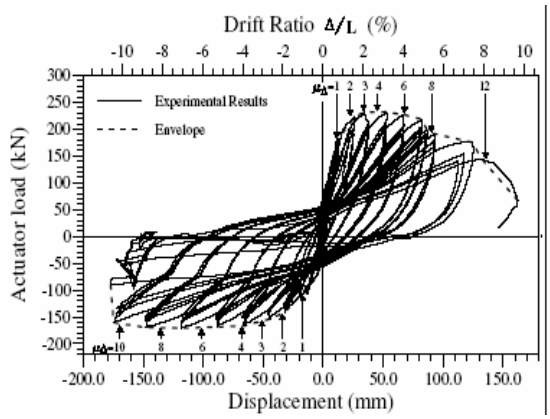


Level IV



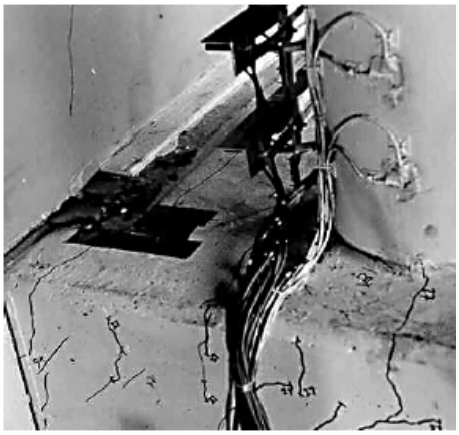
Level V

F3 – Degrading – Ductile

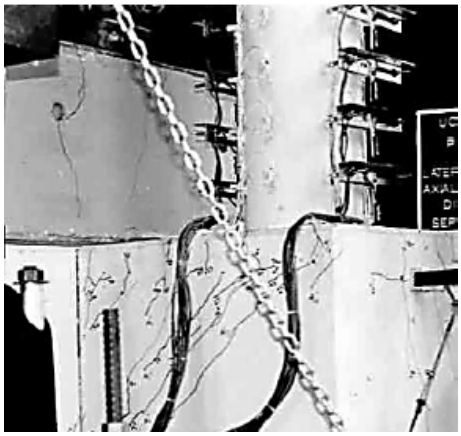


F-d Graph

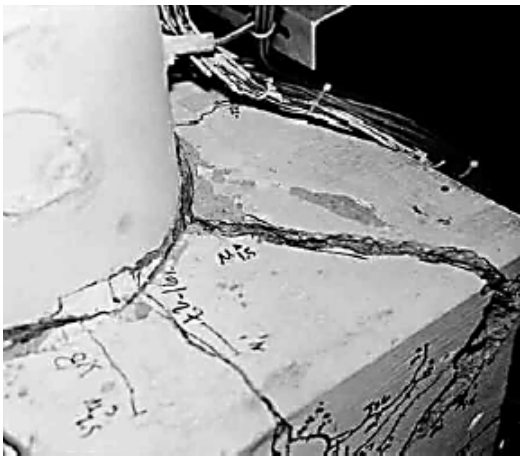
Level I



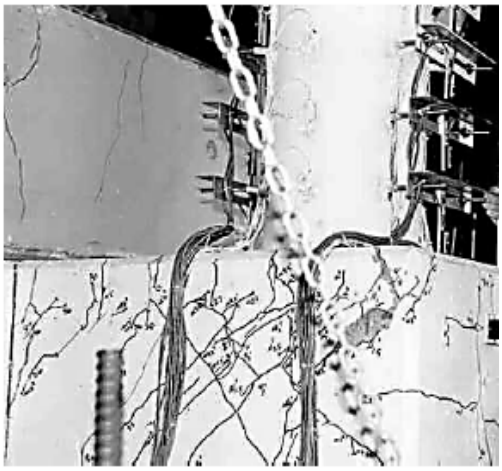
Level II



Level III

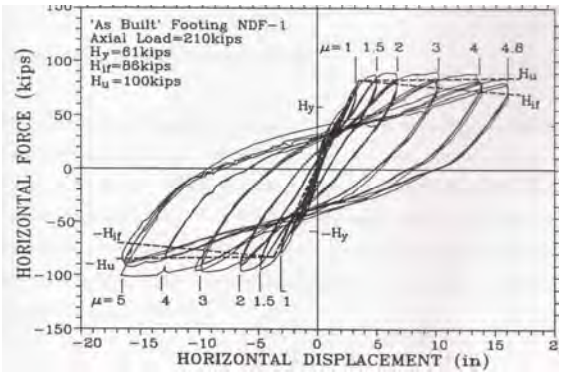


Level IV

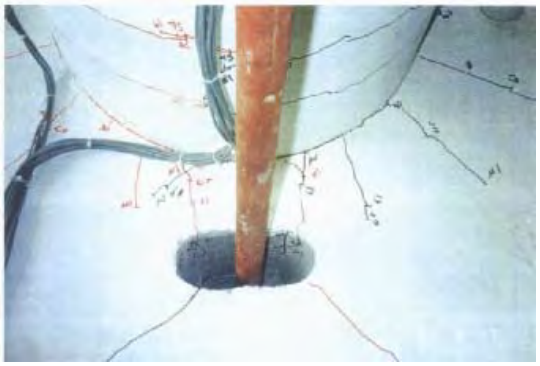


Level V

F4 – Flexural - Ductile



F-d Graph



Level I

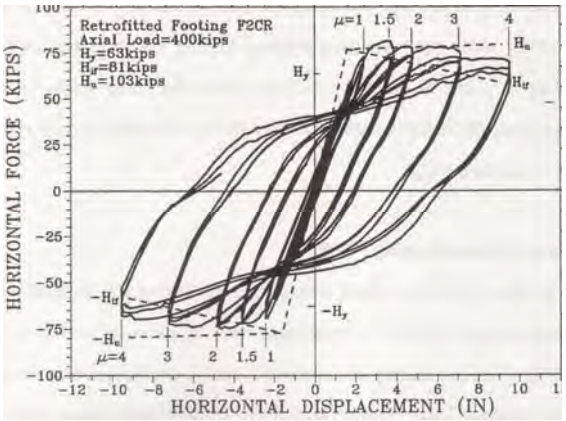
Level II

Level III penetration of footing cracks

Level IV

Level V

F5 – Flexural - Ductile

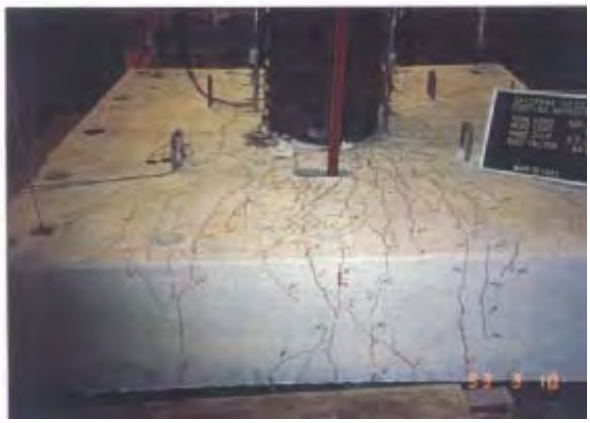


Level I

Level II

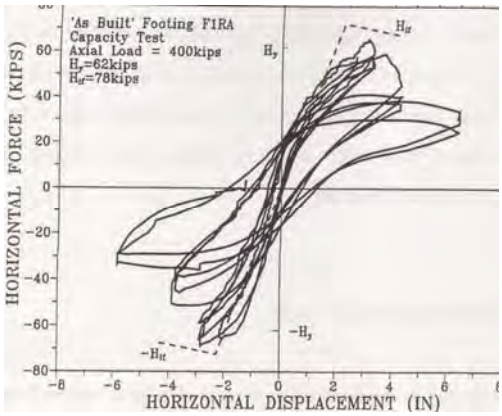
Level III

Level IV



Level V

F6 – Flexural – Brittle

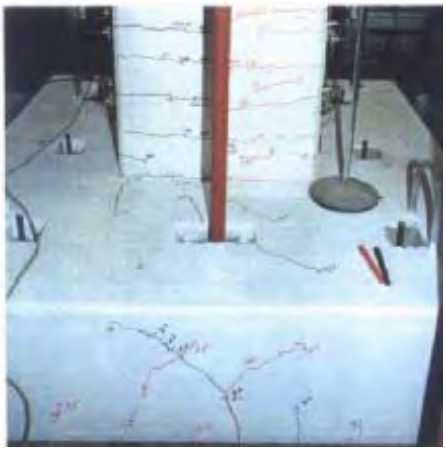


F-d Graph

Level II

Level III

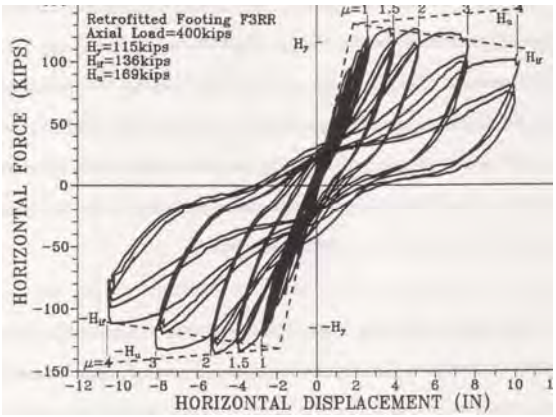
Level IV



Level V

Level V column-footing shear cracks

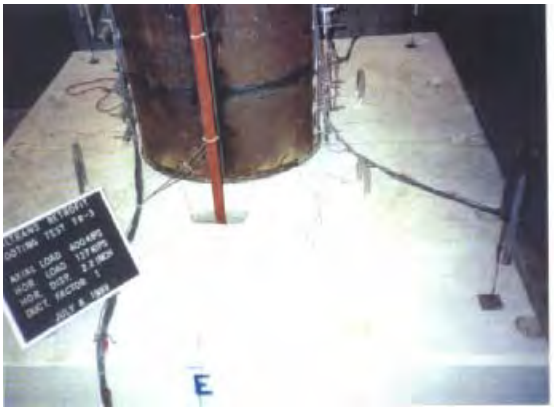
F7 – Flexural - Ductile



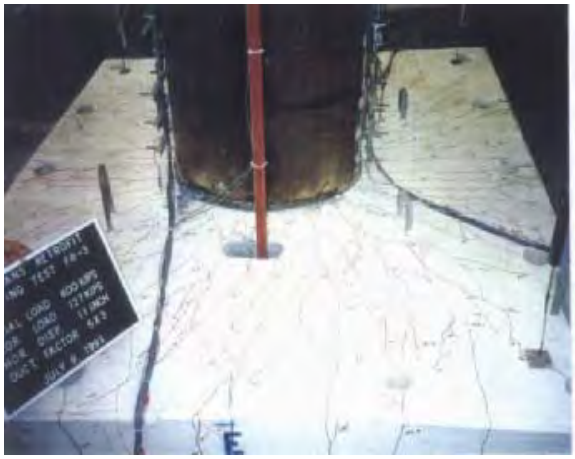
F-d Graph

Level II

Level III



Level IV

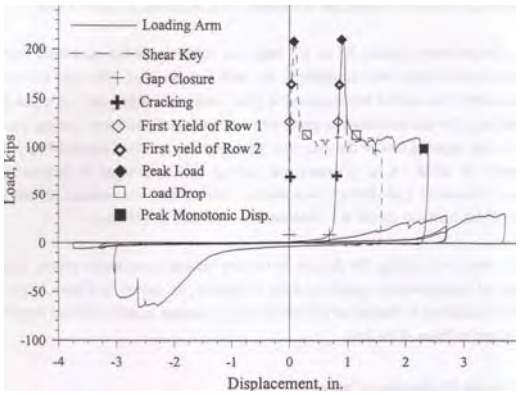


Level V

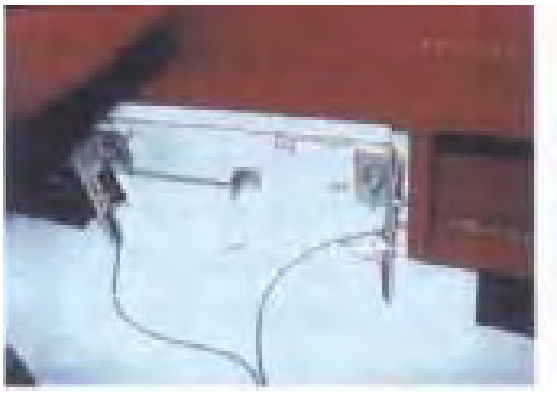
Level V permanent deformation

Abutments/Shear Keys

SK1 – Shear - Brittle



F-d Graph



Level I

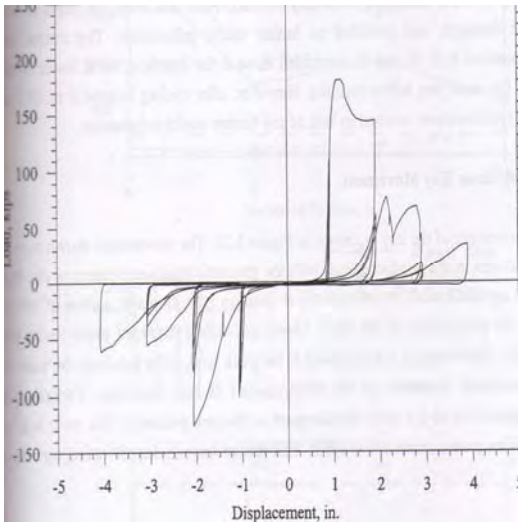
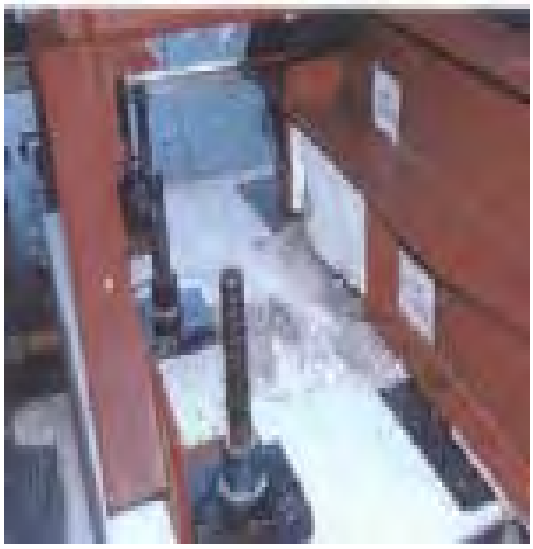
Level II

Level III

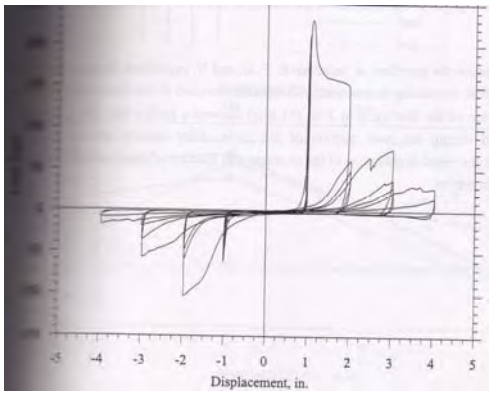
Level IV

Level V

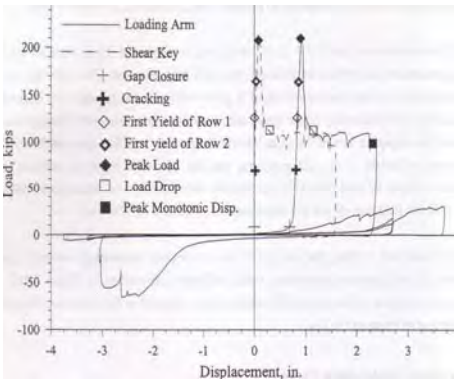
SK2 – Shear - Brittle

	
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

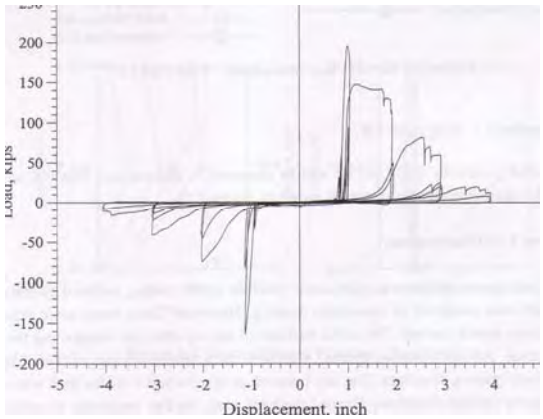
Level II

Level III

Level IV

Level V

SK5 – Shear - Brittle



F-d Graph

Level I

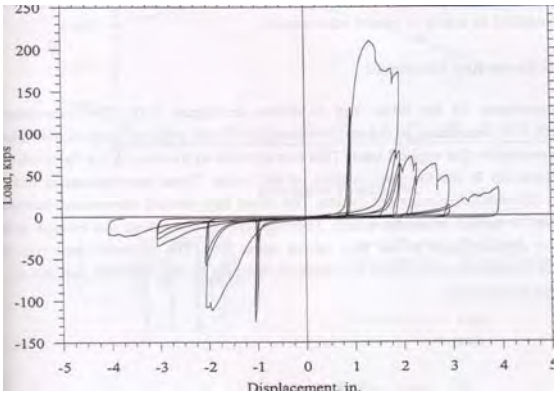
Level II

Level III

Level IV

Level V

SK6 – Shear – Brittle



F-d Graph

Level I

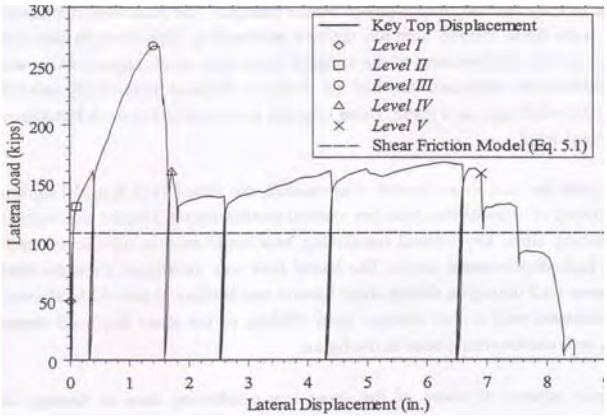
Level II

Level III

Level IV

Level V

SK7 – Shear



Level I

Level II

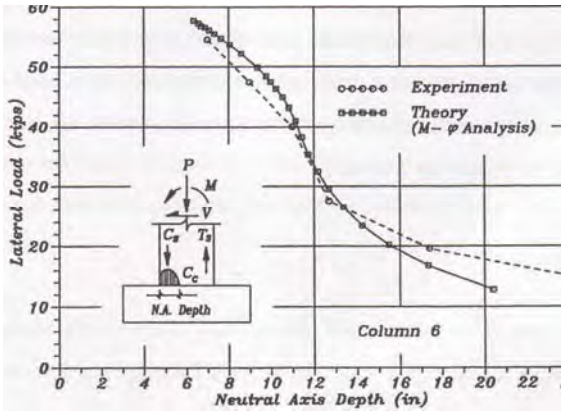
Level III

Level IV

Level V

Retrofit

R1 – Flexural



F-d Graph

Without Retrofit

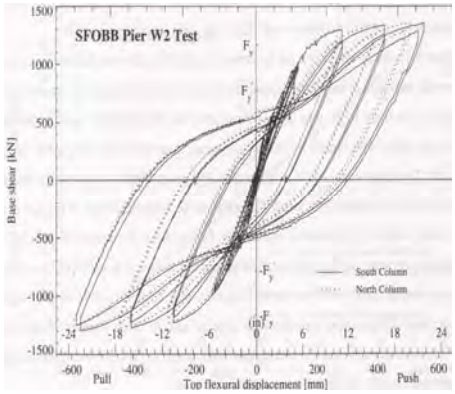
Without - Level IV

Level III

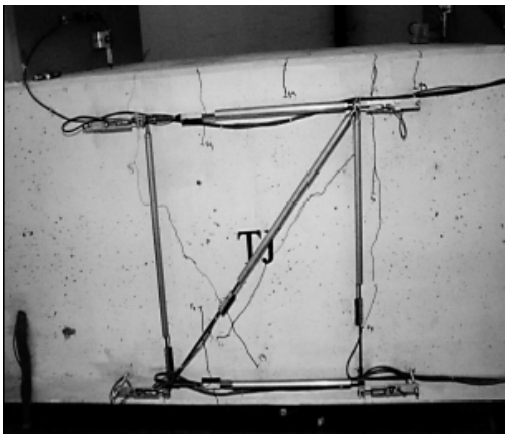
Level V permanent deformation

Level V bars rupture

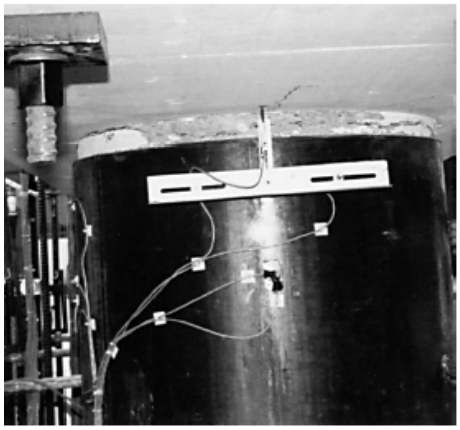
R2 – Flexural - Ductile



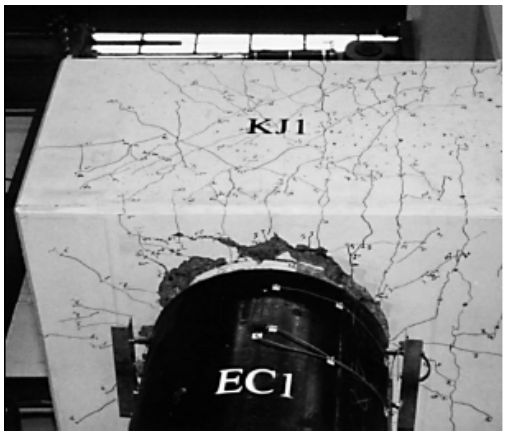
Level I



Level II shear cracking at joint



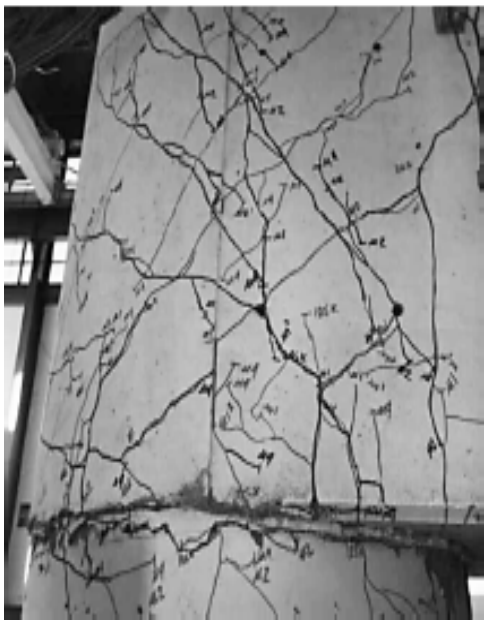
Level III spalling at gap region of cap beam



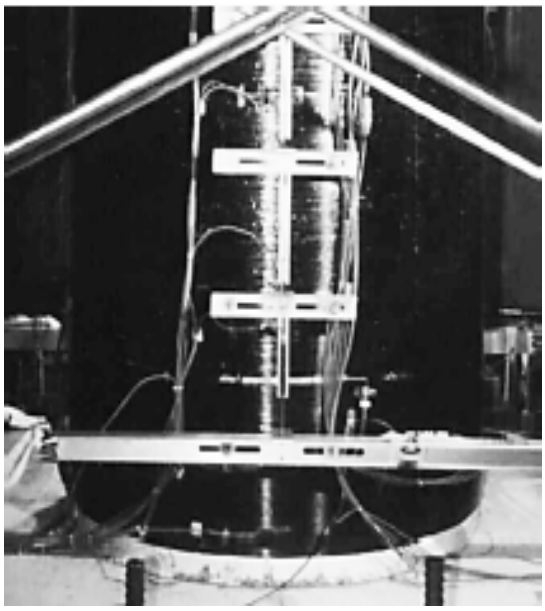
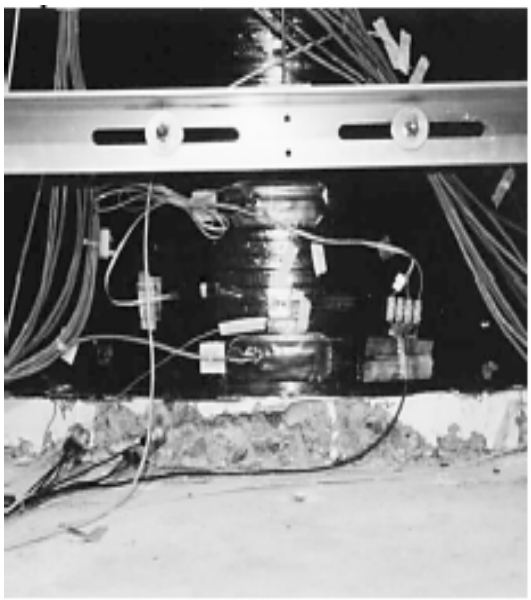
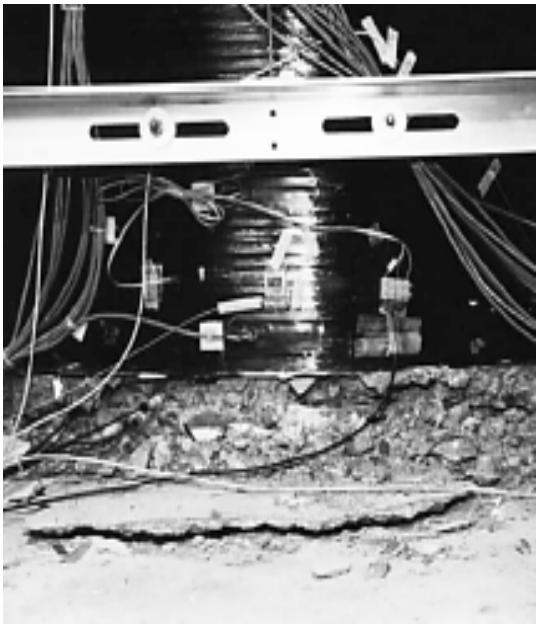
Level IV cap beam penetration of reinforcement

Level V - fracture of long. Bars

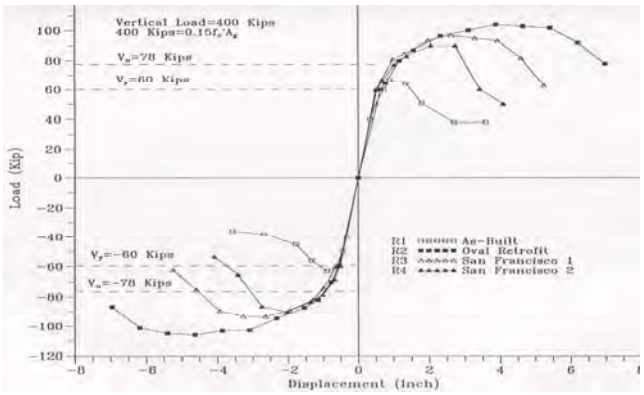
R3 – Flexural

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

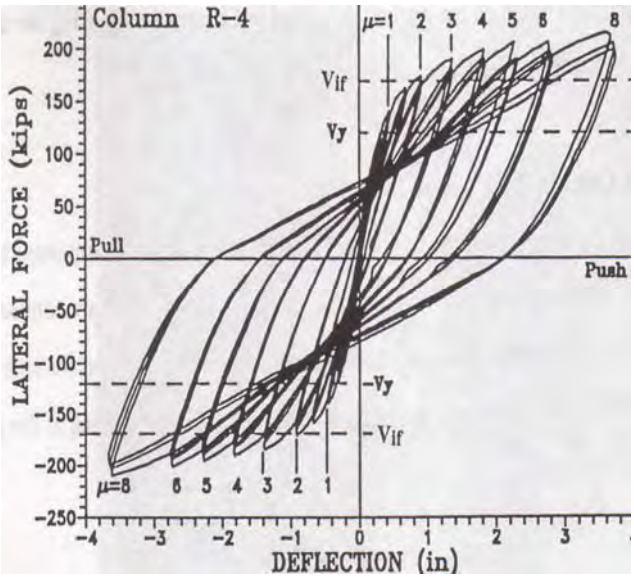
Level V without retrofit

Test setup – retrofit

Level IV after removal of jacket

Level V after removal of jacket

R6 – Shear - Brittle



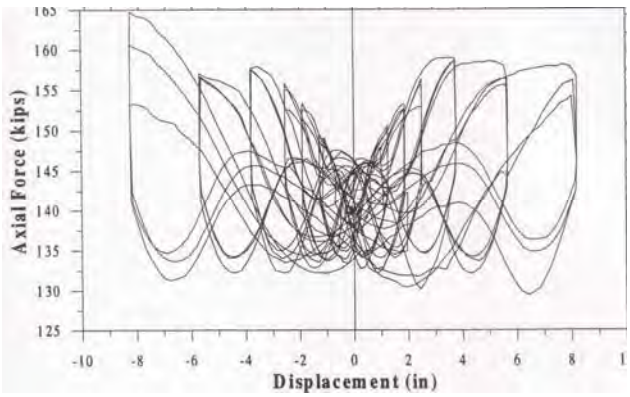
F-d Graph

Test setup

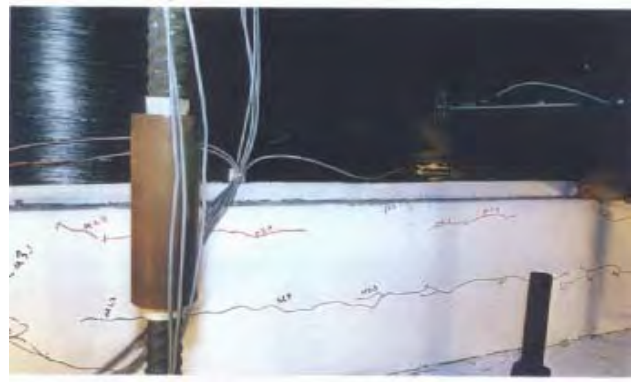
Level III spalling at gap region

Level V permanent deformation

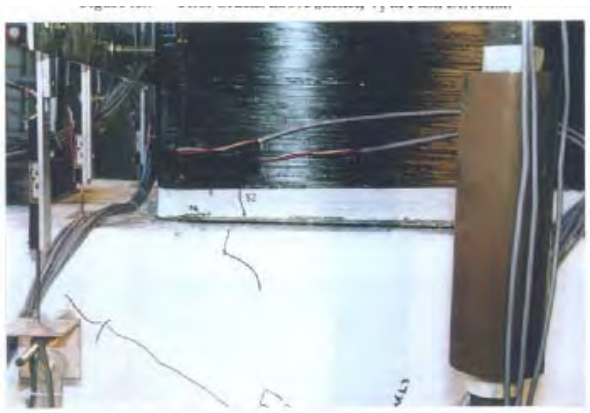
R7 – Flexural - Ductile



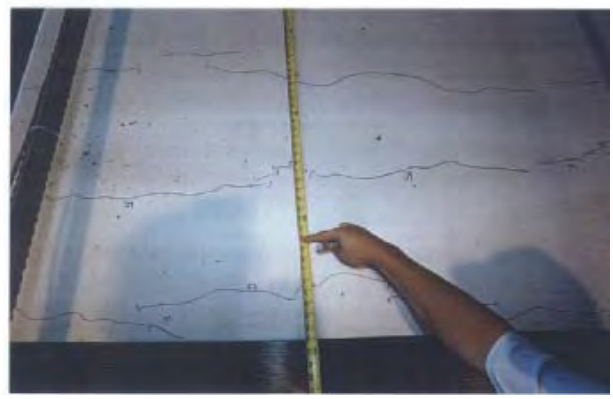
F-d Graph



Level I - Cracks on Pedestal

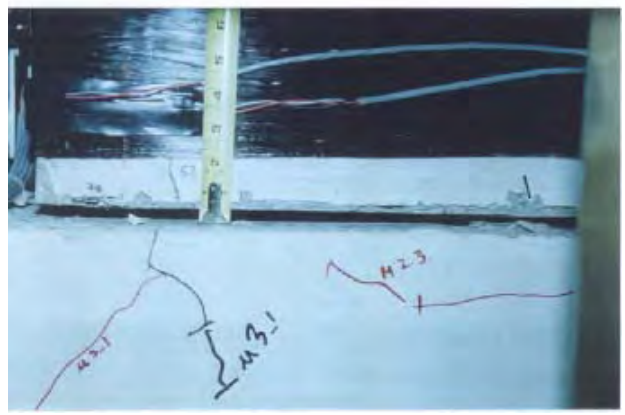


Level I - First vertical on column interface



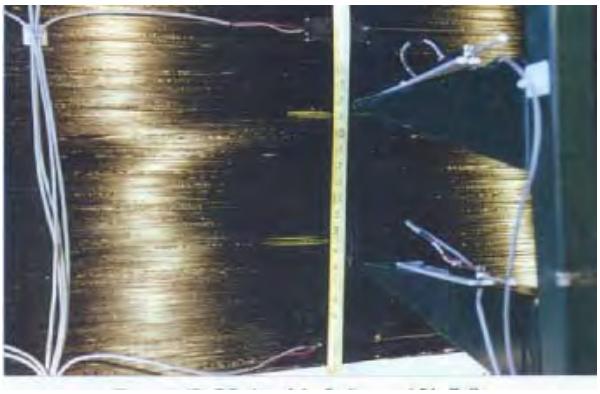
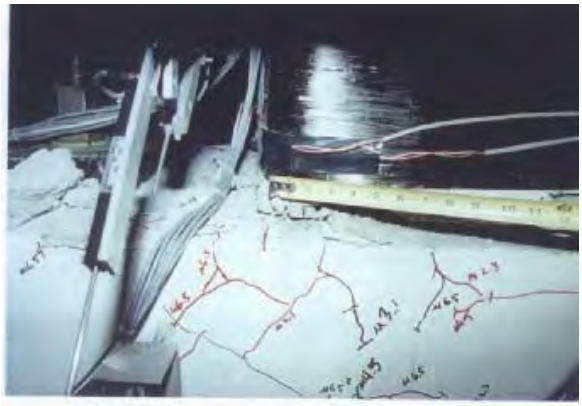
Level II - Above jacket cracks

Level III - Spalling of cover concrete at pedestal

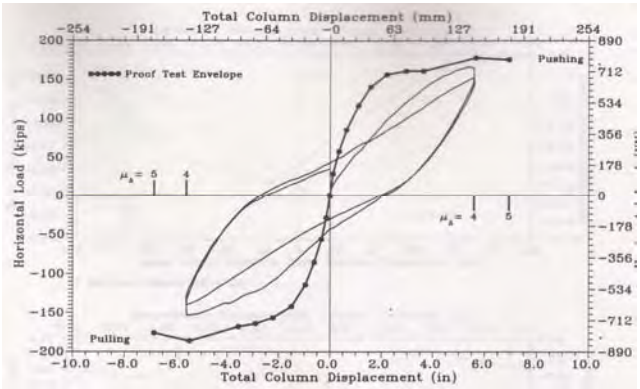


Level IV - Gap between pedestal column

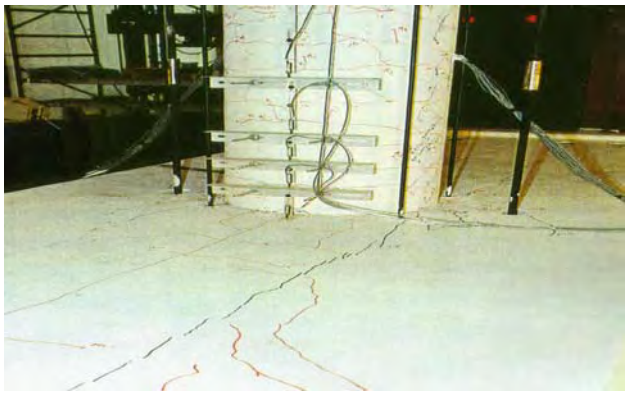
R7 – Flexural

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

R8 – Flexural – Brittle

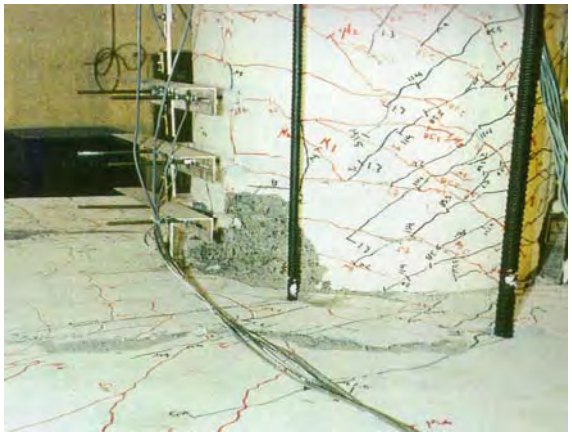


F-d Graph



Level II

Level III

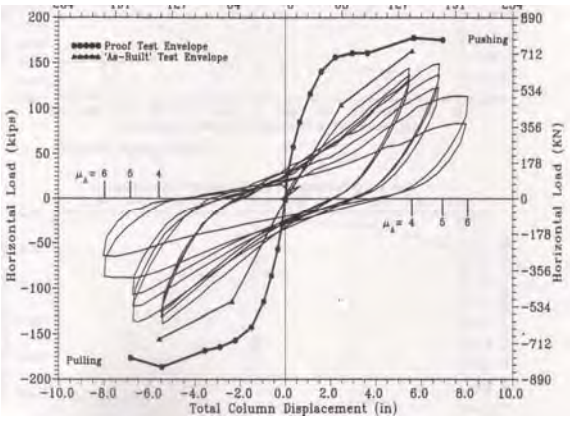


Level III

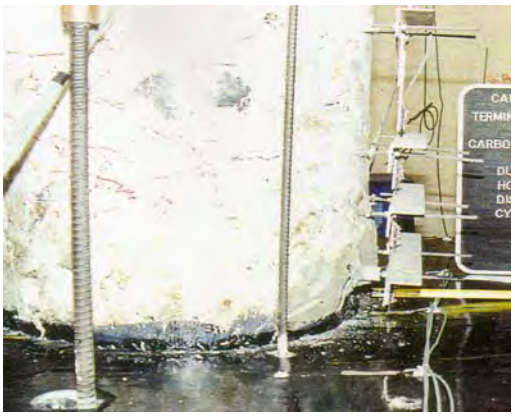
Level IV

Level V

R9 – Flexural – Ductile



F-d Graph



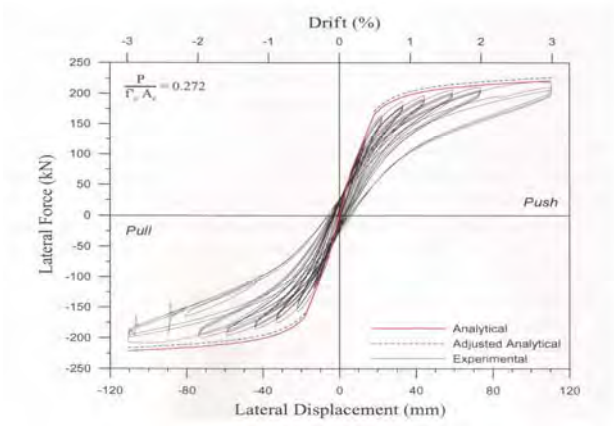
Level III

Level V

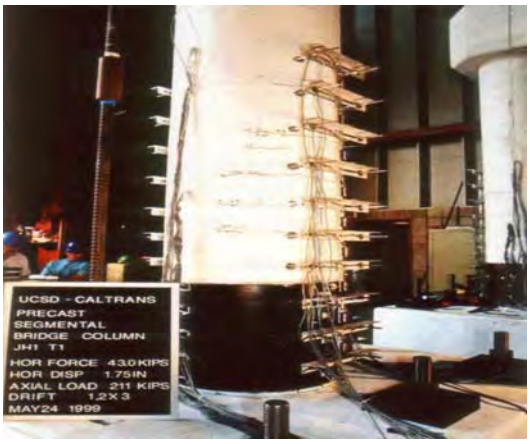
Level V

Level V

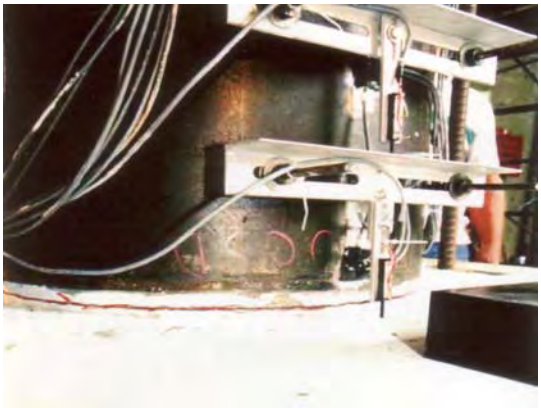
R10 – Flexural - Ductile



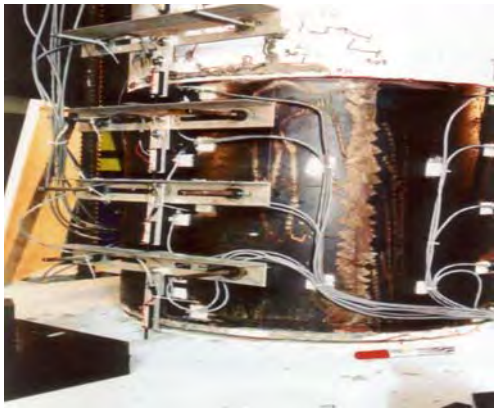
F-d Graph



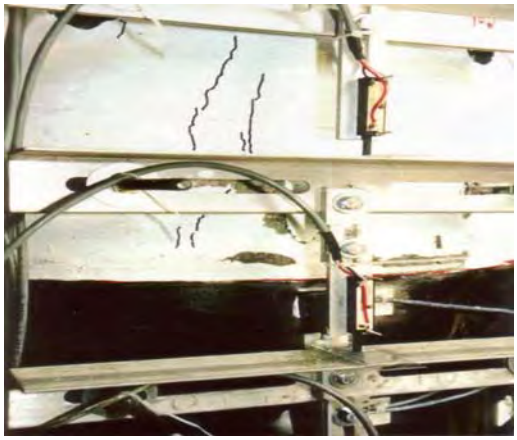
Level I



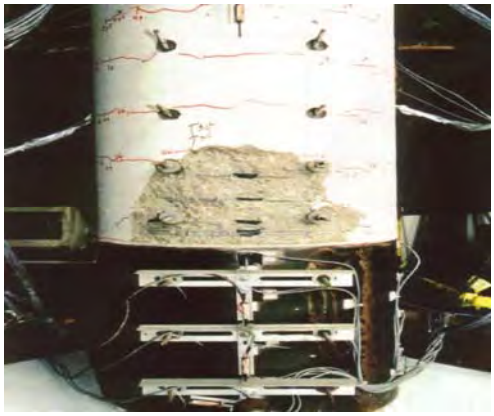
Level II



Level III

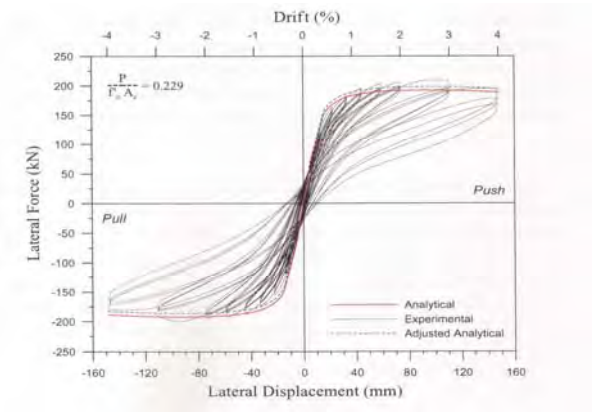


Level IV



Level V

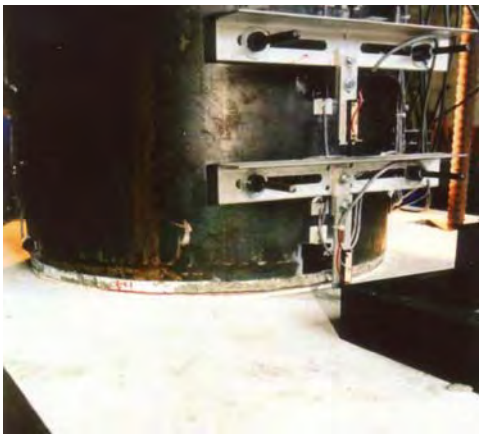
R11 – Flexural - Ductile



F-d Graph

Level II

Level IV

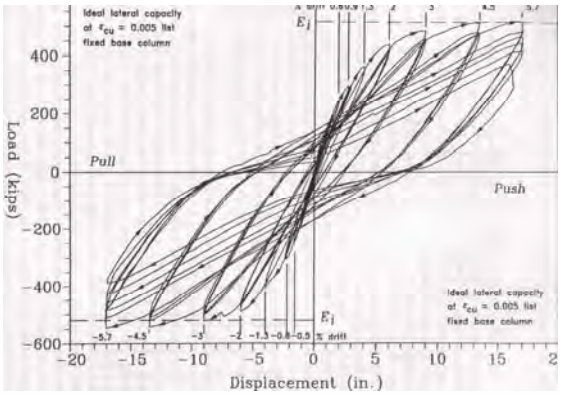


Level IV (Residual crack at end of test)

Sub-Assemblages - Systems

Column Superstructure Sub-Assemblages

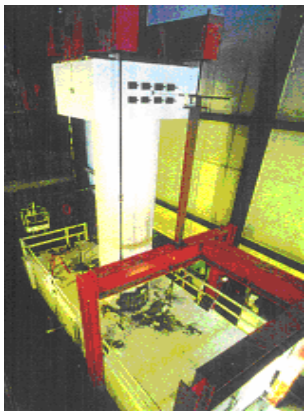
SM1 – Flexural - Ductile



F-d Graph

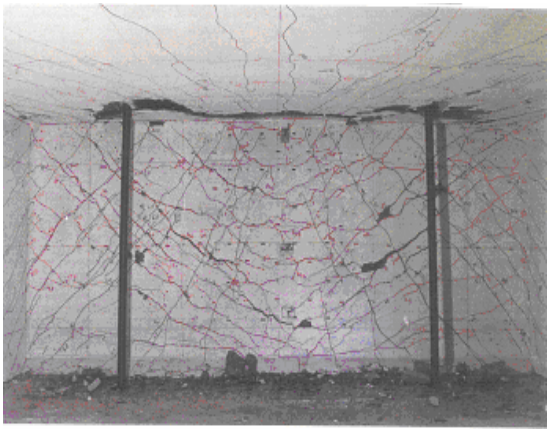
Level III

Level IV



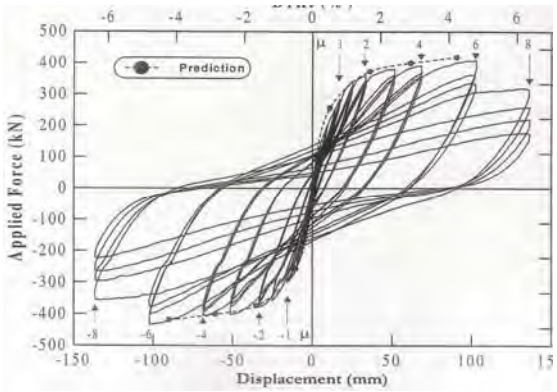
Level V

Level IV superstructure cracks

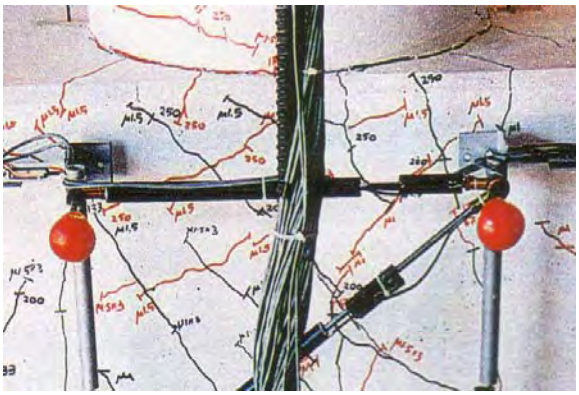


Level IV superstructure cracks

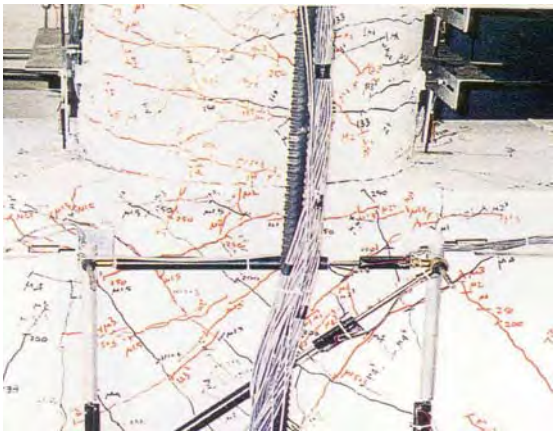
SM2 – Flexural – Ductile



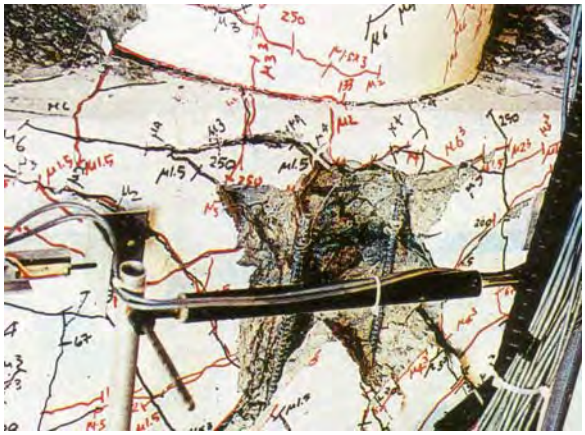
F-d Graph



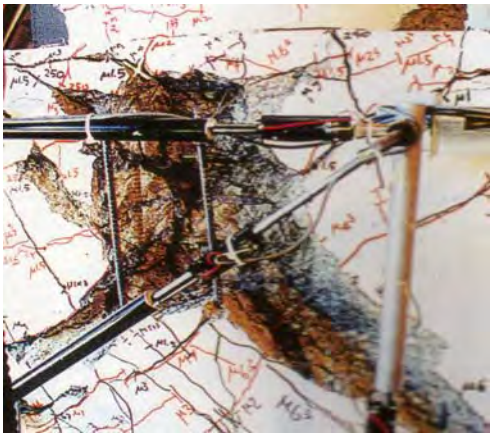
Level II



Level III



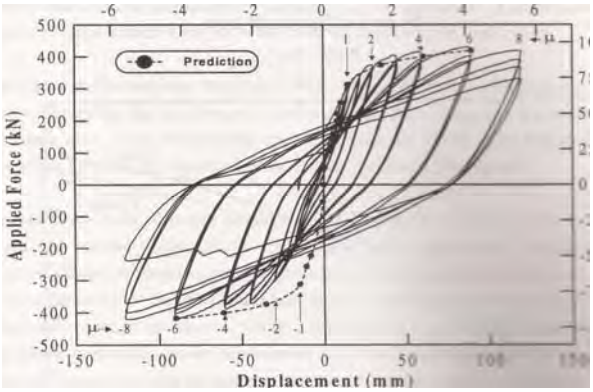
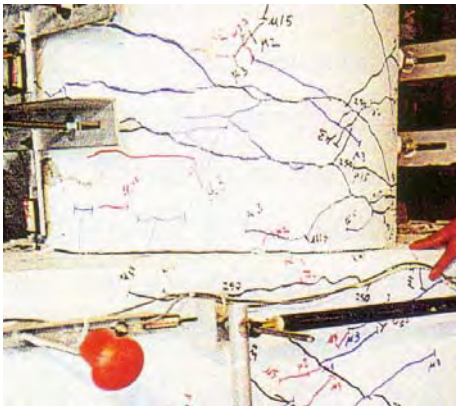
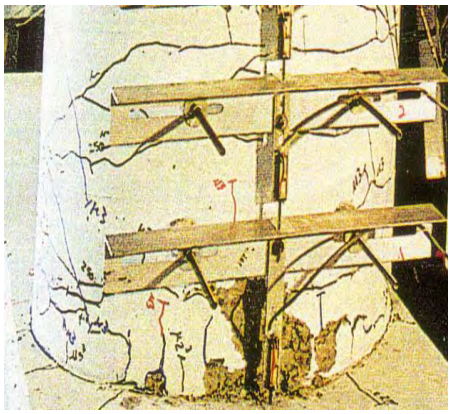
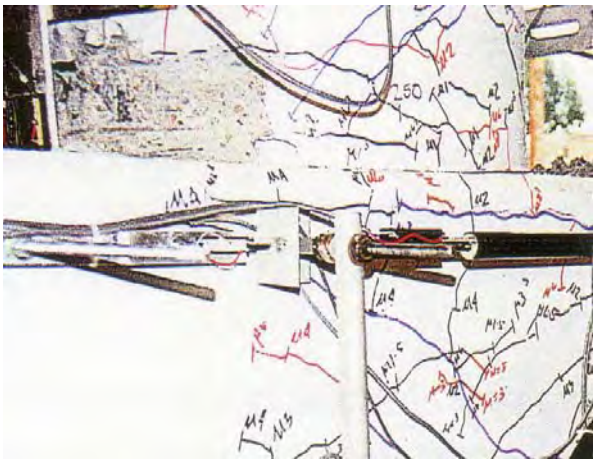
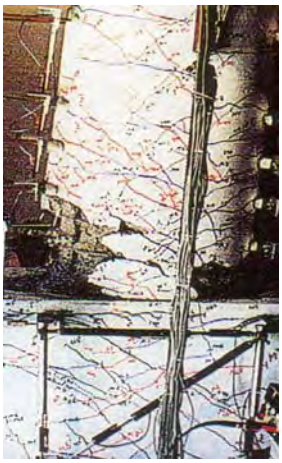
Level IV



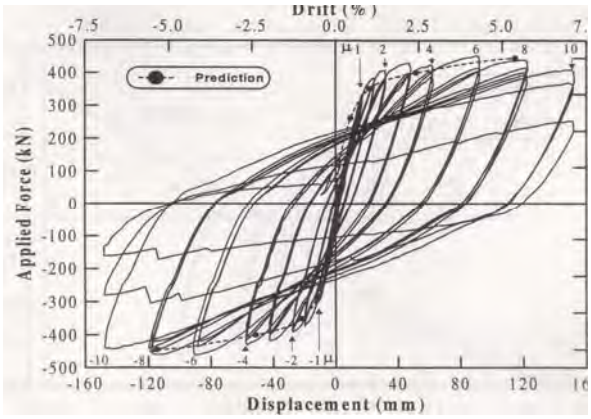
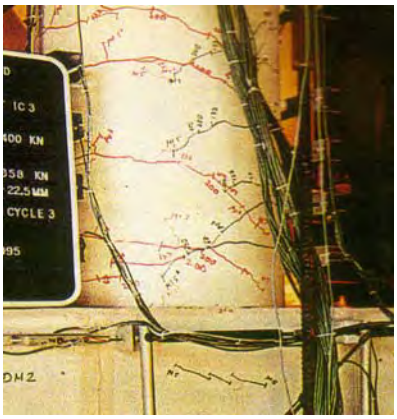
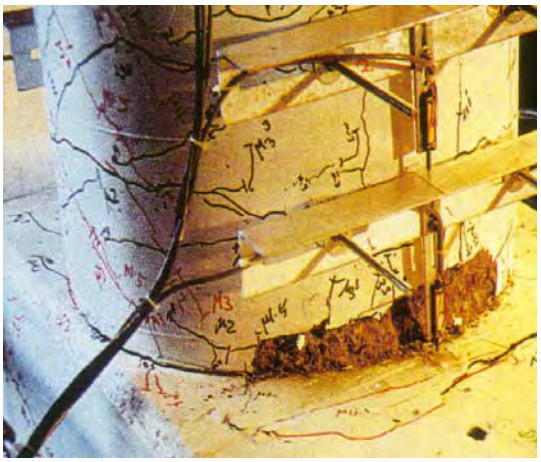
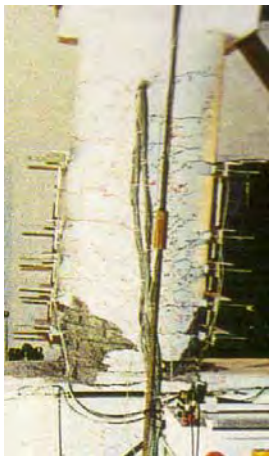
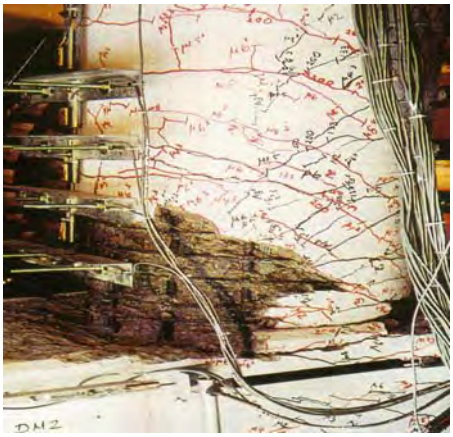
Level V

Level V

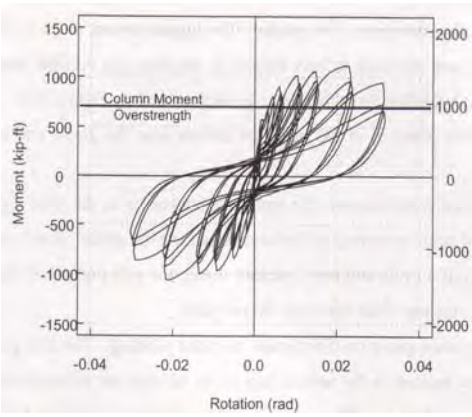
SM3 – Flexural – Ductile

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

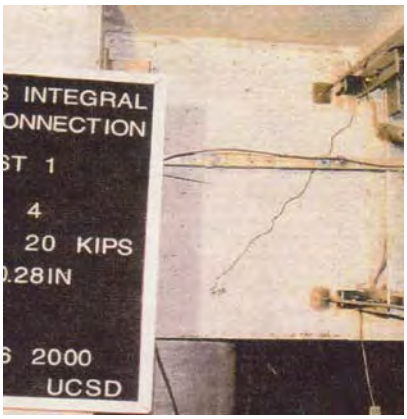
SM4 – Flexural - Ductile

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

SM5 – Shear - Brittle



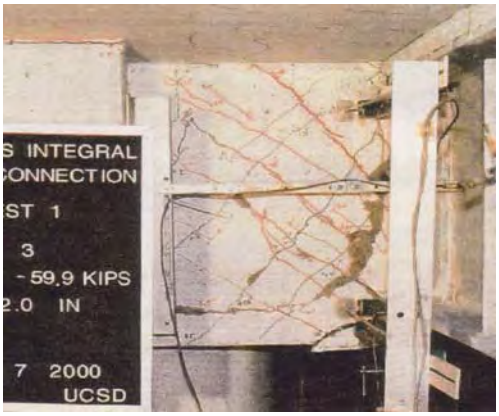
F-d Graph



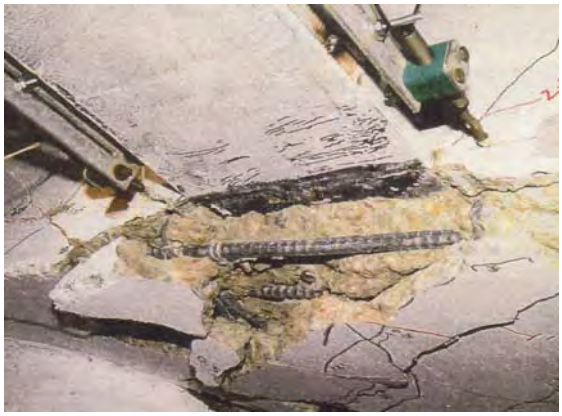
Level III

Level III at bottom

Level IV

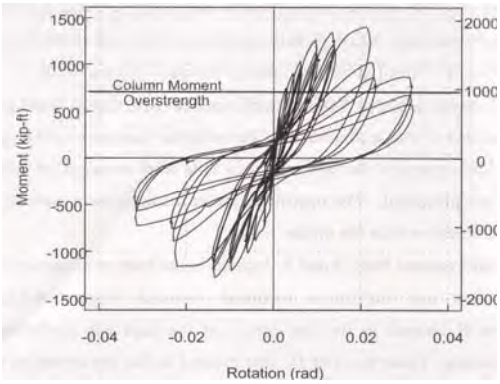
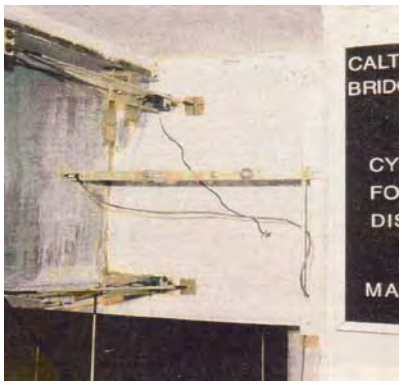
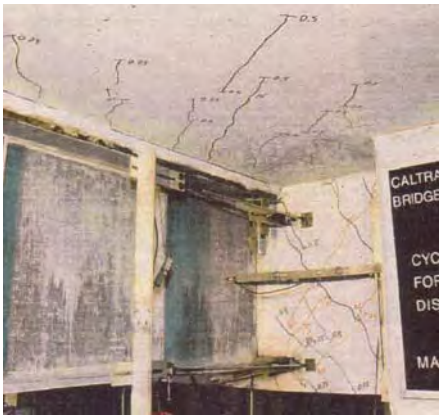
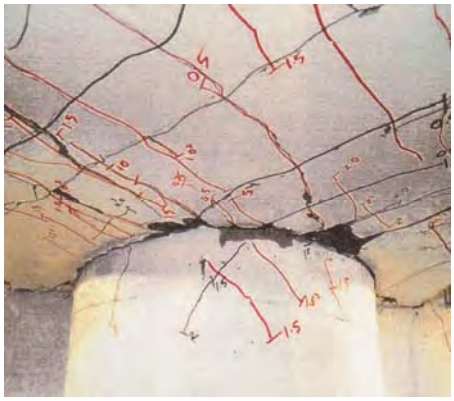
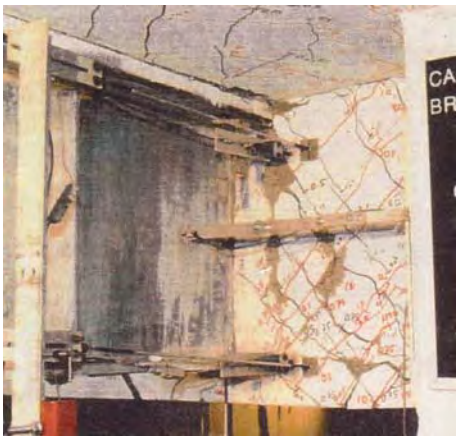


Level IV

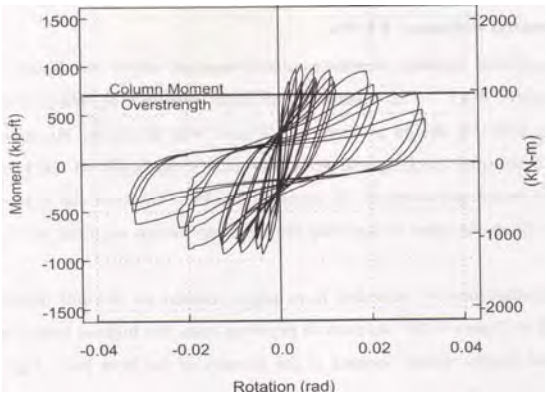


Level V Girder

SM6 – Shear – Brittle

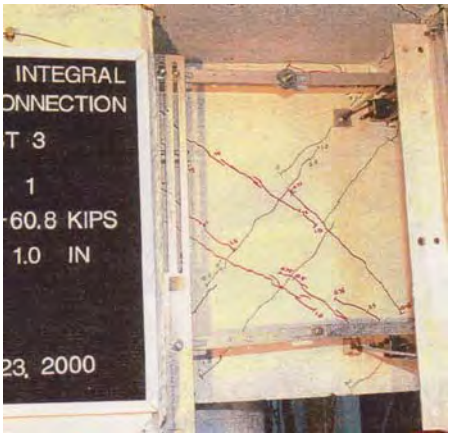
	
F-d Graph	Level III
	
Level IV	Level IV
	
Level IV	Level V

SM7 – Shear – Brittle



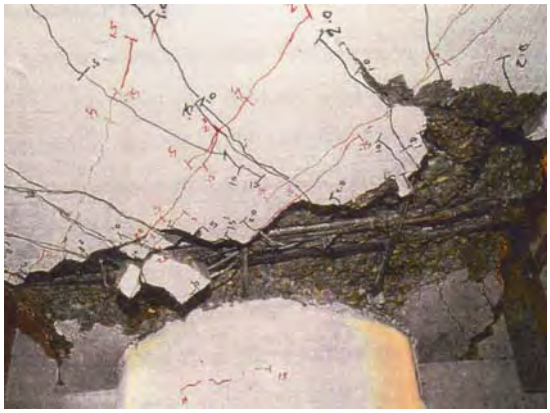
F-d Graph

Level II



Level III

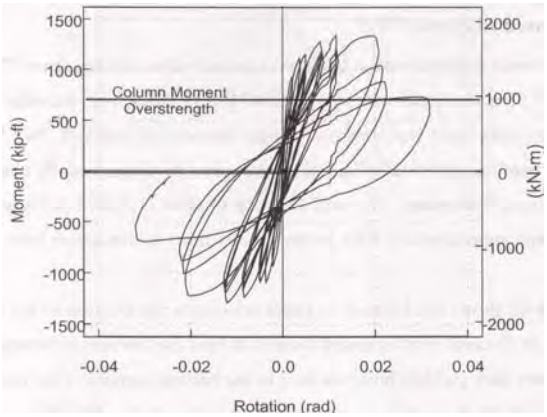
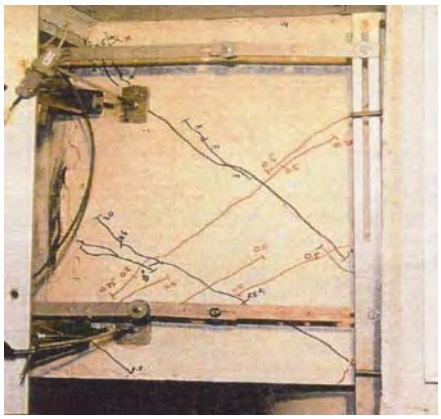
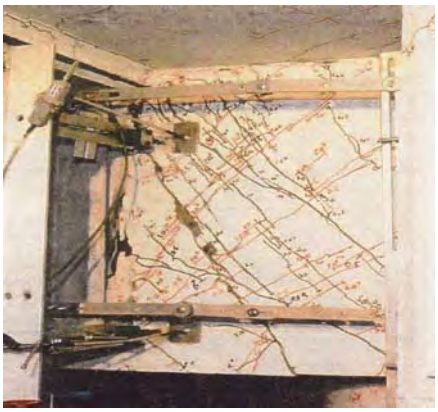
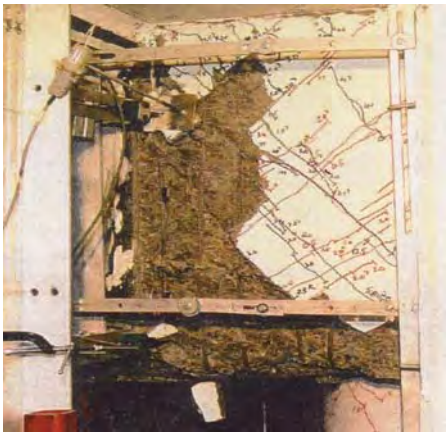
Level IV



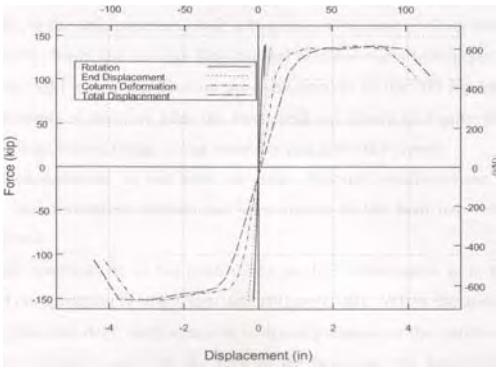
Level IV bent cap

Level V bent cap/girder

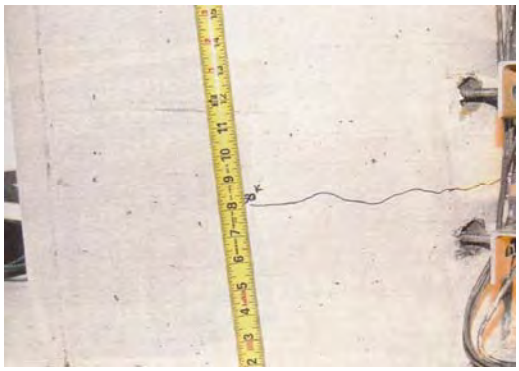
SM8 – Shear – Brittle

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

SM9 – Flexural – Ductile

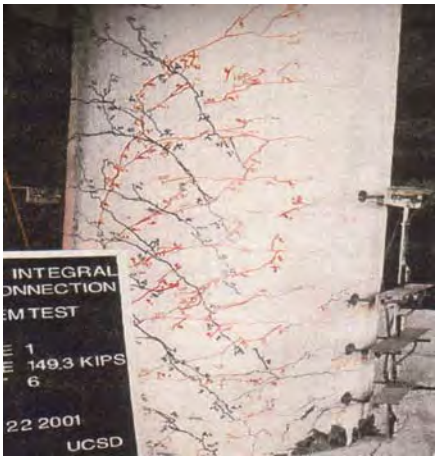


F-d Graph

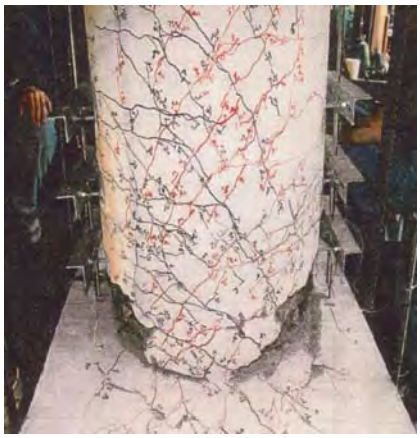


Level II

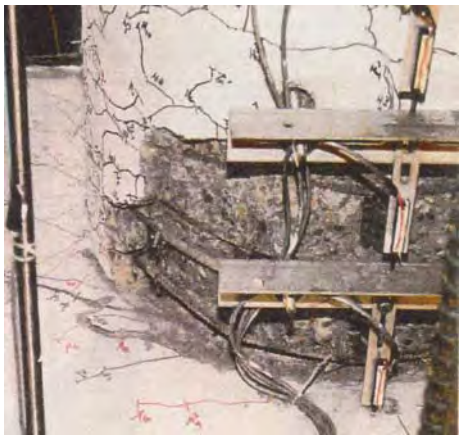
Level II



Level III



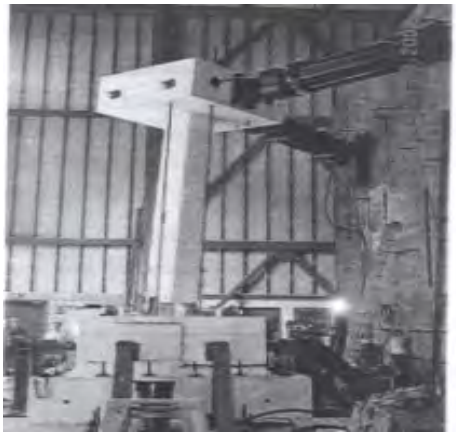
Level IV



Level V

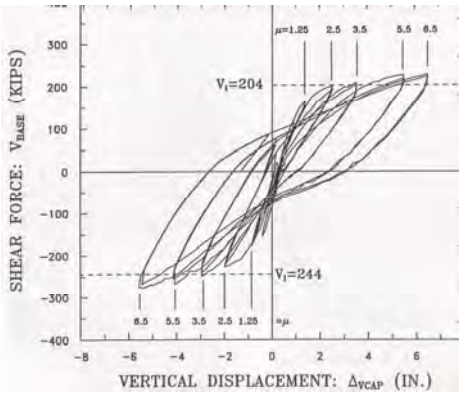
Column Foundation Sub-Assemblages

SM10 – Flexural

Test setup	
Level III	Level V pile cap rotation
	
Level V residual displacement	Level V

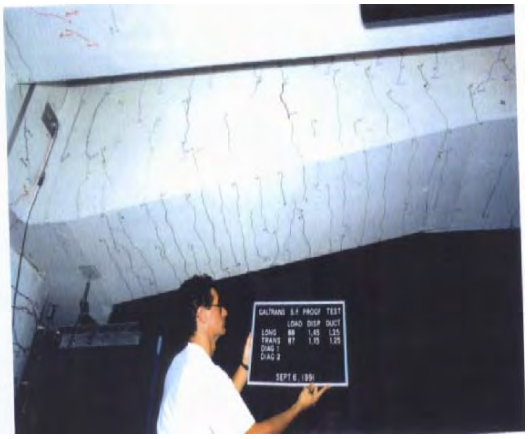
Double Deck Viaduct

SM11 – Flexural - Ductile



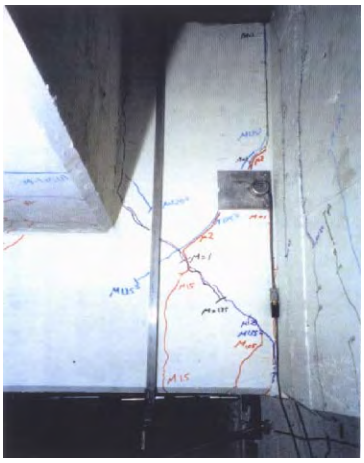
F-d Graph

Level II



Level II edge girder

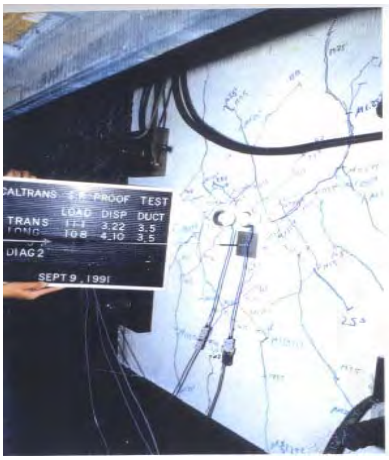
Level II outside face cap column



Level II cap beam between superstructure-girder

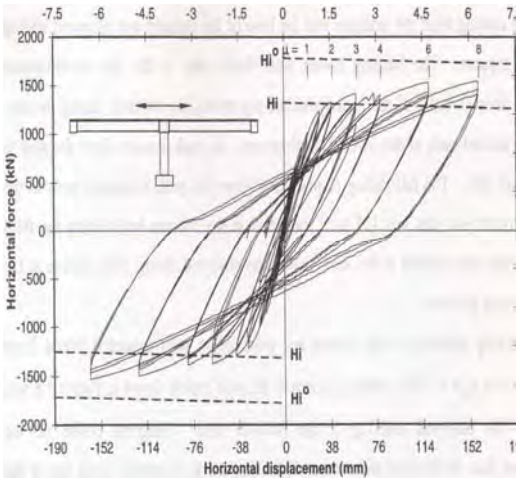
Level III

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



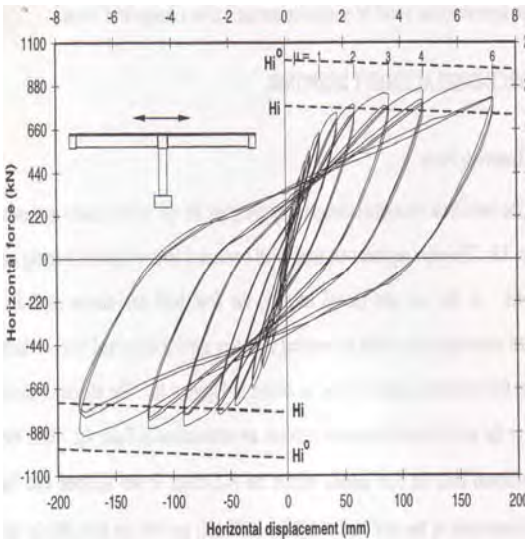
F-d Graph

Level III

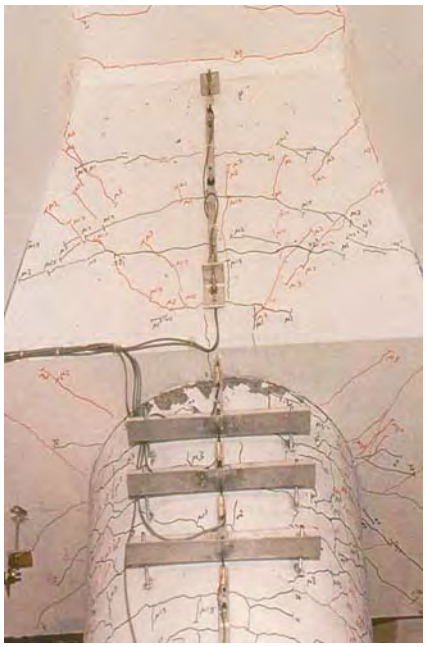
Level III

Level IV

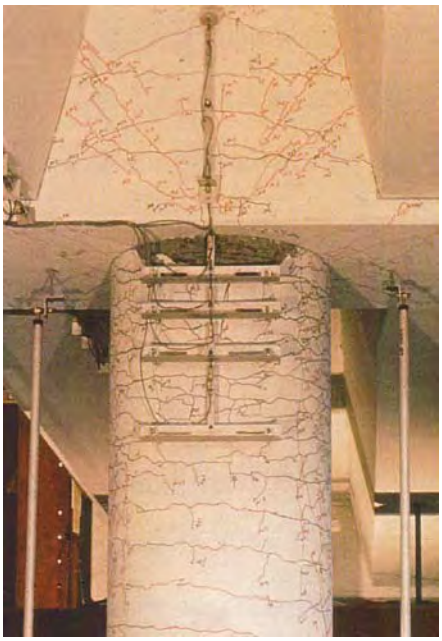
SM13 – Flexural – Ductile



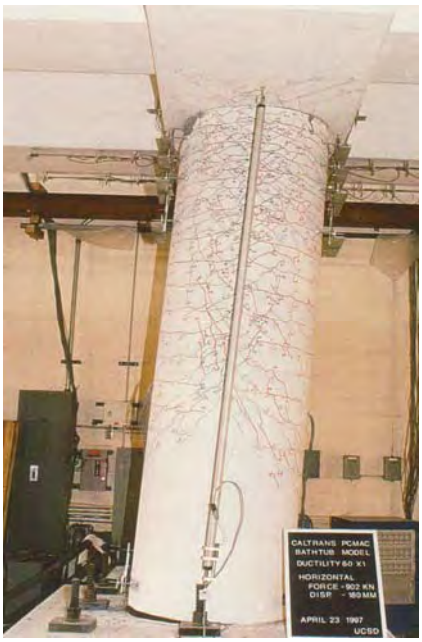
F-d Graph



Level III

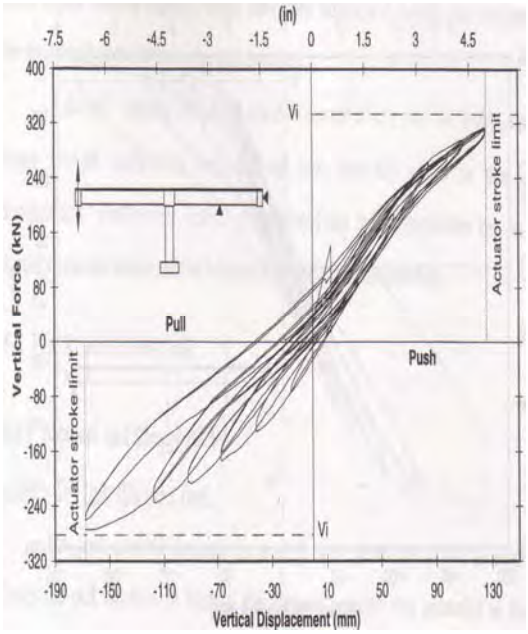


Level IV



Level V

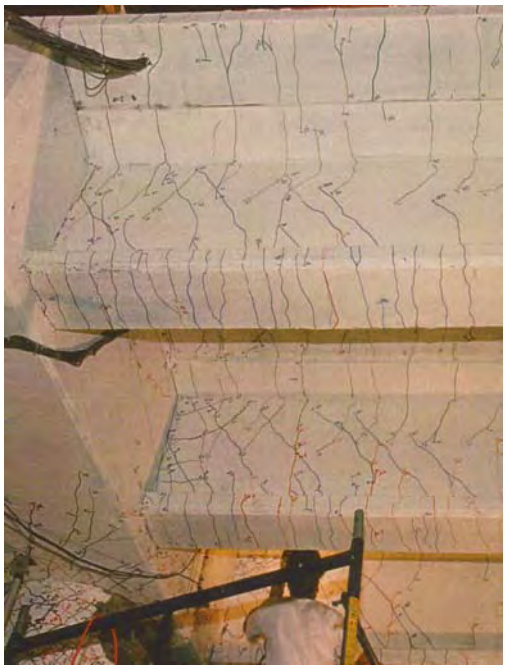
SM14 – Shear – Brittle



F-d Graph

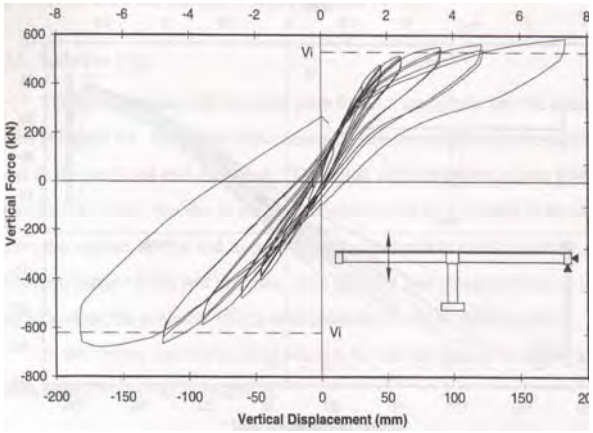
Level III

Level IV

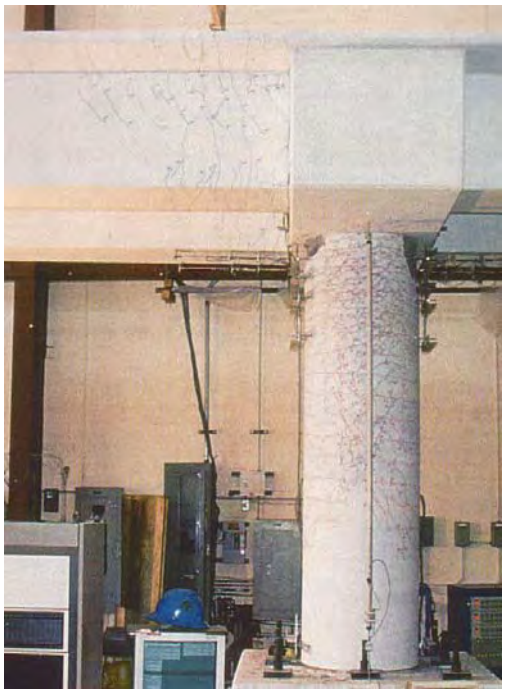


Level IV

SM15 – Flexural - Ductile

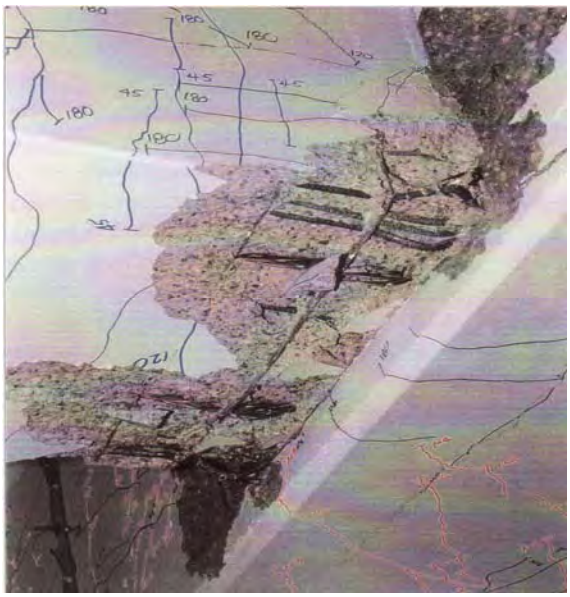


F-d Graph



Level III

Level IV



Level V

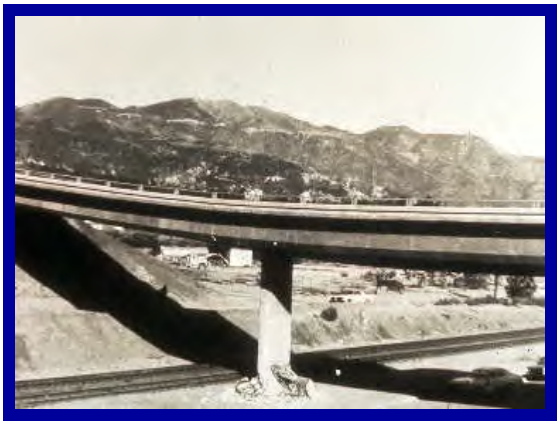
Part II

Field photo database - Earthquake events

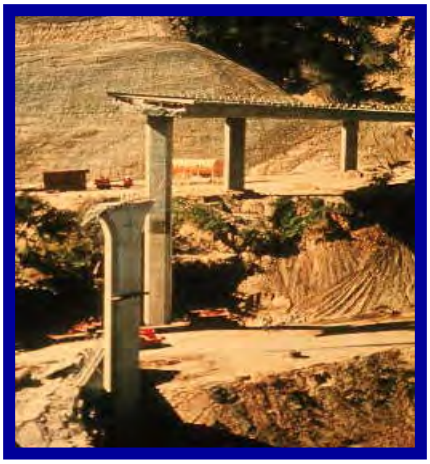
Classification according to Earthquake

San Fernando, USA 1971

San Fernando, USA 1971

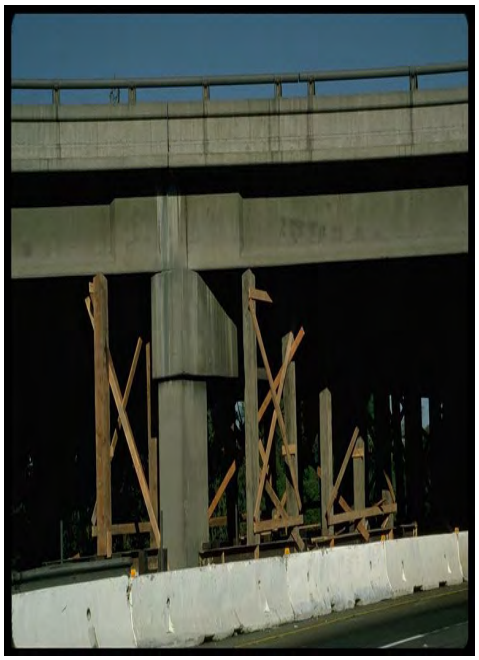
Failure – buckling of long bars	Failure – buckling of long bars
Shear failure	Shear failure
	
Failure at Column Base	Shear failure

San Fernando, USA 1971

Total failure	Total failure
	
Span failure	Pullout Failure
Exterior shear key failure	

Imperial Valley, USA 1979

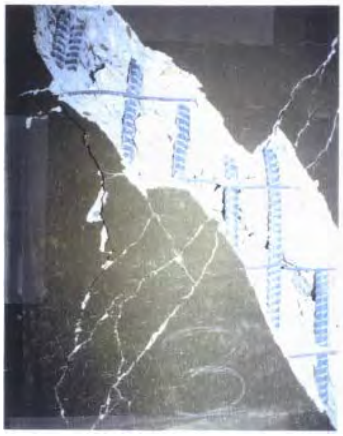
Imperial Valley, USA 1979

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

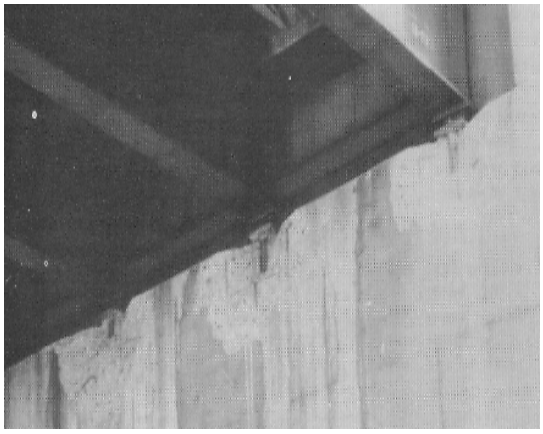
New River Bridge

Whittier Narrows, USA 1987

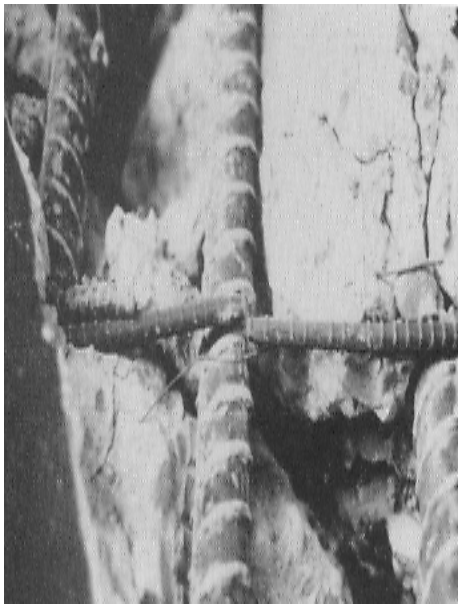
Whittier Narrows, USA 1987

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

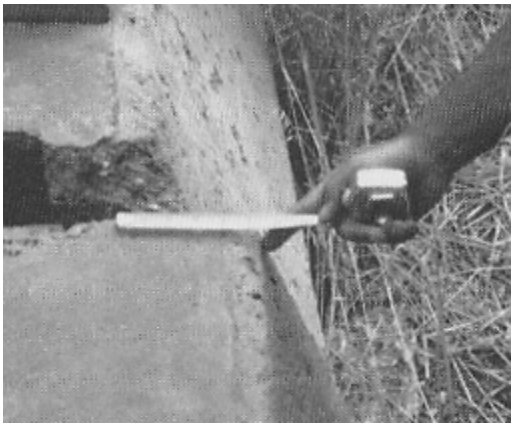
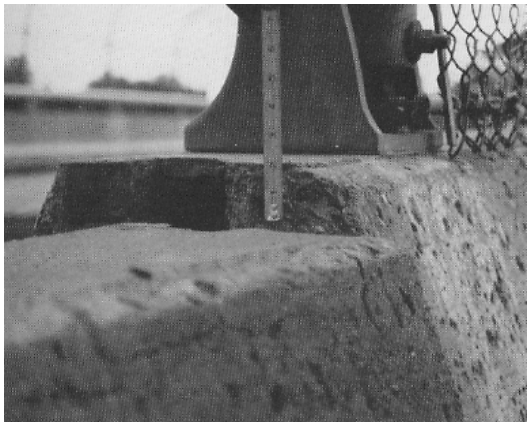
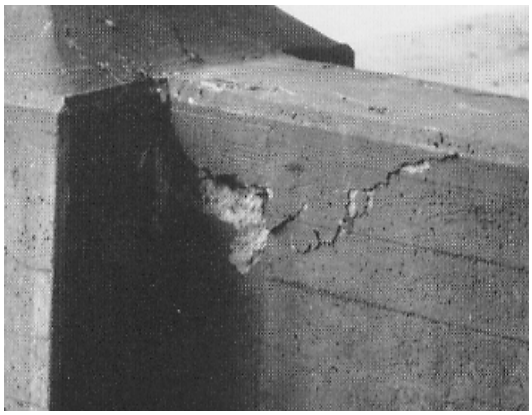
Loma Prieta, USA 1989

Shear failure	Shear failure
Joint damage – Level V	

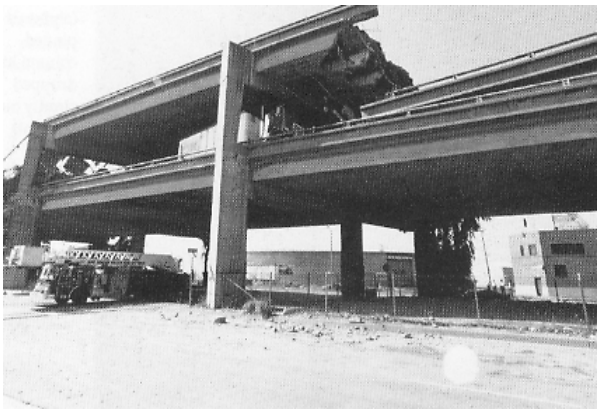
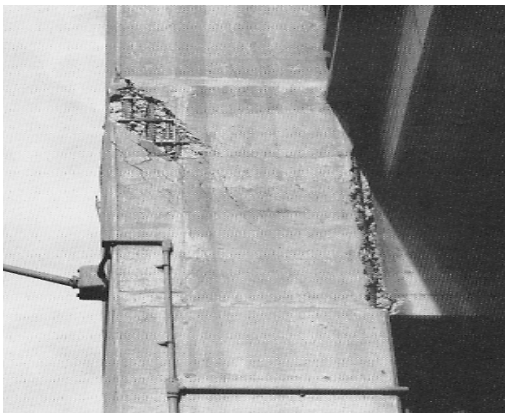
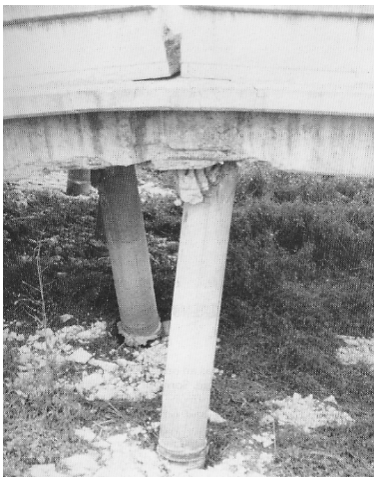
Loma Prieta, USA 1989

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

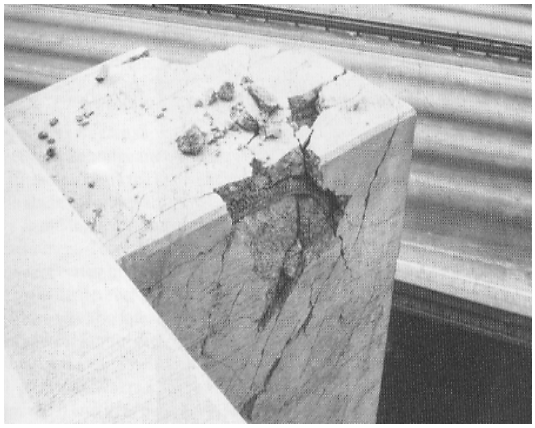
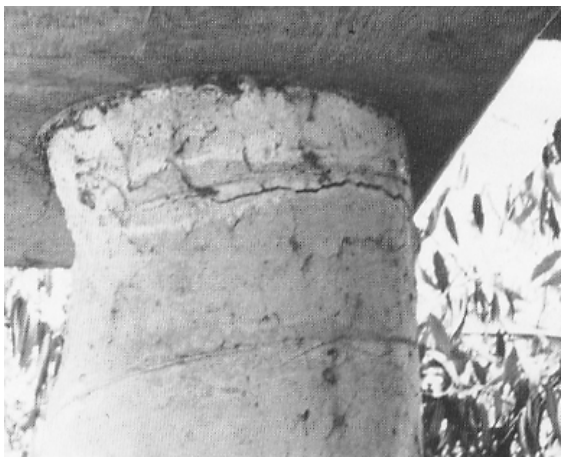
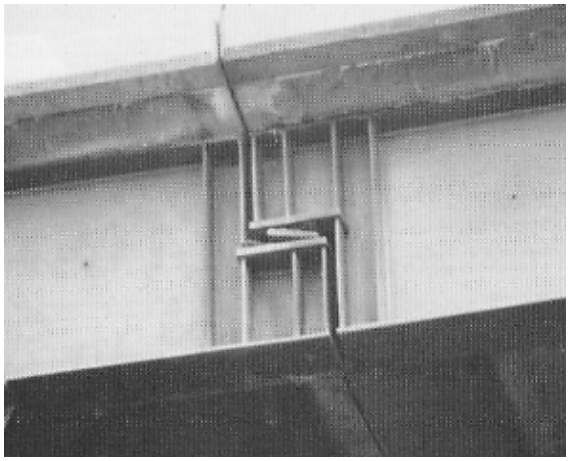
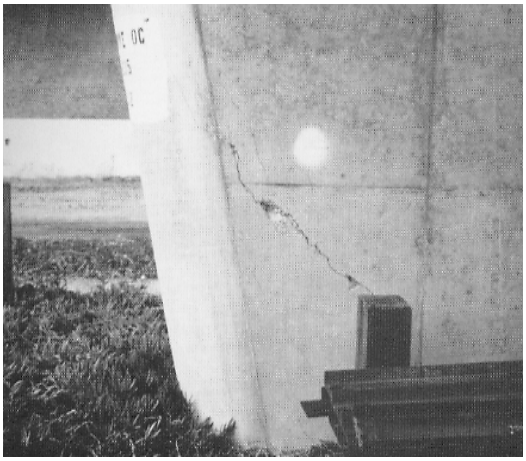
Loma Prieta, USA 1989

	
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

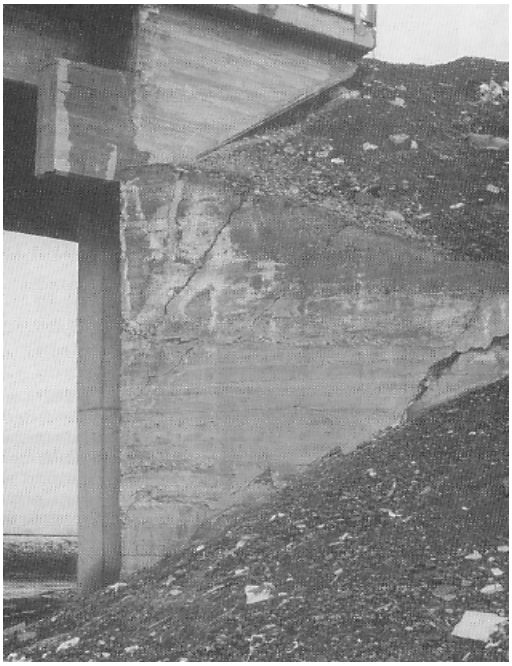
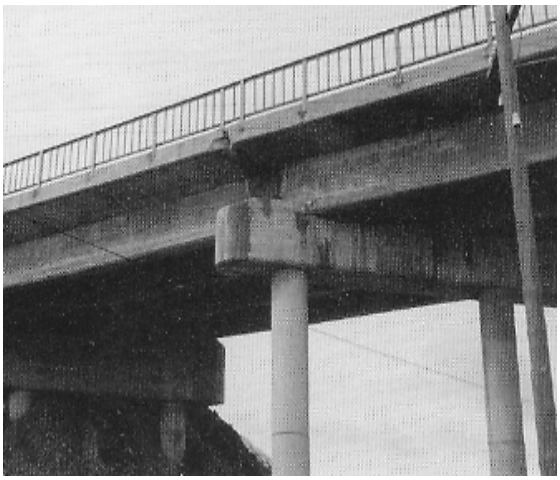
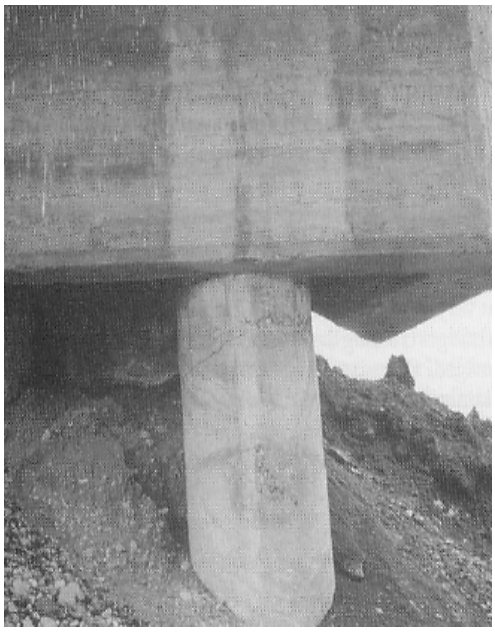
Total Failure	Collapsed deck (Struve Slough Bridge)
	
Collapsed deck (Cypress Street Viaduct)	Shear cracking- Level IV
	
Lateral Displacement – Level V(Struve Slough)	Deck cut-through by piers (Struve Bridge)

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

	
Cracking of abutment wall – Level IV	Pounding above piers – Level V
	
Shear crack on column – Level IV	

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

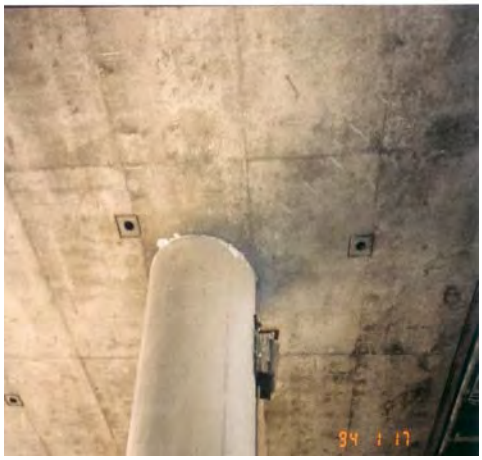
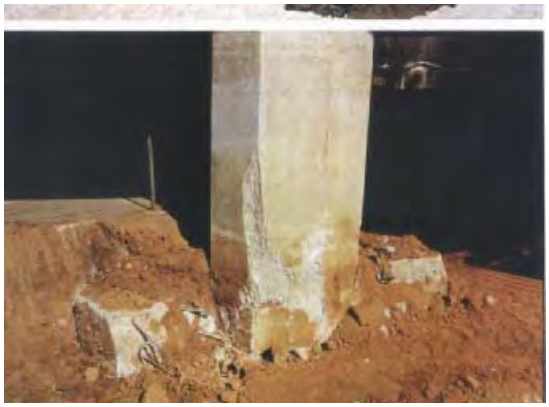
Northridge, USA 1994

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

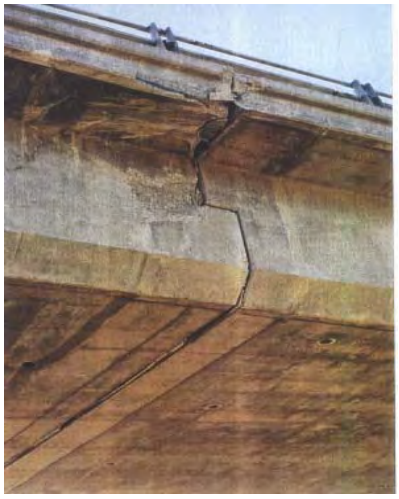
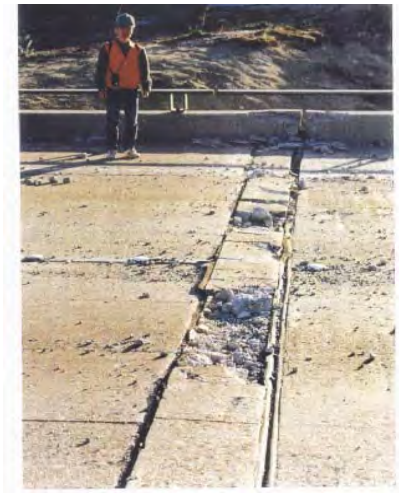
Northridge, USA 1994

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

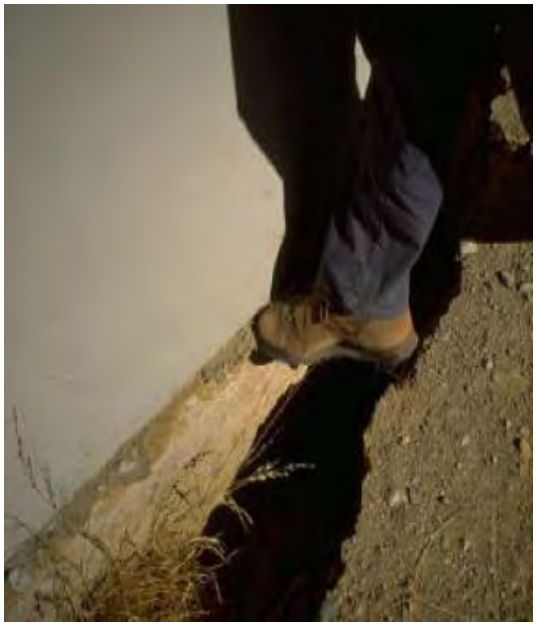
Northridge, USA 1994

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

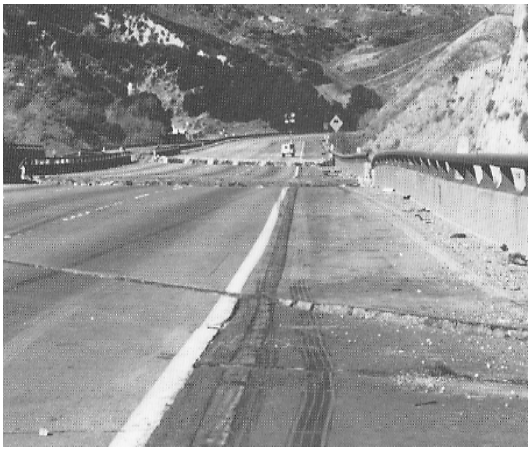
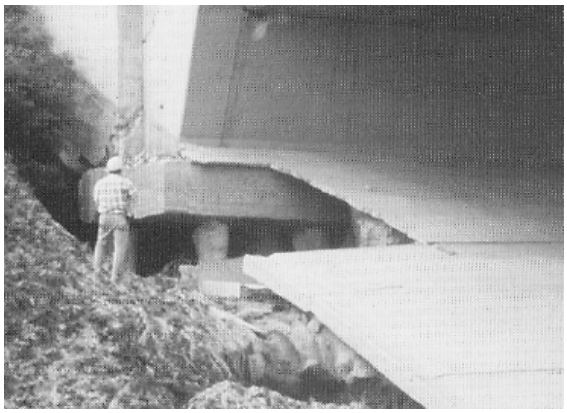
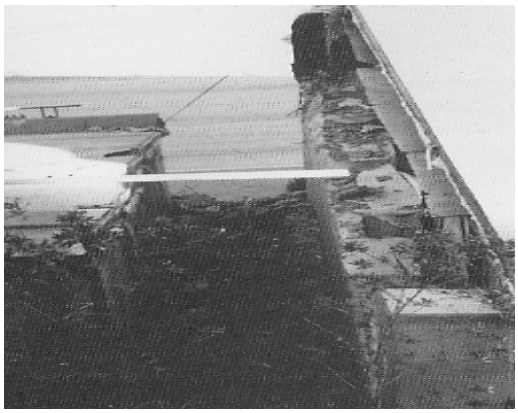
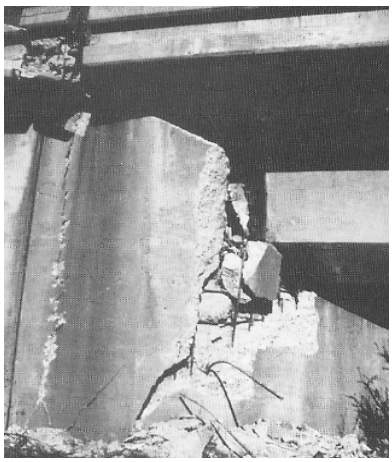
Northridge, USA 1994

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

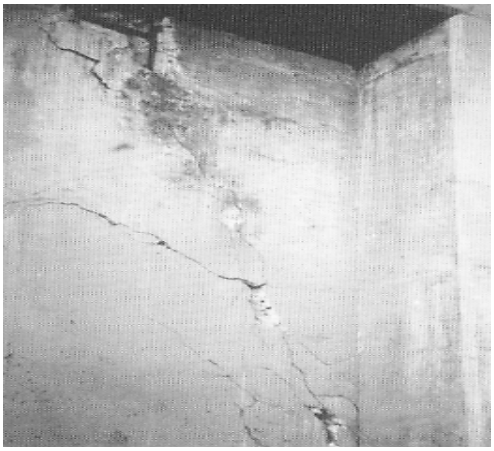
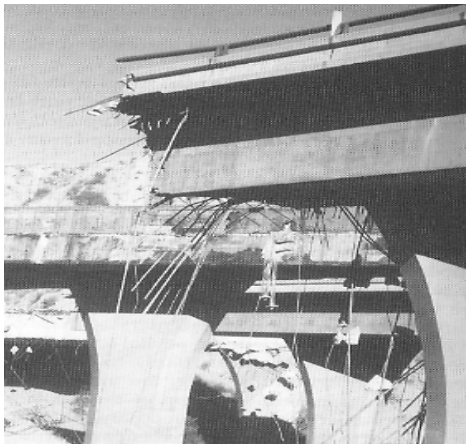
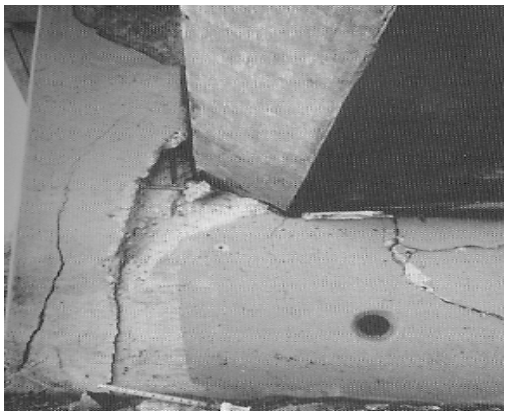
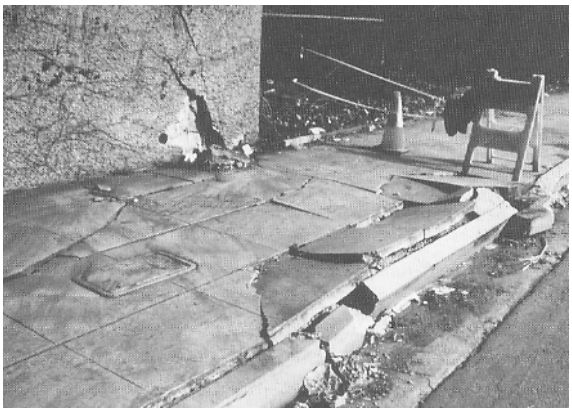
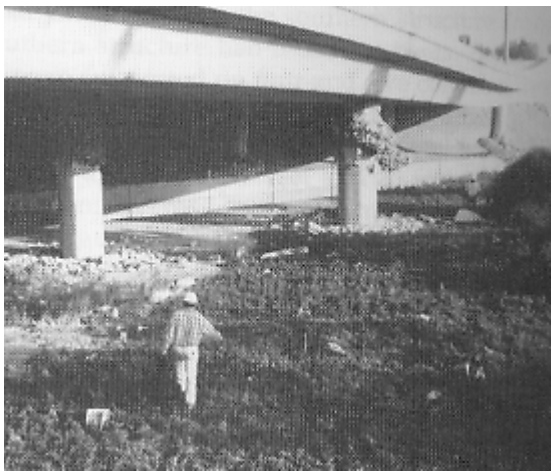
Northridge, USA 1994

	
Soil separation	Barrier cracking – Level IV
Deck damage- Level IV	Curb separation – Level IV

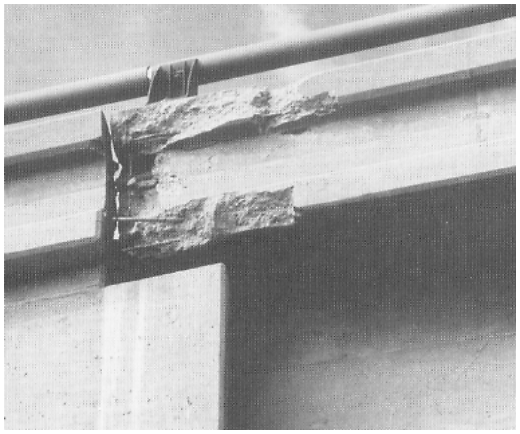
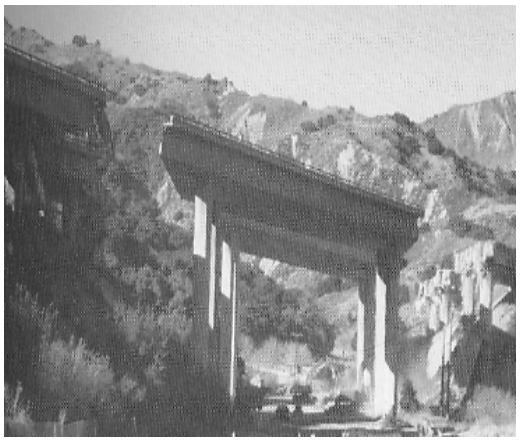
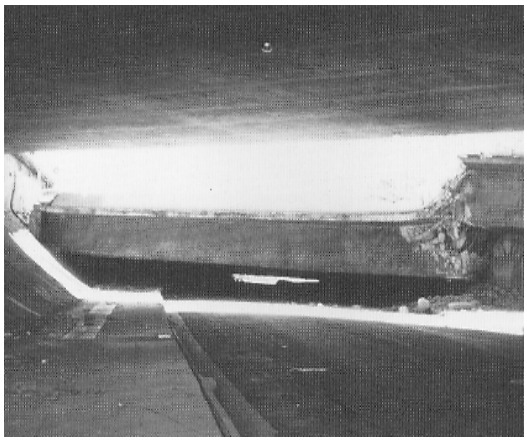
Northridge, USA 1994

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

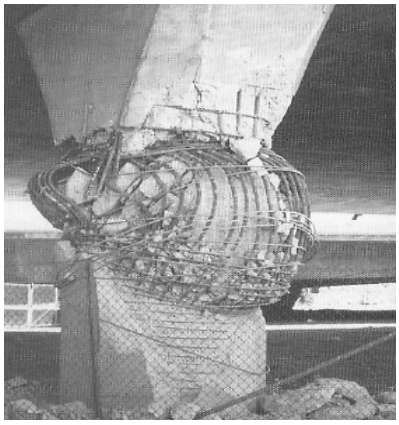
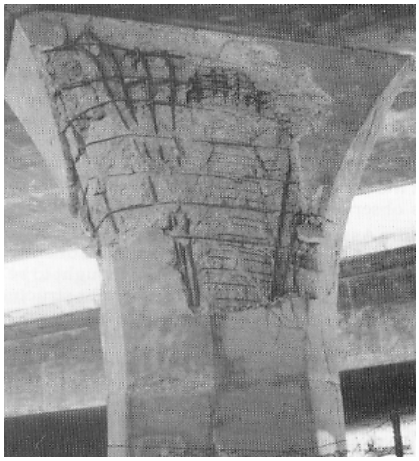
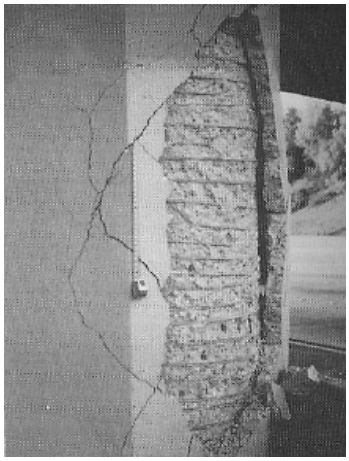
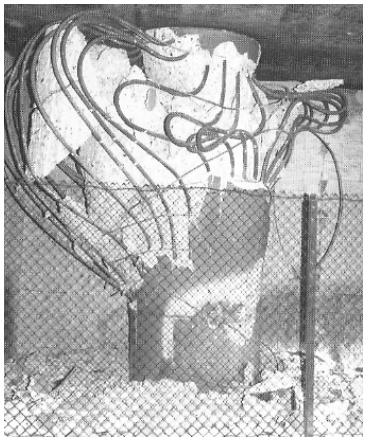
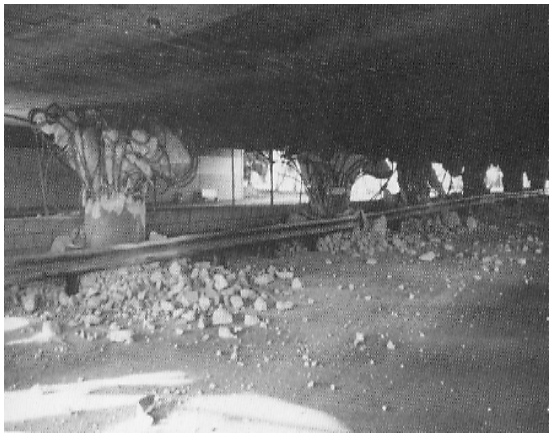
Northridge, USA 1994

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

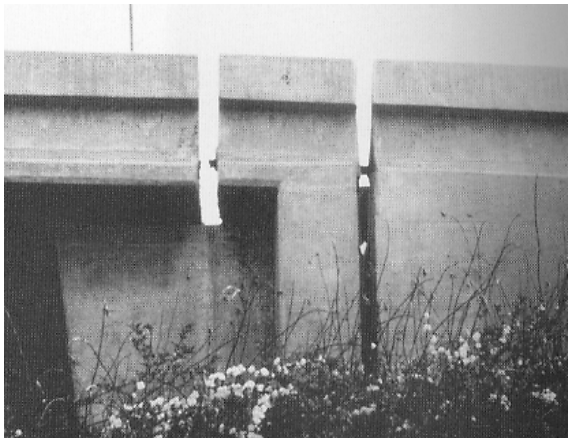
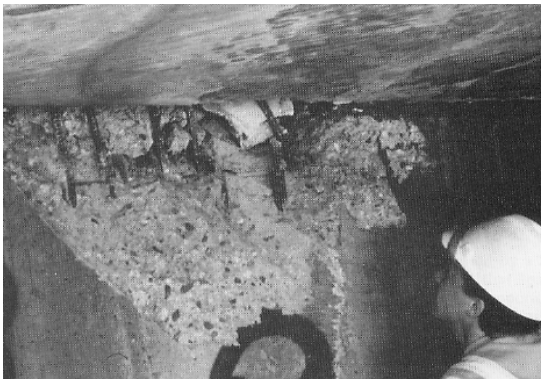
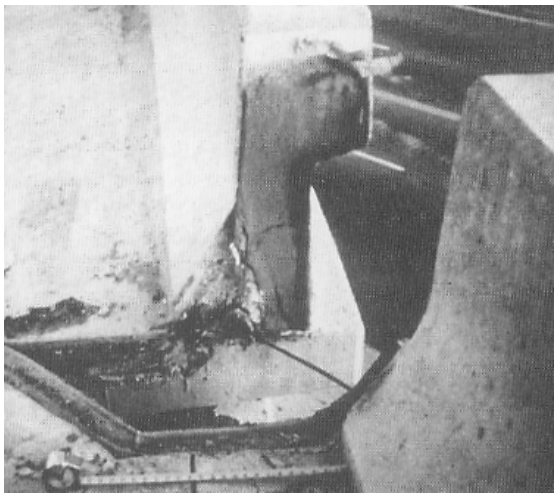
Northridge, USA 1994

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

Northridge, USA 1994

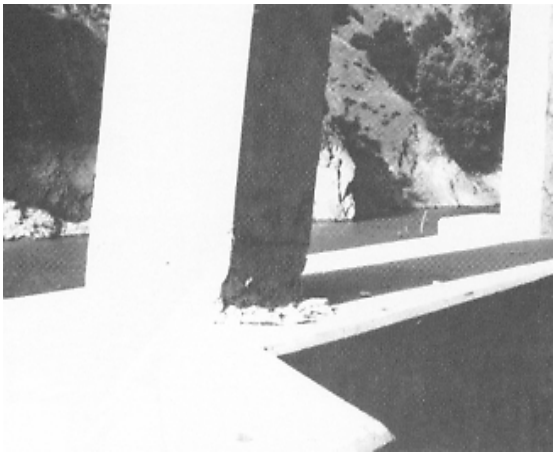
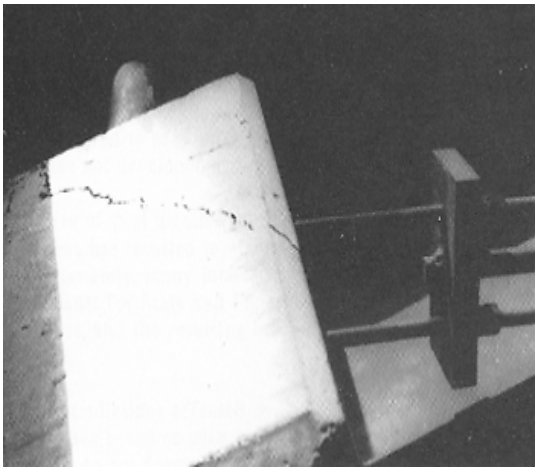
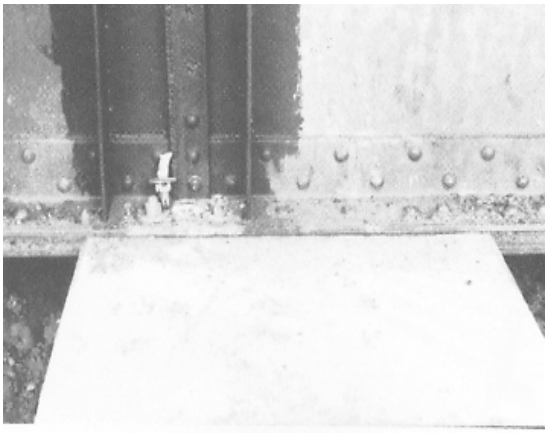
	
Shear Failure	Shear - Level V
	
Shear Level V	Shear Level V
	
Column Failure	Column Failure

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

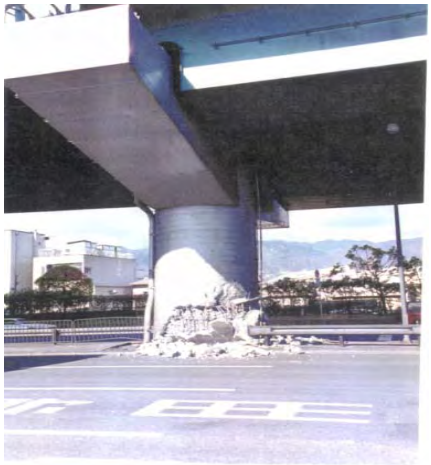
Kobe, Japan 1995

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

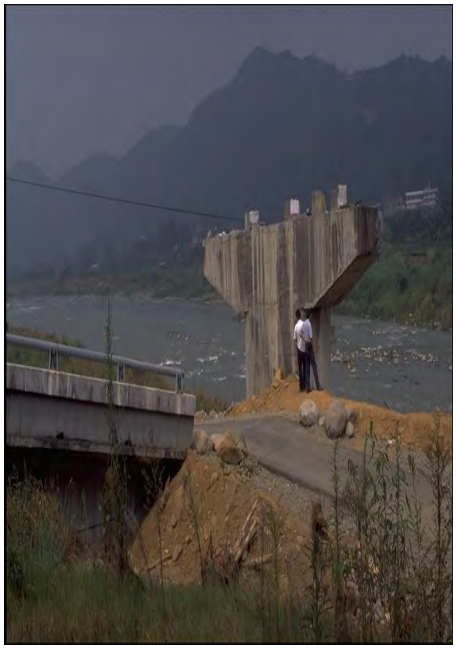
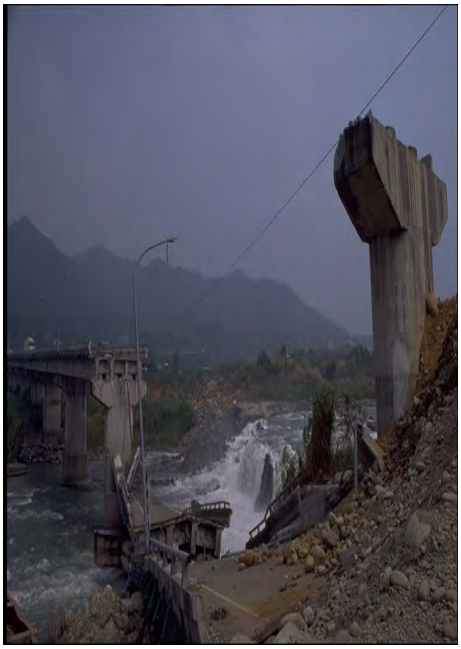
Chi-Chi, Taiwan 1999

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

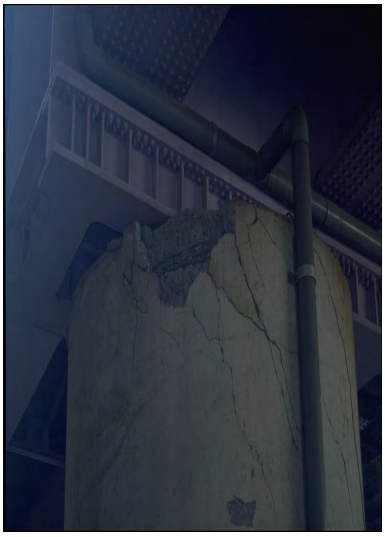
Chi-Chi, Taiwan 1999

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

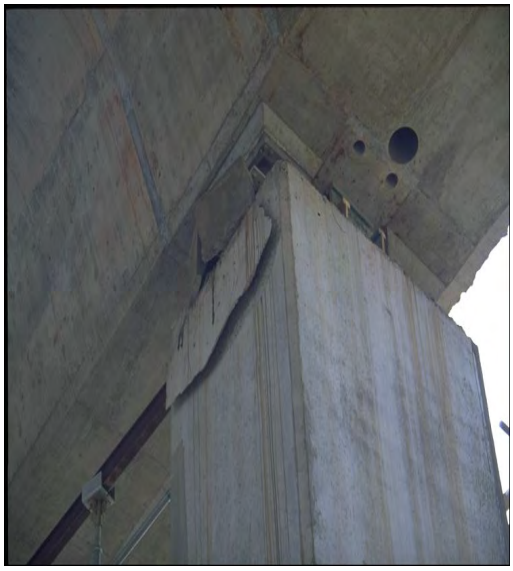
	
Unseating of Superstructure	Unseating of Superstructure
Unseating of Superstructure	Unseating of Superstructure

Chi-Chi, Taiwan 1999

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

Mau-uo-Shi Bridge

Chi-Chi, Taiwan 1999

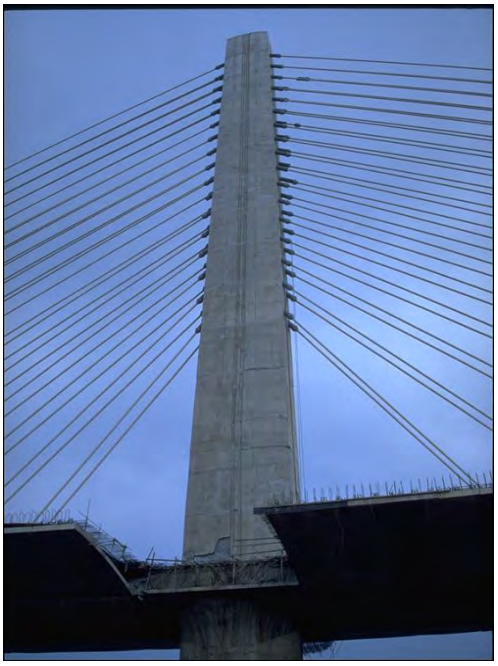
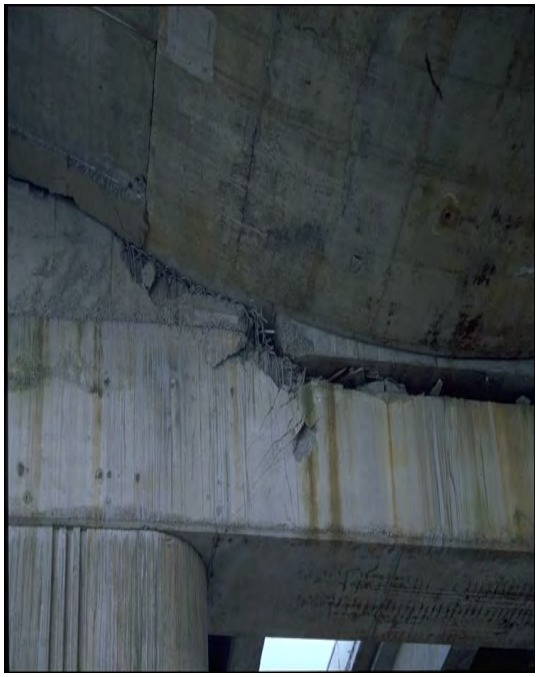
	
Column Damage, Level V	Column, Bearing Damage, Level V
Lateral movement - Level V	Bearing Damage – Level V

Chi-Chi, Taiwan 1999

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

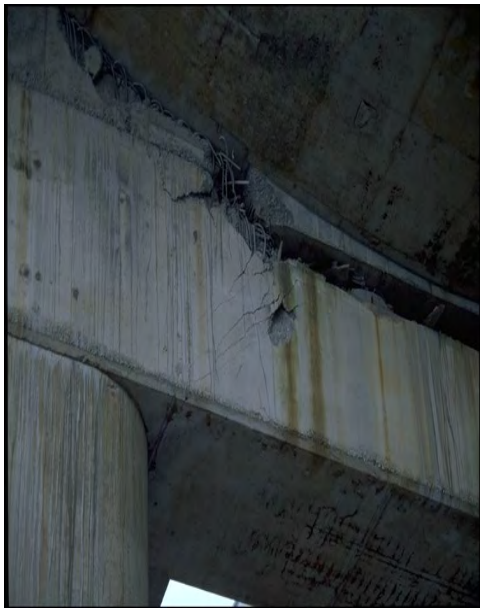
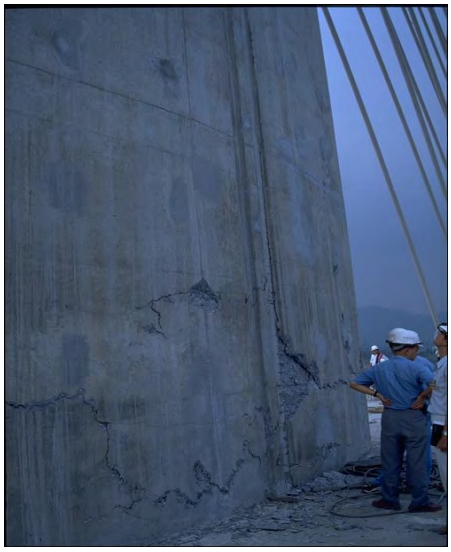
I-jiang Bridge

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	

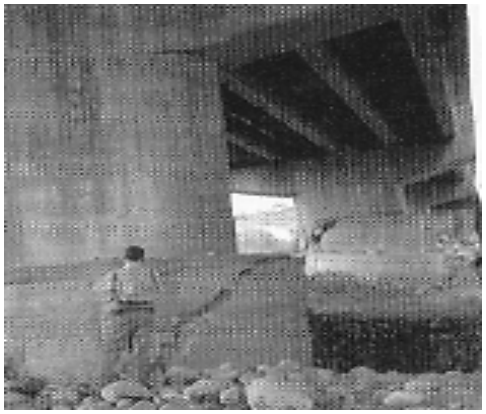
Shih-Wui Bridge

Chi-Chi, Taiwan 1999

Total Failure	Total Failure
Total Failure	

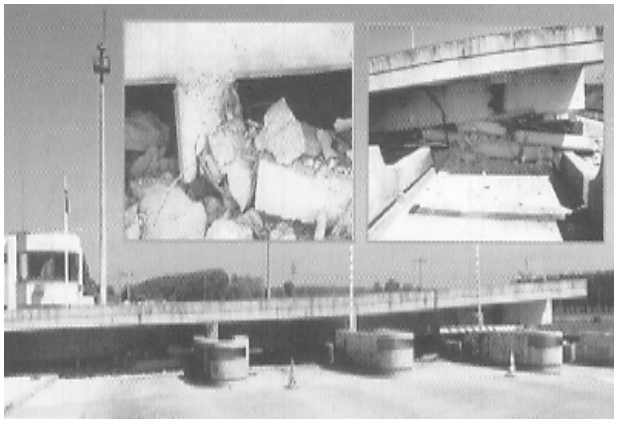
Ming Ju Bridge

Chi-Chi, Taiwan 1999

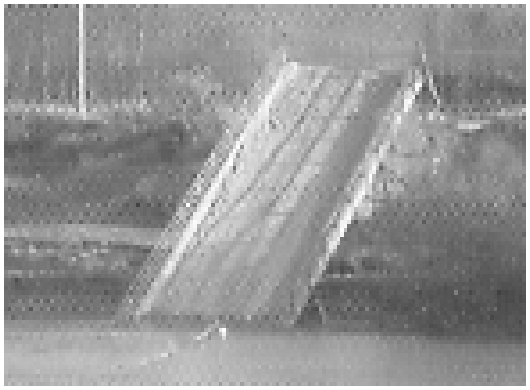
Total Failure	Expansion of joints-Level V
	
Shear-Level V	Shear Failure (Wu Shu Bridge)
Total Failure (Pin ling bridge)	

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

Level IV -Displaced spans (TEM Sakarya Viaduct)	Total Failure (TEM Arifiye Road Bridge)
	
Total Failure (Sakarya Bridge)	

Mid Niigata Prefecture Earthquake, Japan 2004

Mid Niigata Prefecture Earthquake, Japan 2004

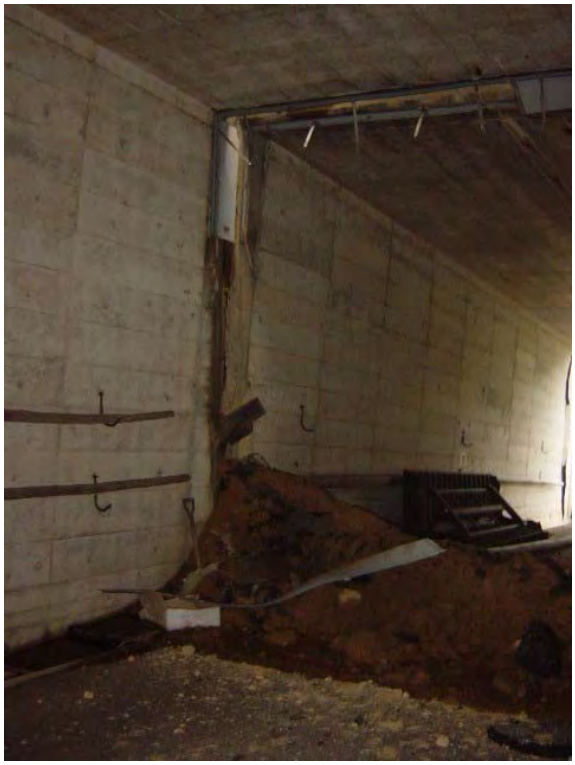
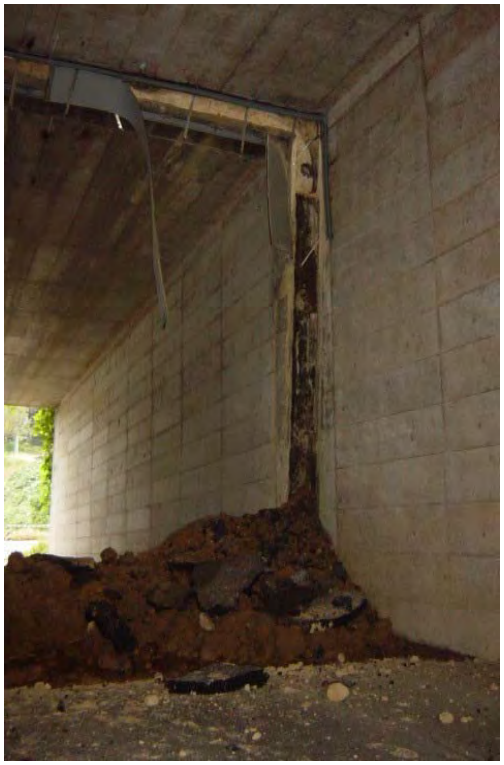
Shear-Level V	Shear-Level V
Shear-Level V	Shear-Level V

‘

Mid Niigata Prefecture Earthquake, Japan 2004

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

Mid Niigata Prefecture Earthquake, Japan 2004

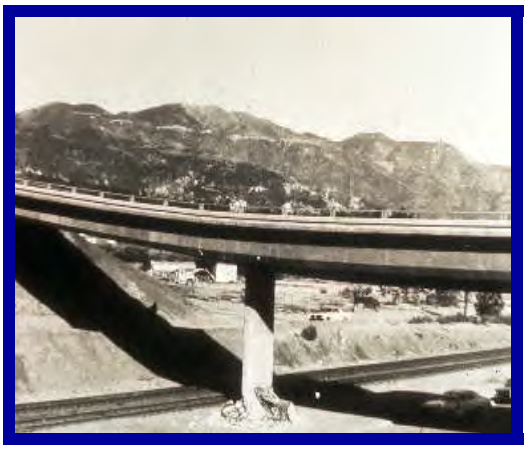
Abutment-Level V	Abutment-Level V
	

Classification according to type of Damage

Columns

Flexural Damage

Flexural Damage

Level III	Level V
	
Level V	Failure
Level II	Level III

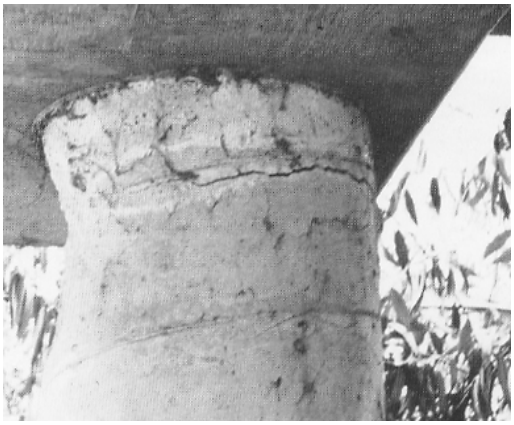
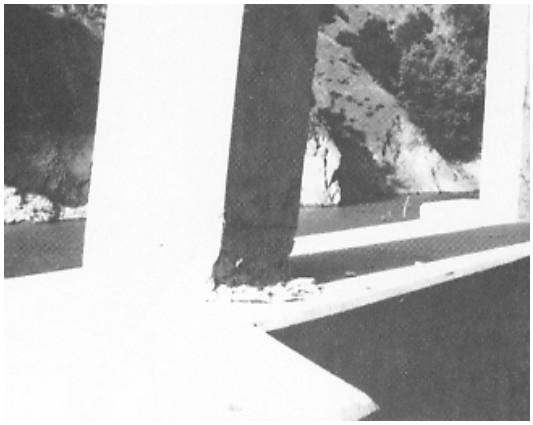
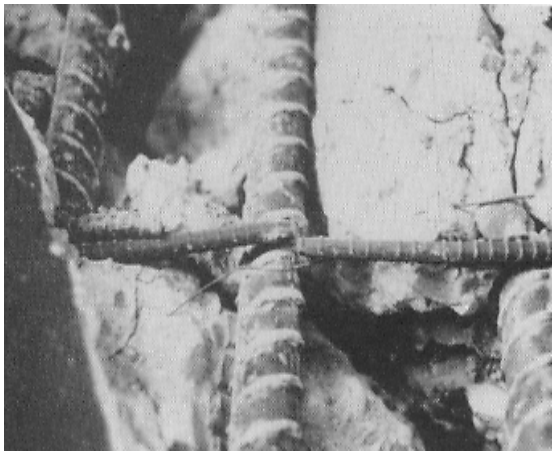
Flexural Damage

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

Flexural Damage

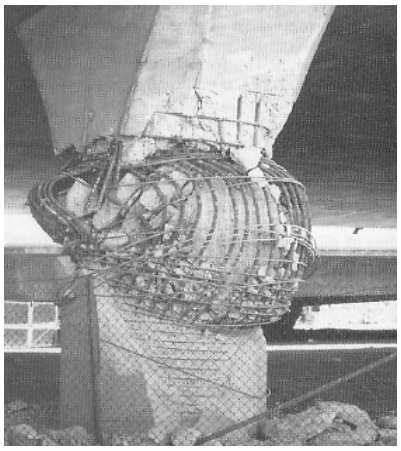
Level IV	Level III
Level IV	Level IV
Level V	Level III

Flexural Damage

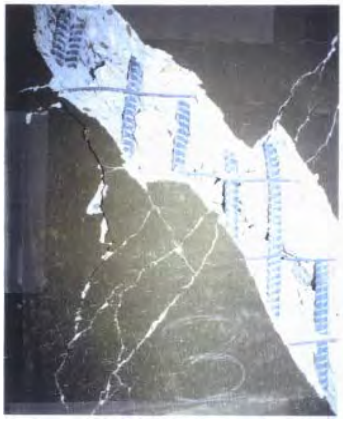
	
Level III	Level V
Failure	Level V
	
Level V Fractured steel bars	Failure

Shear Damage

Shear Damage

Failure	Failure
Failure	Failure
	
Failure	Failure

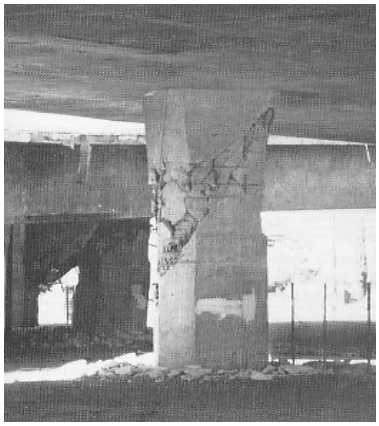
Shear Damage

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

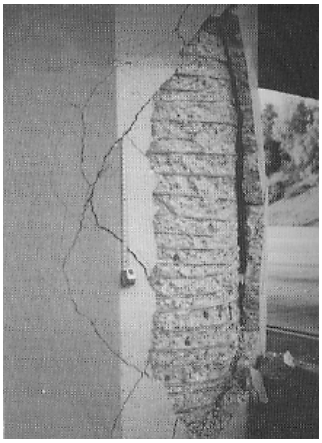
Shear Damage

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

Shear Damage

Failure	Failure
Failure	Failure
Failure	Failure

Shear Damage

Level V	Failure
Level IV	Failure
	
Level V	Level V

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

Level V	Level V
Level V	Level V
Failure	Failure

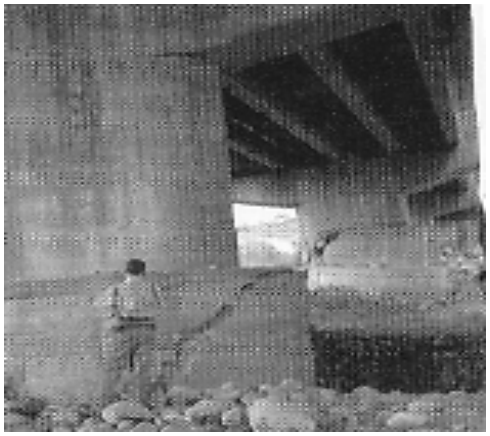
Shear Damage

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

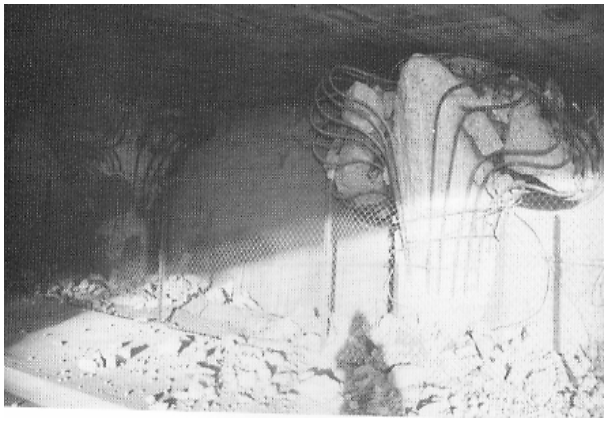
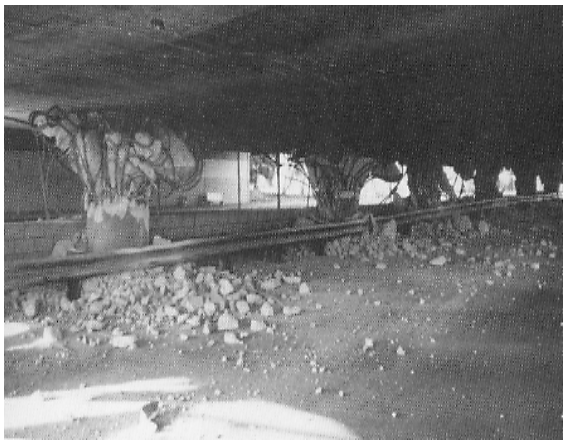
Shear Damage

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

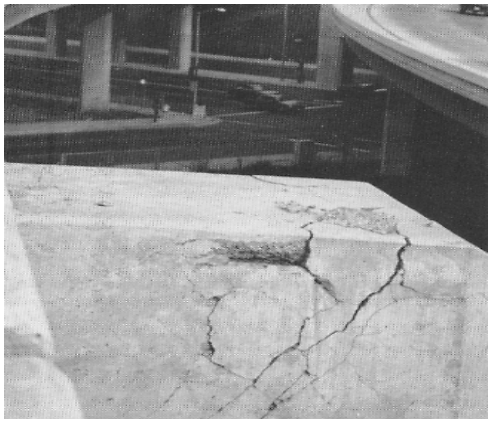
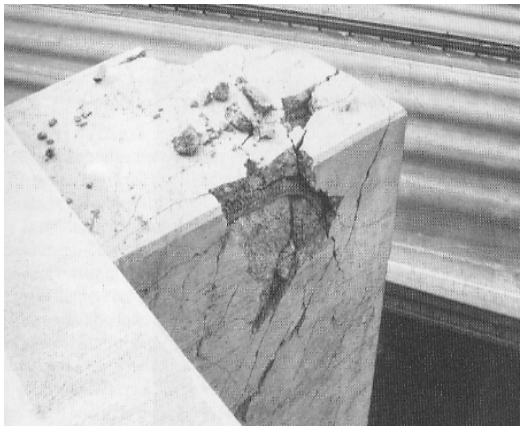
Lap splice retrofit	Lap splice retrofit
Lap splice retrofit	Lap splice retrofit

Joint Damage

Joint Damage

	Joint-Shear Crack Level V
Level IV	Level V
Level V	Level V

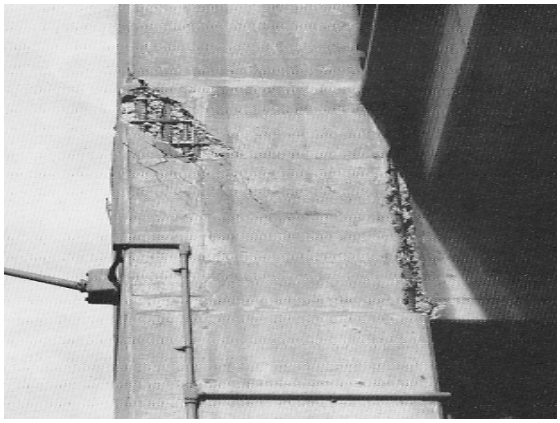
Joint Damage

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

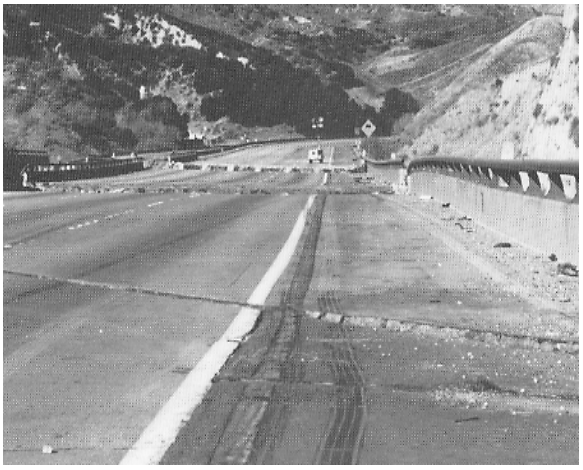
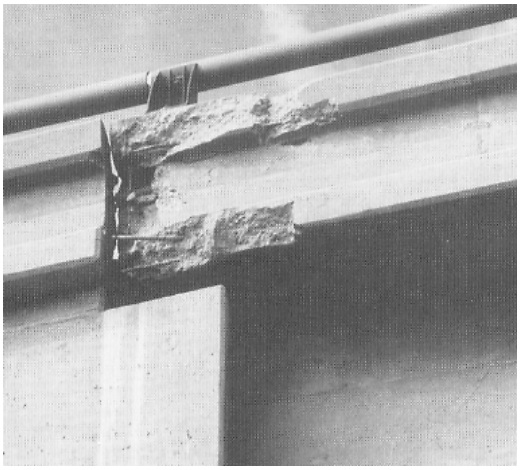
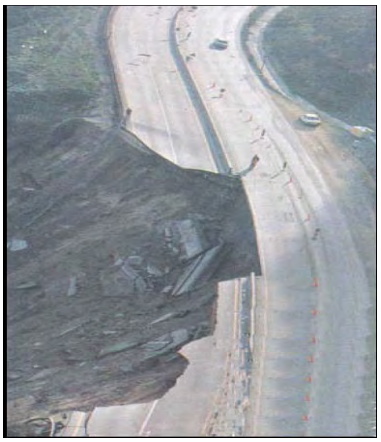
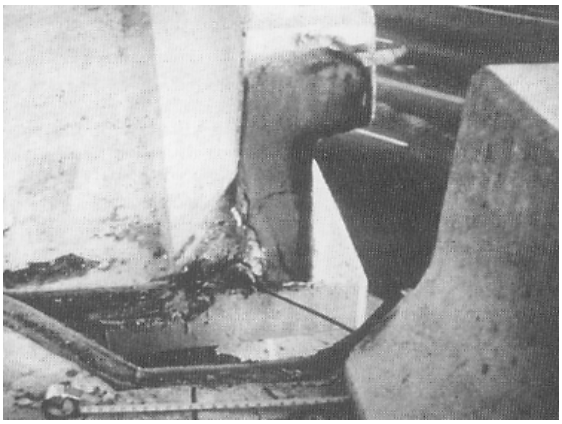
Deck Damage

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

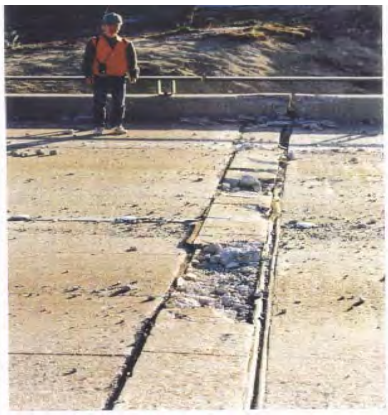
Deck Damage

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

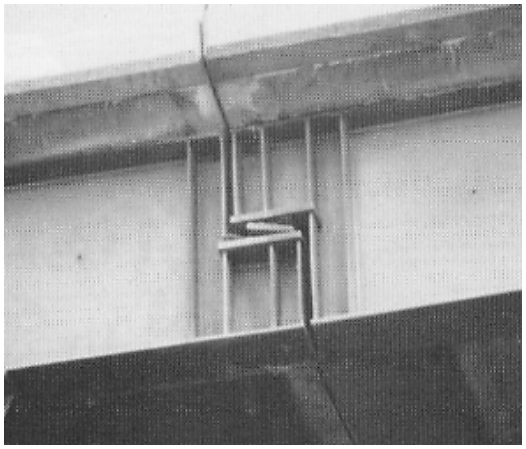
Deck Damage

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

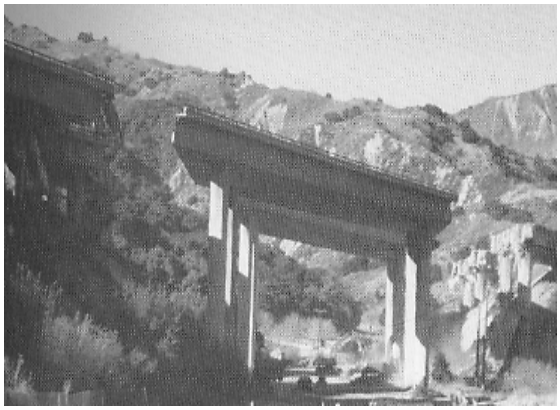
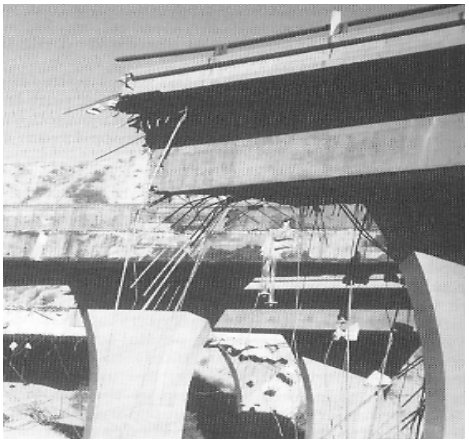
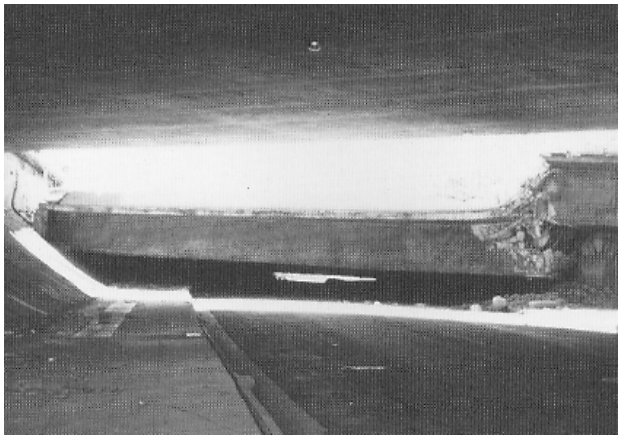
Span Collapse

Span Collapse	Span Collapse
Span Collapse	Span Collapse
Collapsed span	Span Collapse

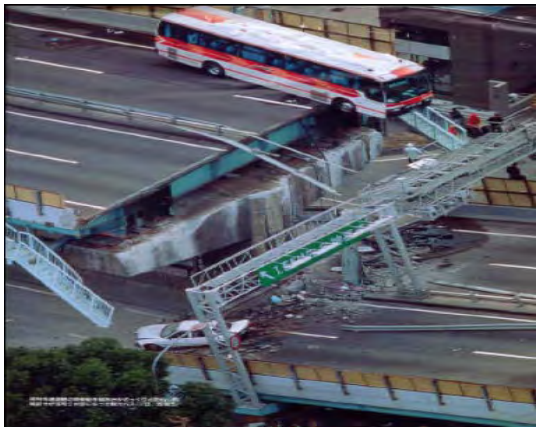
Span Collapse

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

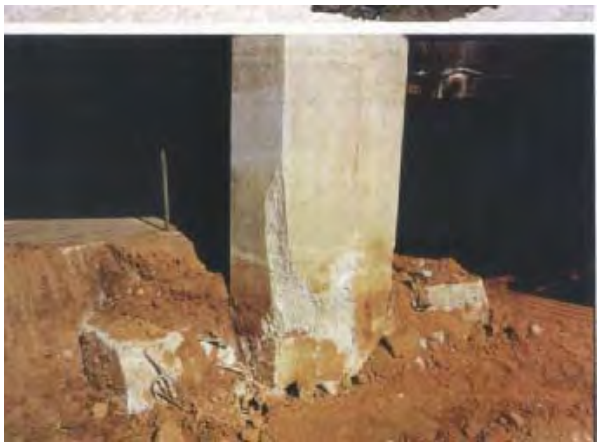
Movement Level IV	Level V Longitudinal movement
Level V- Transversal movement	Excessive movement – Level V
Level V– Longitudinal movement	

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

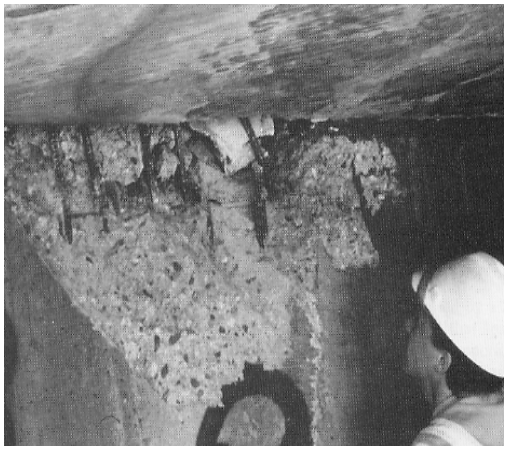
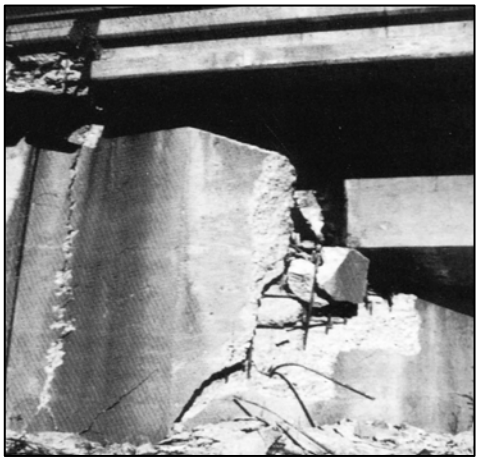


Abutments/Shear Keys

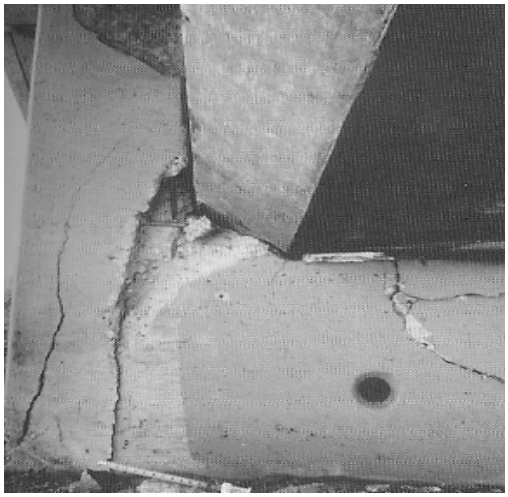
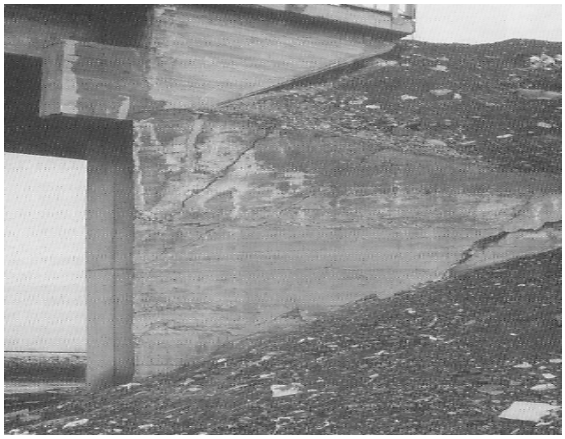
Abutments/Shear Keys

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

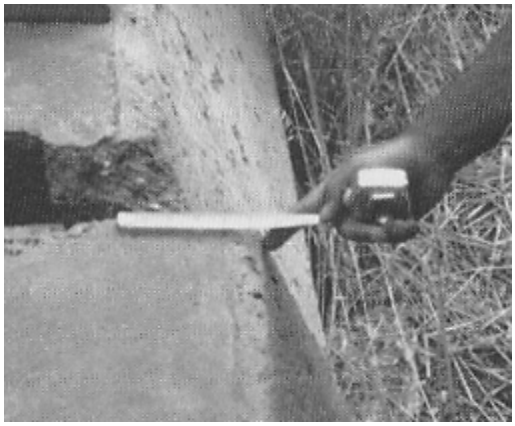
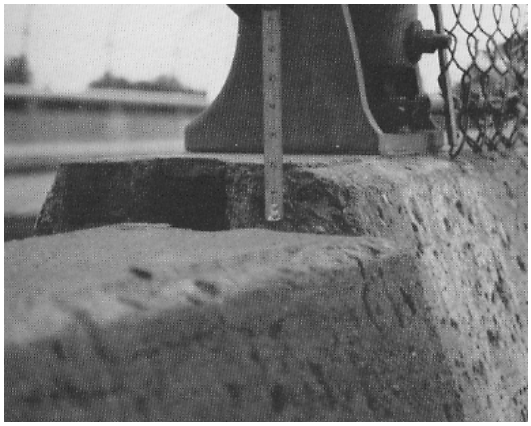
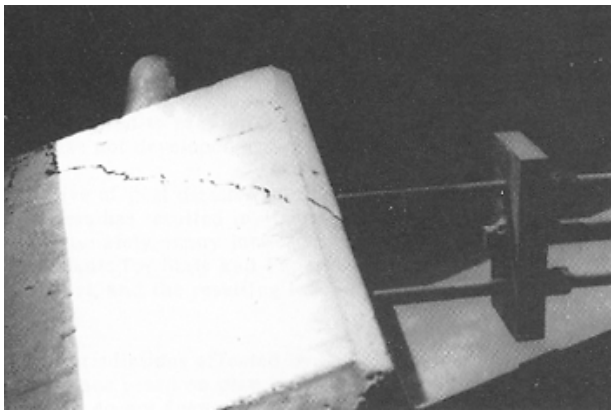
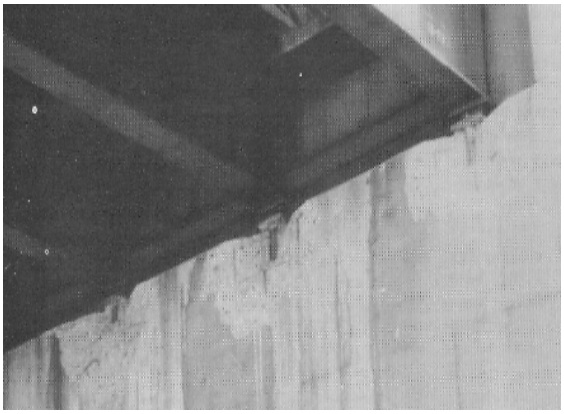
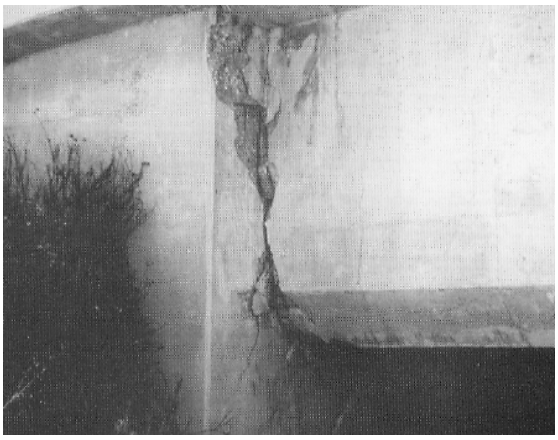
Abutments/Shear Keys

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

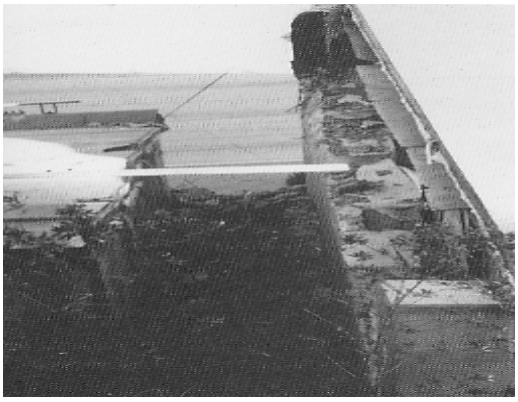
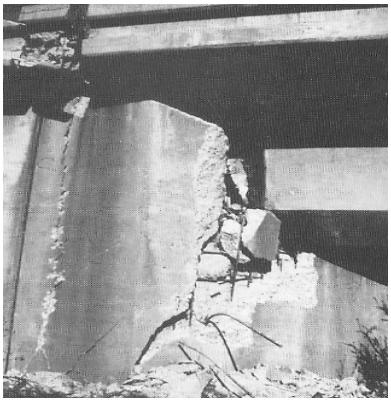
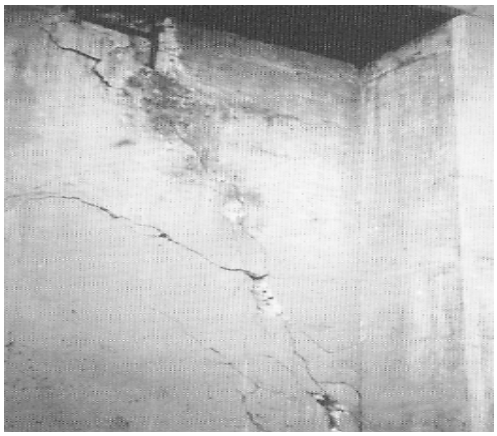
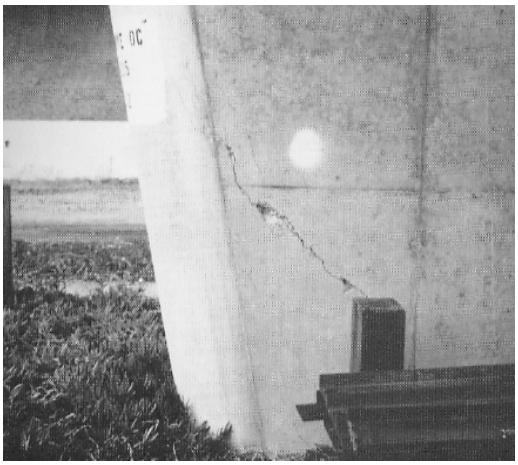
Abutments/Shear Keys

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

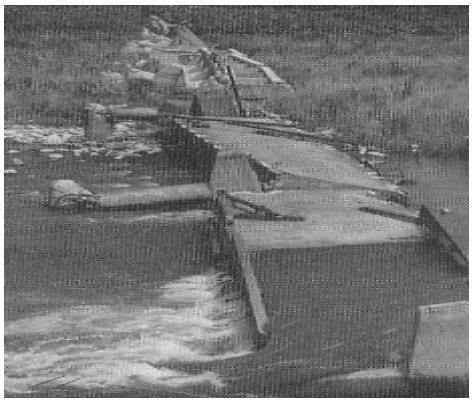
Failure of Elastomeric bearing	Failure of anchor bolts on girder
Girder movement causes bearing failure	Failure of bearing pad
	Bearing sliding

Bearing Damage

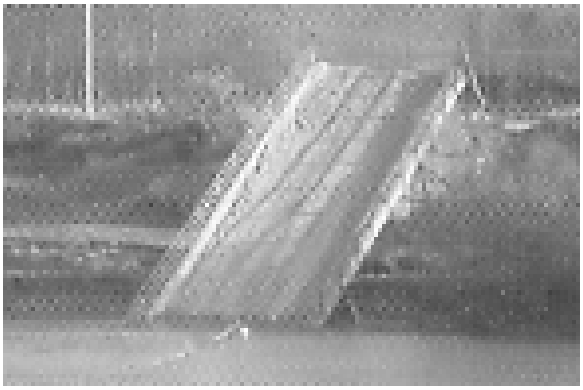
Level IV	Level IV
Level V	

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

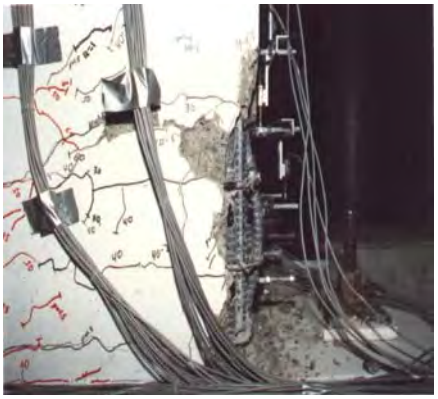
Part III

Correlation of Field photo with Laboratory database

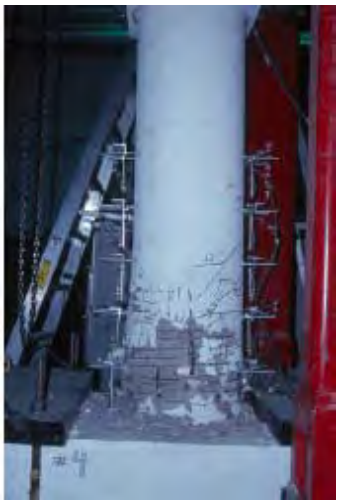
Flexural

Flexural

Flexural – Level IV



Flexural – Level IV



Flexural Level V

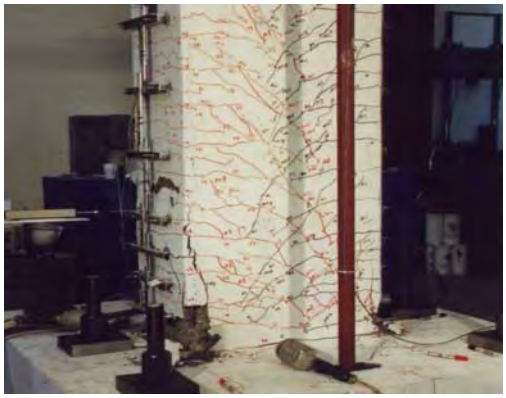
Flexural

Flexural – Level V

Flexural – Level V

Flexural – Level V

Flexural



Flexural – Level III

Flexural – Level V – rupture of long. Bars

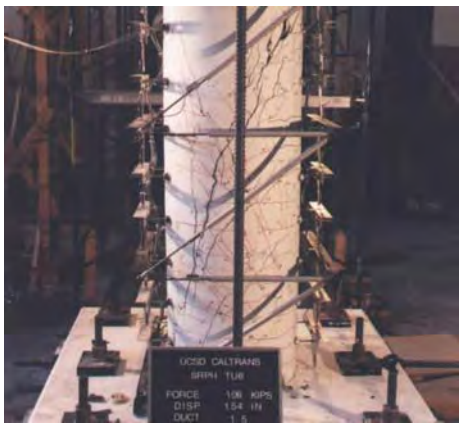
Flared Columns-Level IV

Shear

Shear

Shear – Level III

Shear - Level V



Shear - Level IV

Shear

Shear - Level V

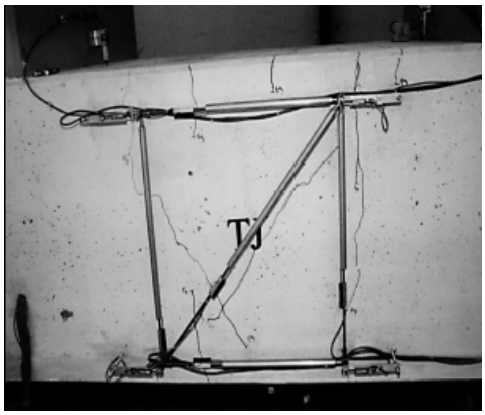
Shear - Level V

Lap splice – Base – Level IV

Joints

Joints

Knee Joint - Level IV

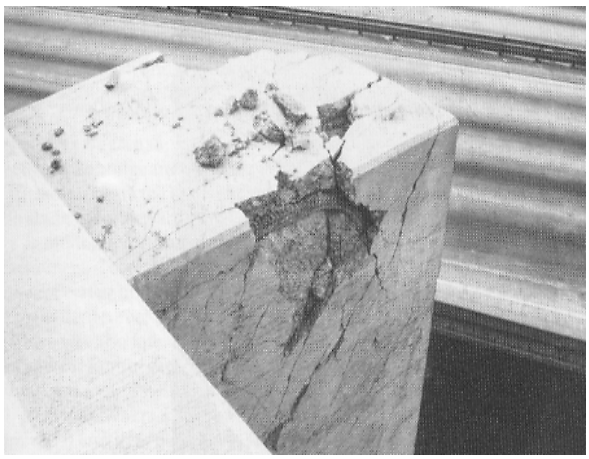


Tee Joint - Level IV

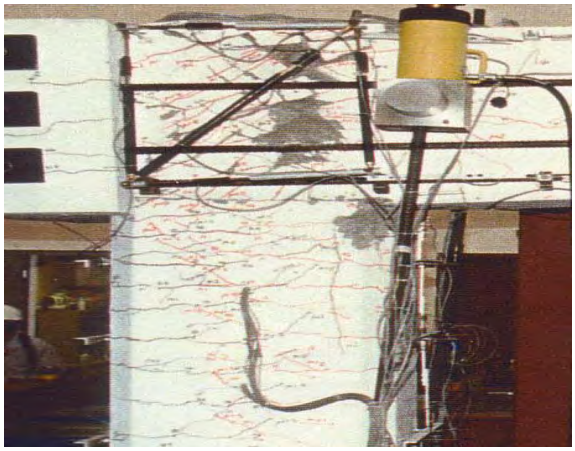
Tee joint – Level V

Joints

Level V



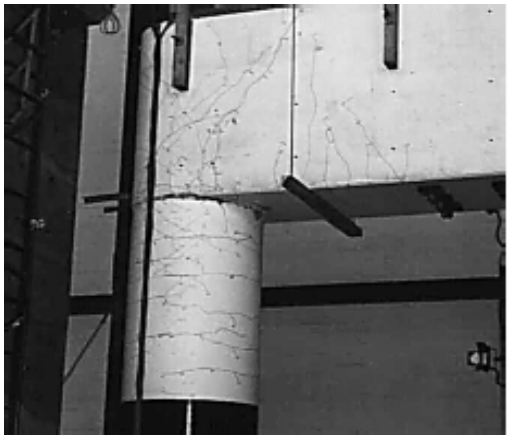
Level IV



Level V

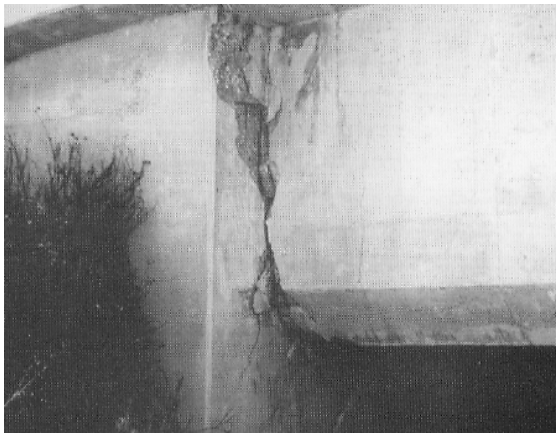
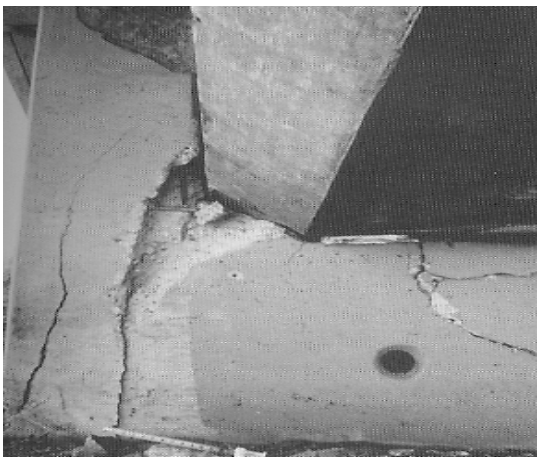
Cap Beam-Column

Cap Beam-Column

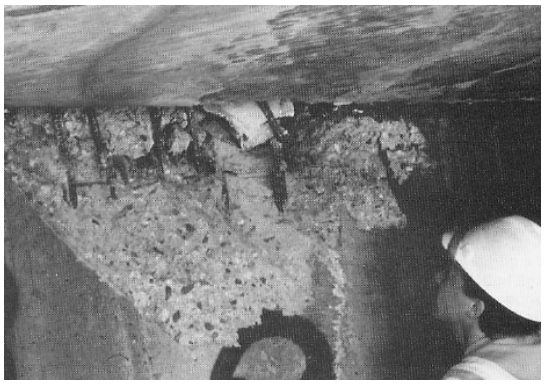
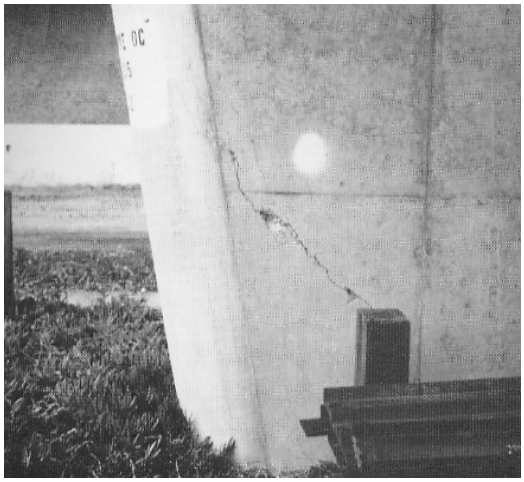
Level III	
	
Level IV	

Abutments-Shear Keys

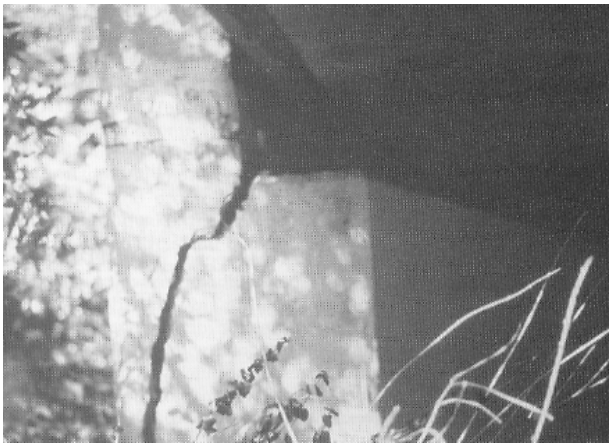
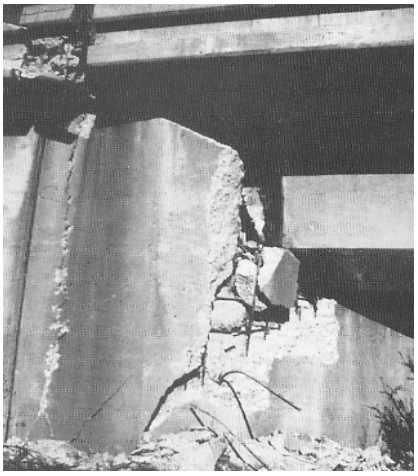
Abutments-Shear Keys

Level V	
	
Level V	
	
Level III	

Abutments-Shear Keys

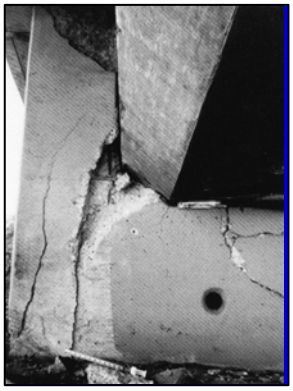
Level IV	
	
Level V	
	
Level IV	

Abutments-Shear Keys

	
Level V	
Level v	
	
Level V	

Abutments-Shear Keys

Abutment-Shear key –Level V



Superstructure

Super Structure

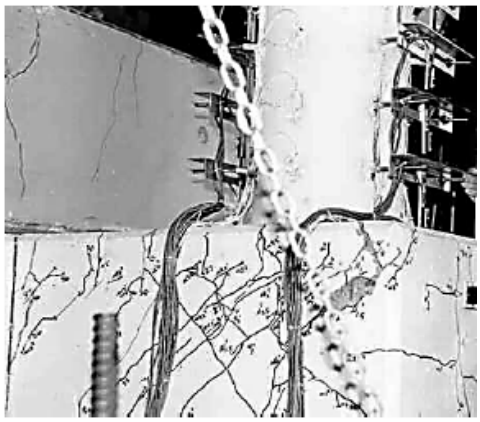
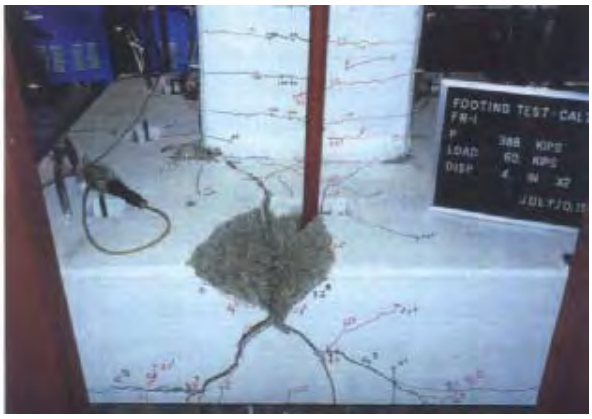
Level IV

Level IV

Level V

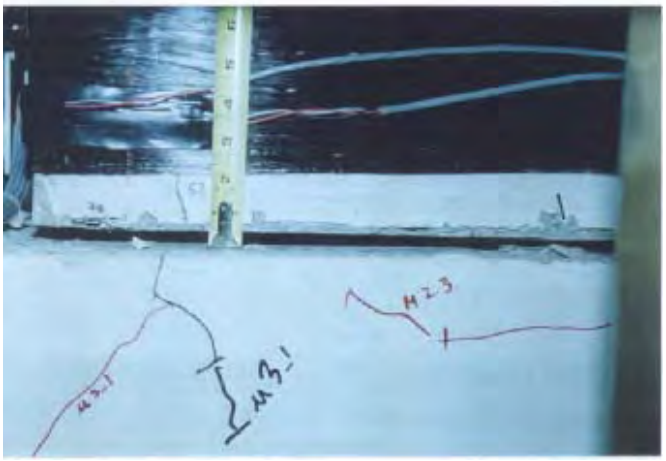
Foundation

Foundation

	
Level V	
	
Level V	

Other Cases

Other Cases



Level V –gap between pedestal column

PART IV

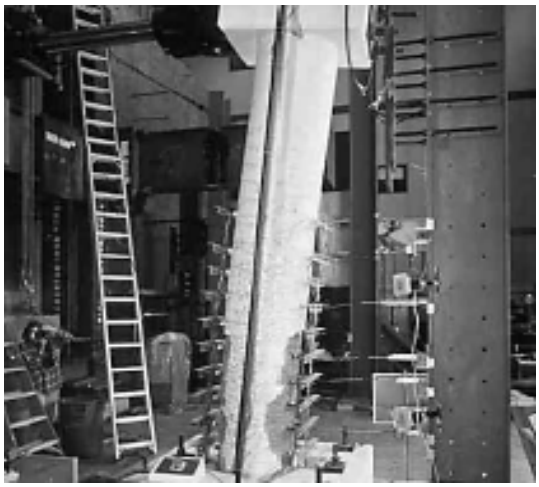
Details of Extreme Performance Levels

Flexural Level V

Buckling of longitudinal reinforcement

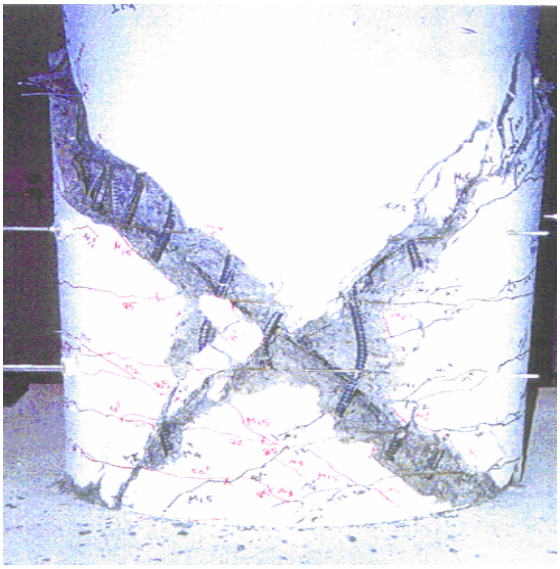
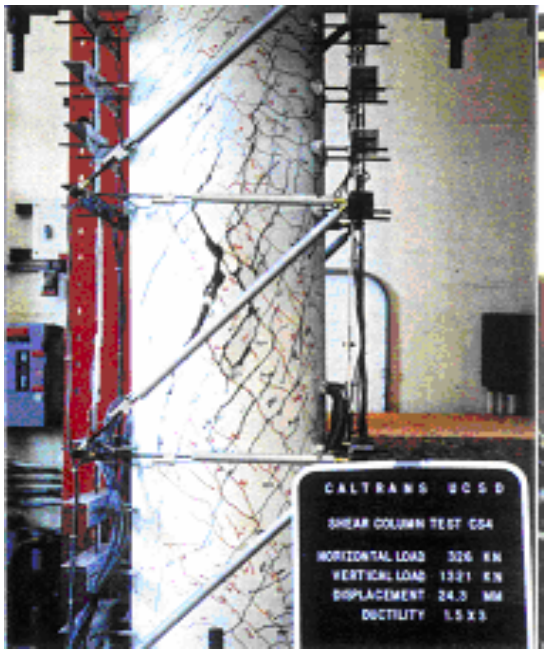
Fracture of longitudinal bars and stirrups

Fracture of longitudinal bars

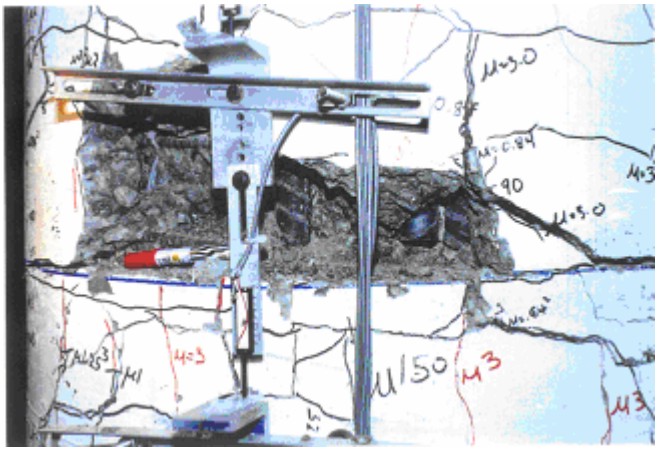


Permanent deformation

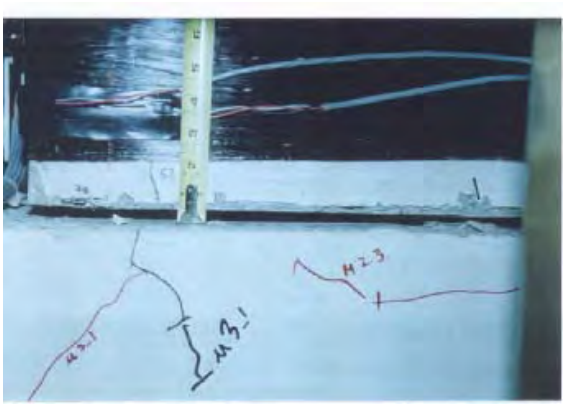
Shear Level V

	
diagonal crack (plastic hinge region-base)	Diagonal crack- midheight
	
	Diagonal crack - midheight

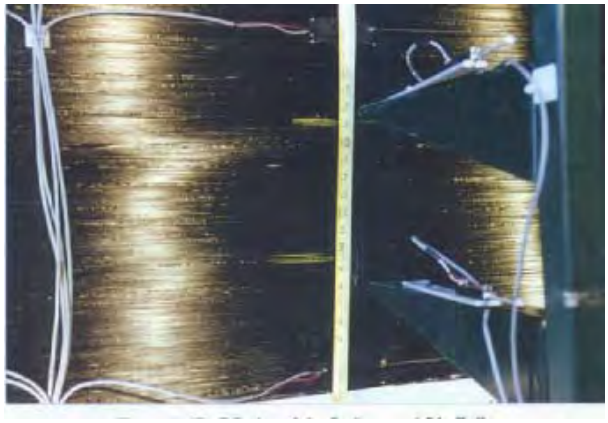
Lap Splice

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

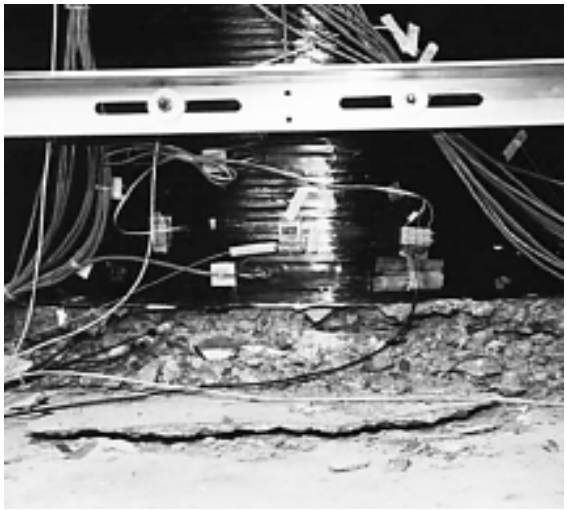
Retrofit Level IV



Gap between column pedestal



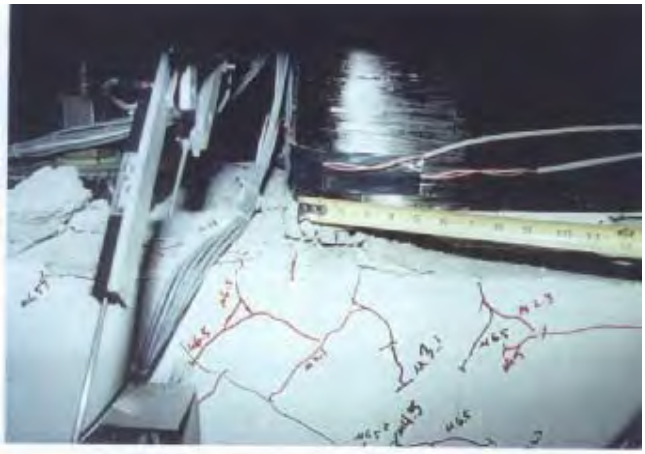
Dilation of jacket



Extensive spalling – plastic hinge region

Retrofit Level V

Buckling of long bars

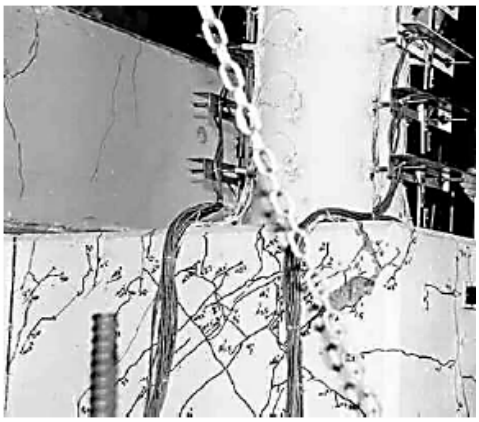
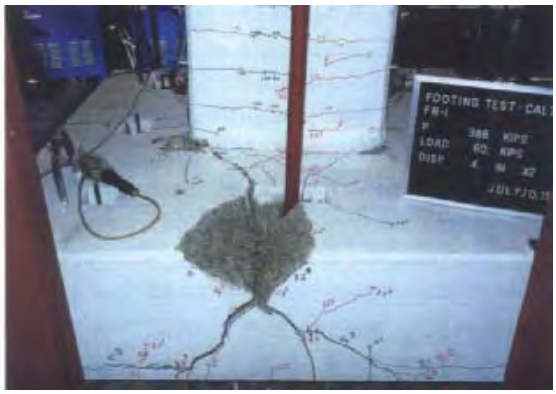


Sliding of column | Permanent deformation

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

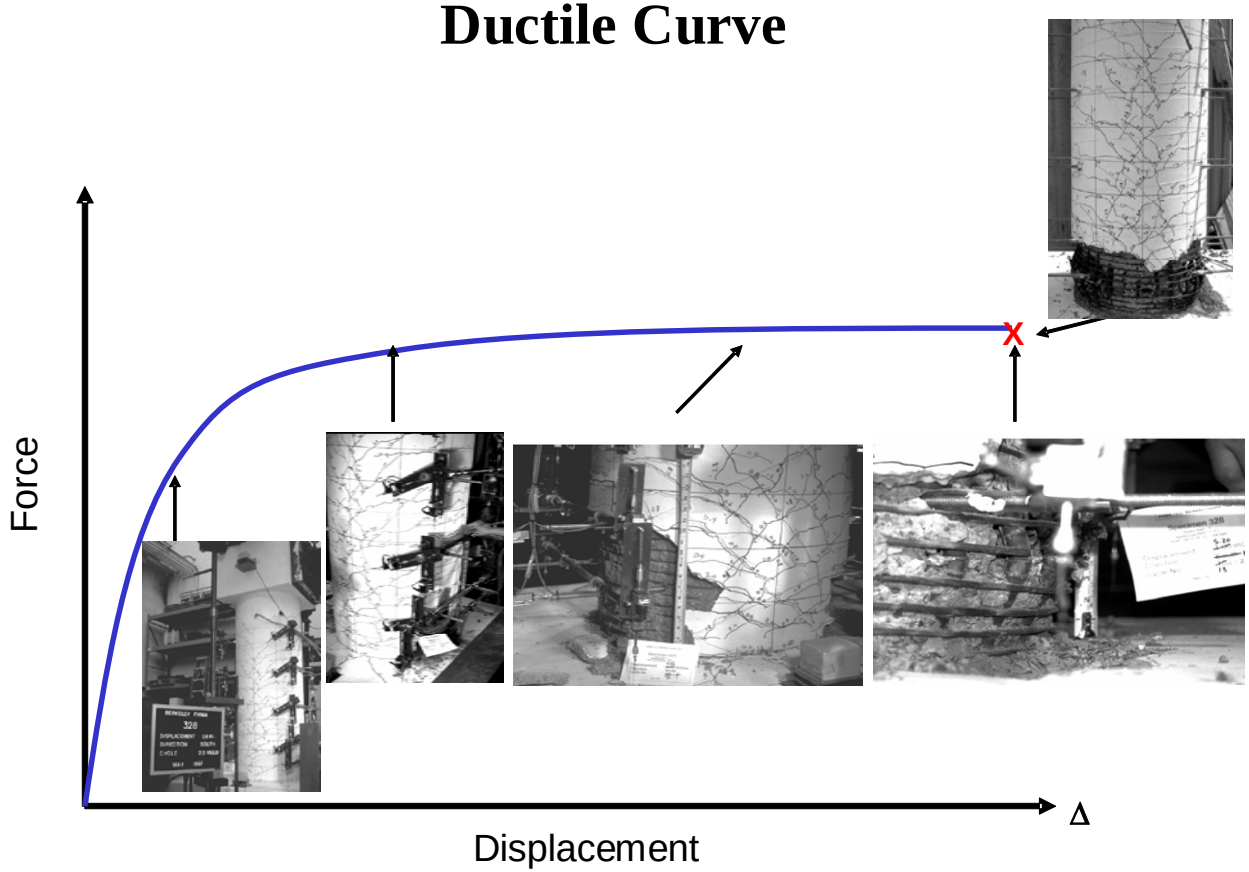
Diagonal Shear crack

Part V

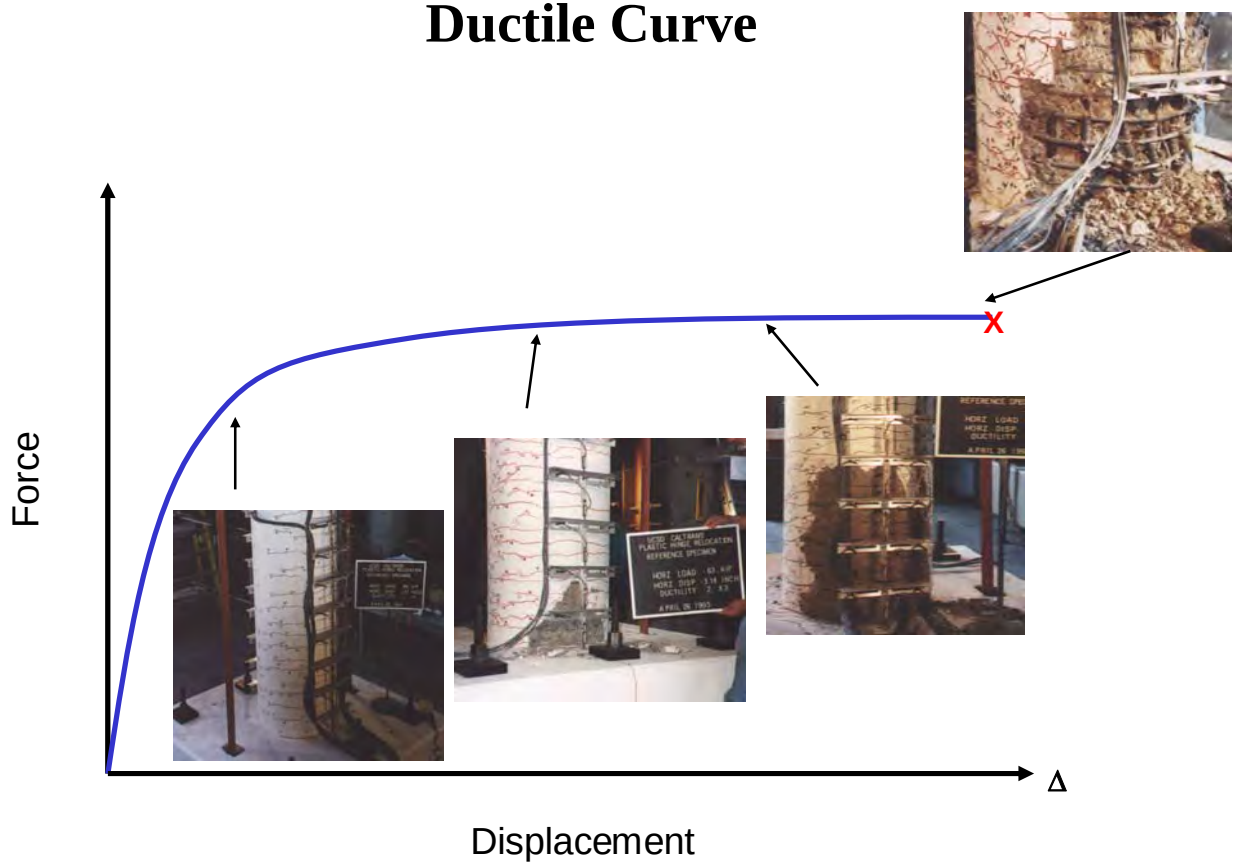
Correlation of lab photos with Performance Curves

Column Performance Curves

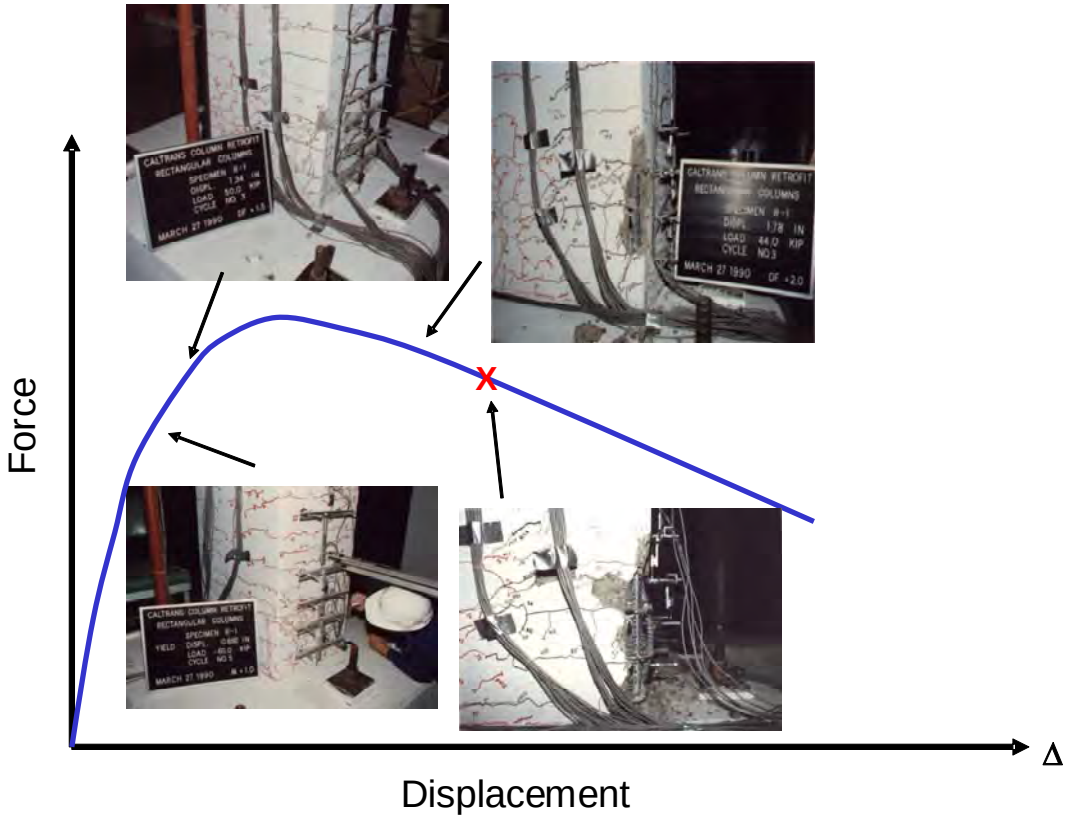
Ductile Curve



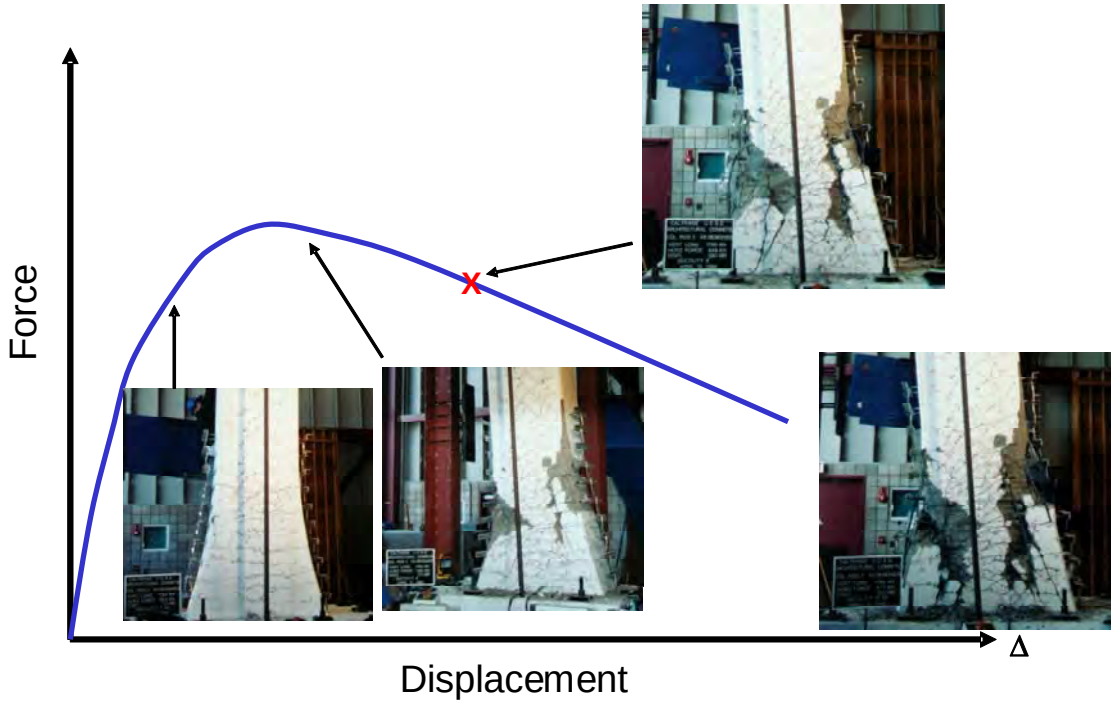
Ductile Curve



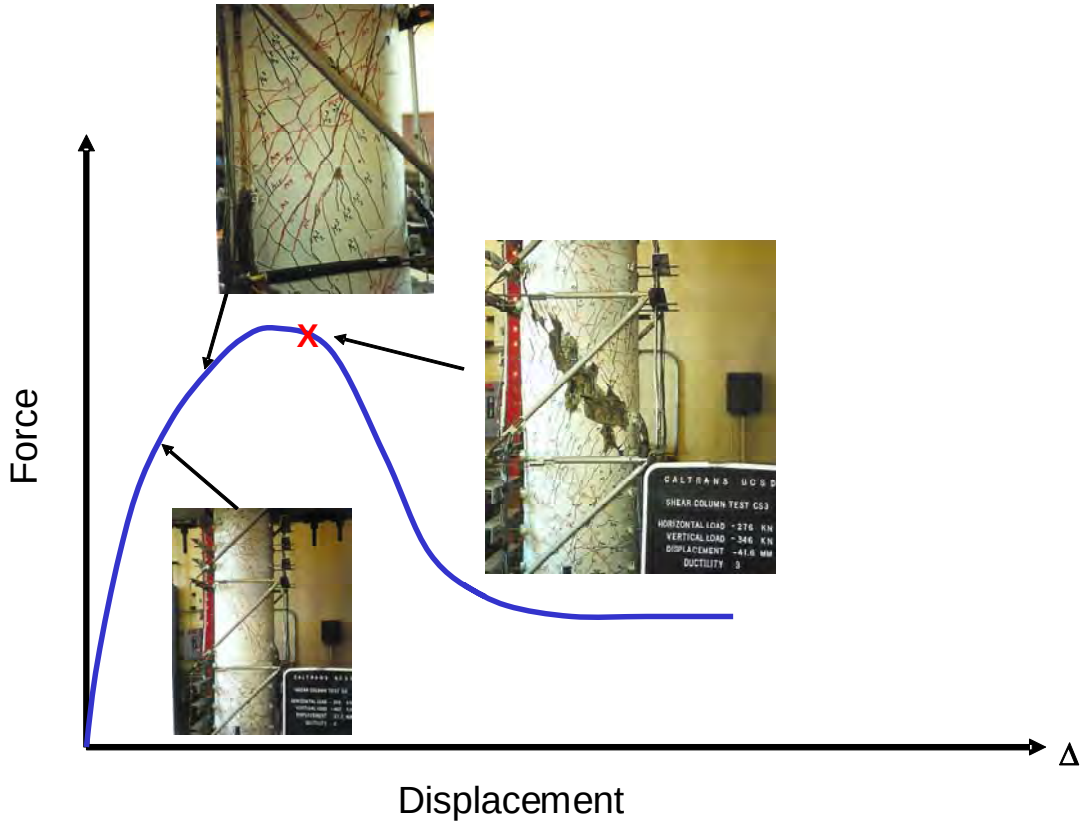
Strength Degrading Curve



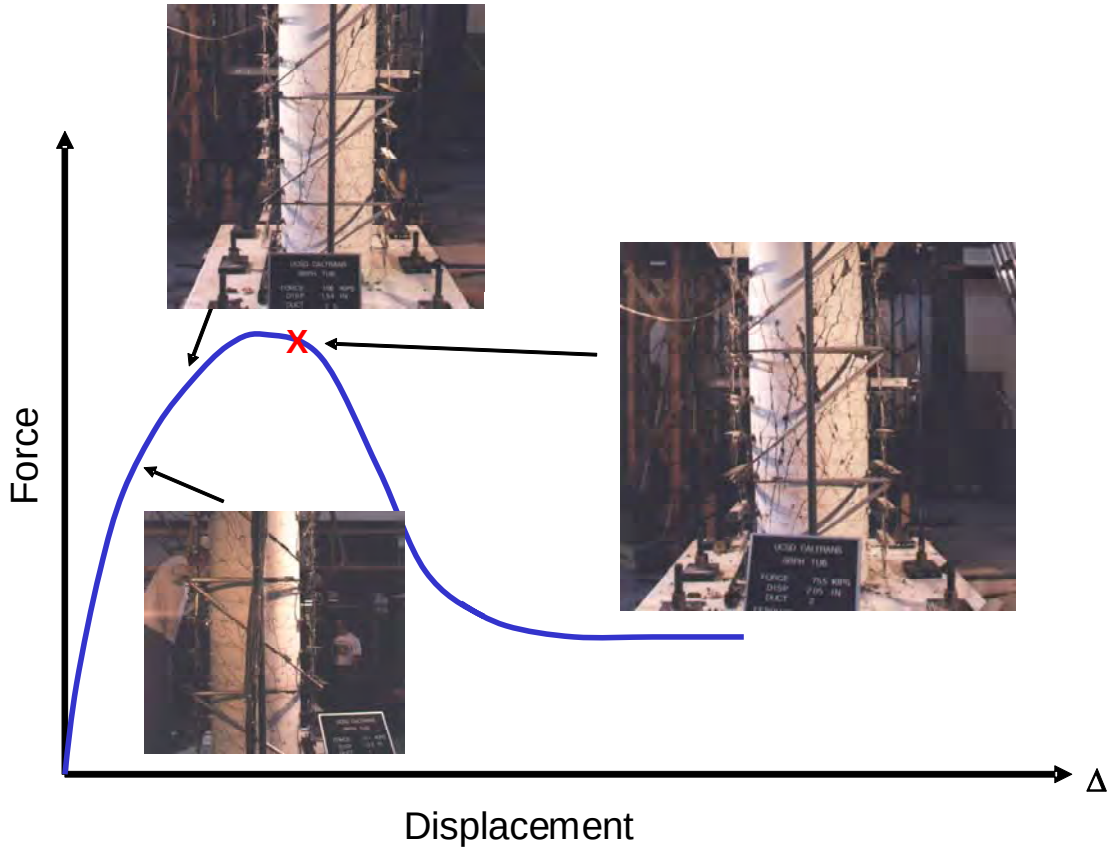
Strength Degrading Curve



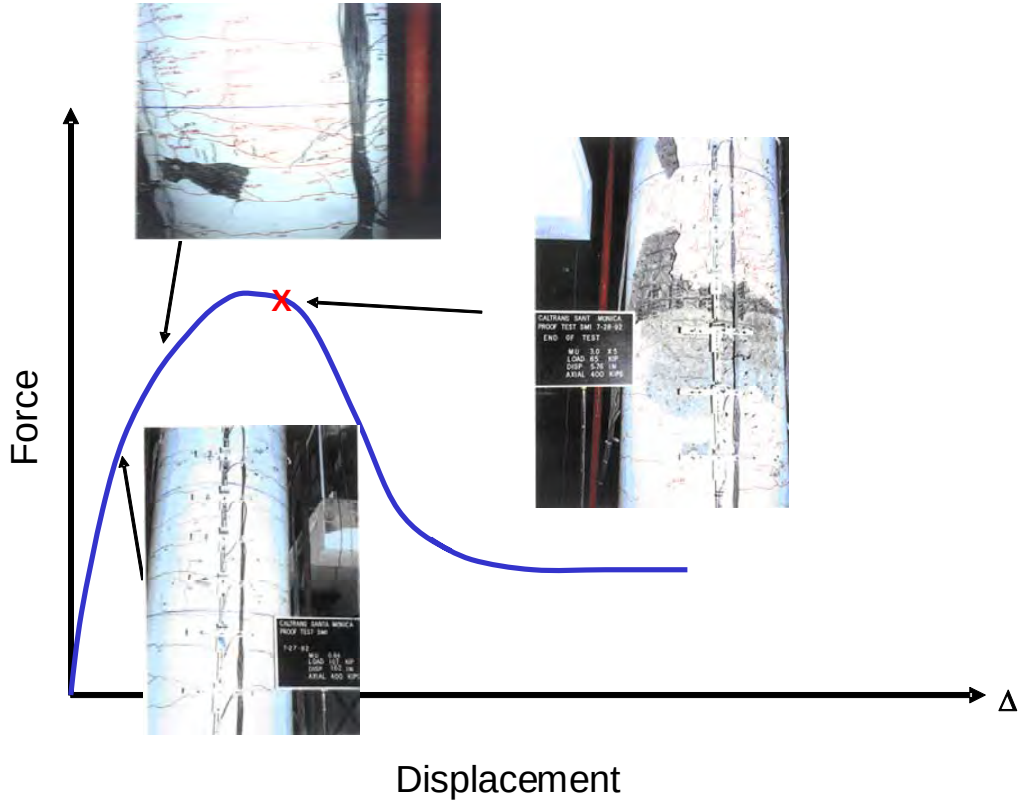
Brittle Curve



Brittle Curve

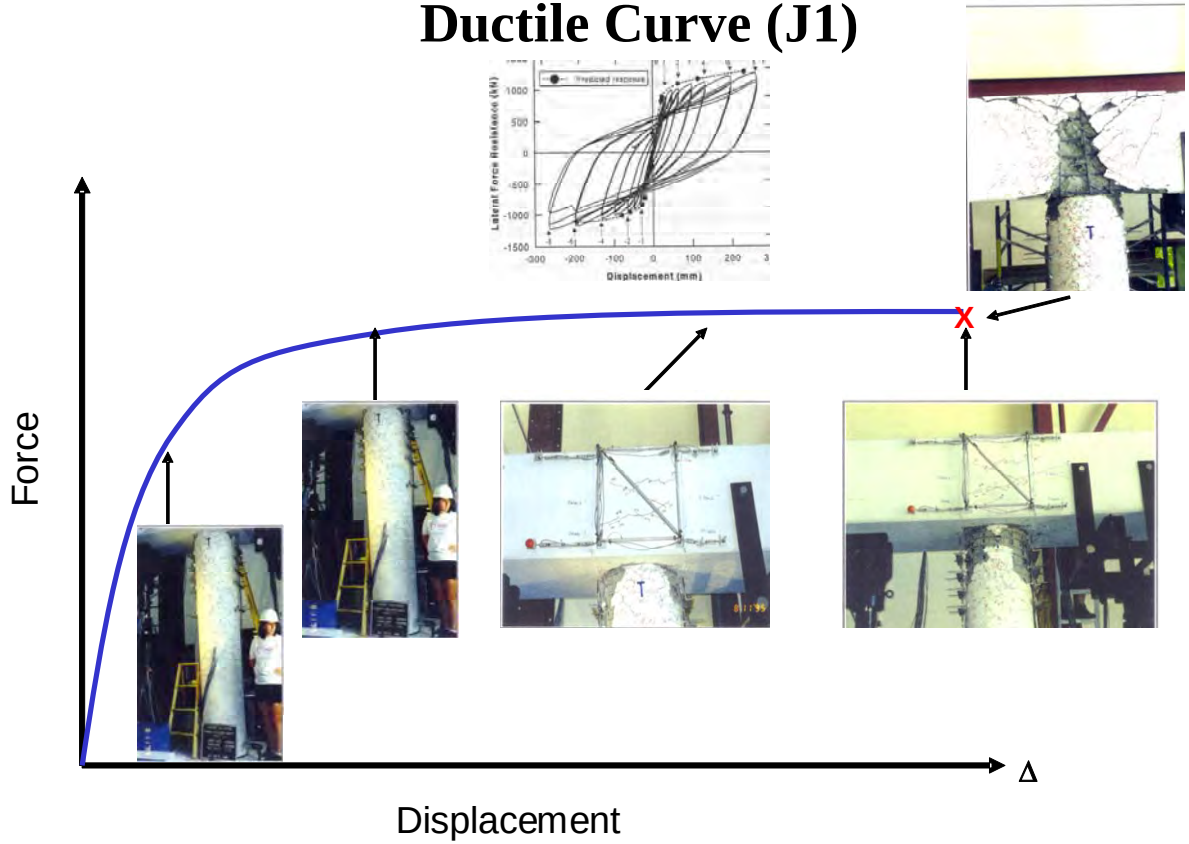


Brittle Curve

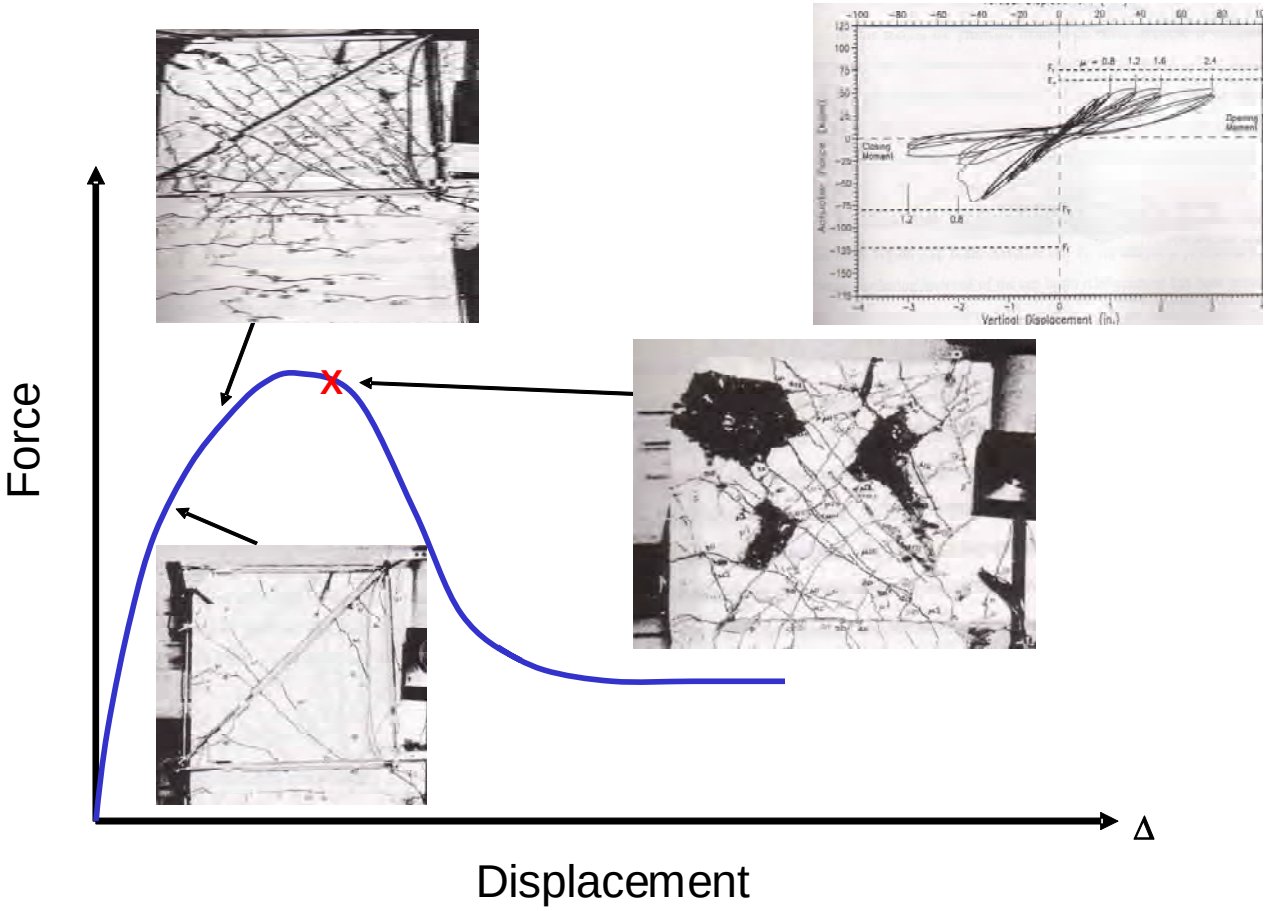


Joint Performance Curves

Ductile Curve (J1)

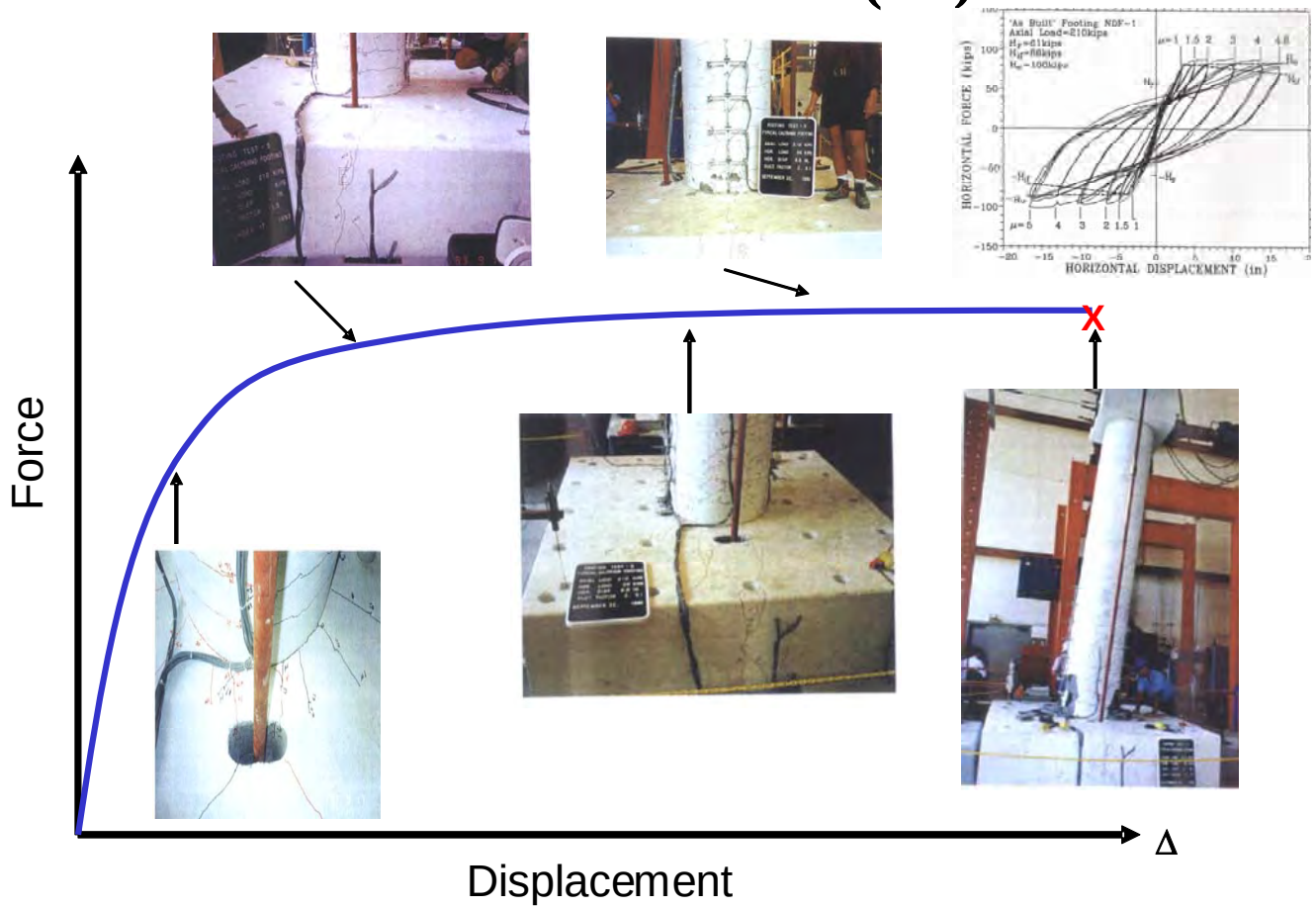


Brittle Curve (J2)

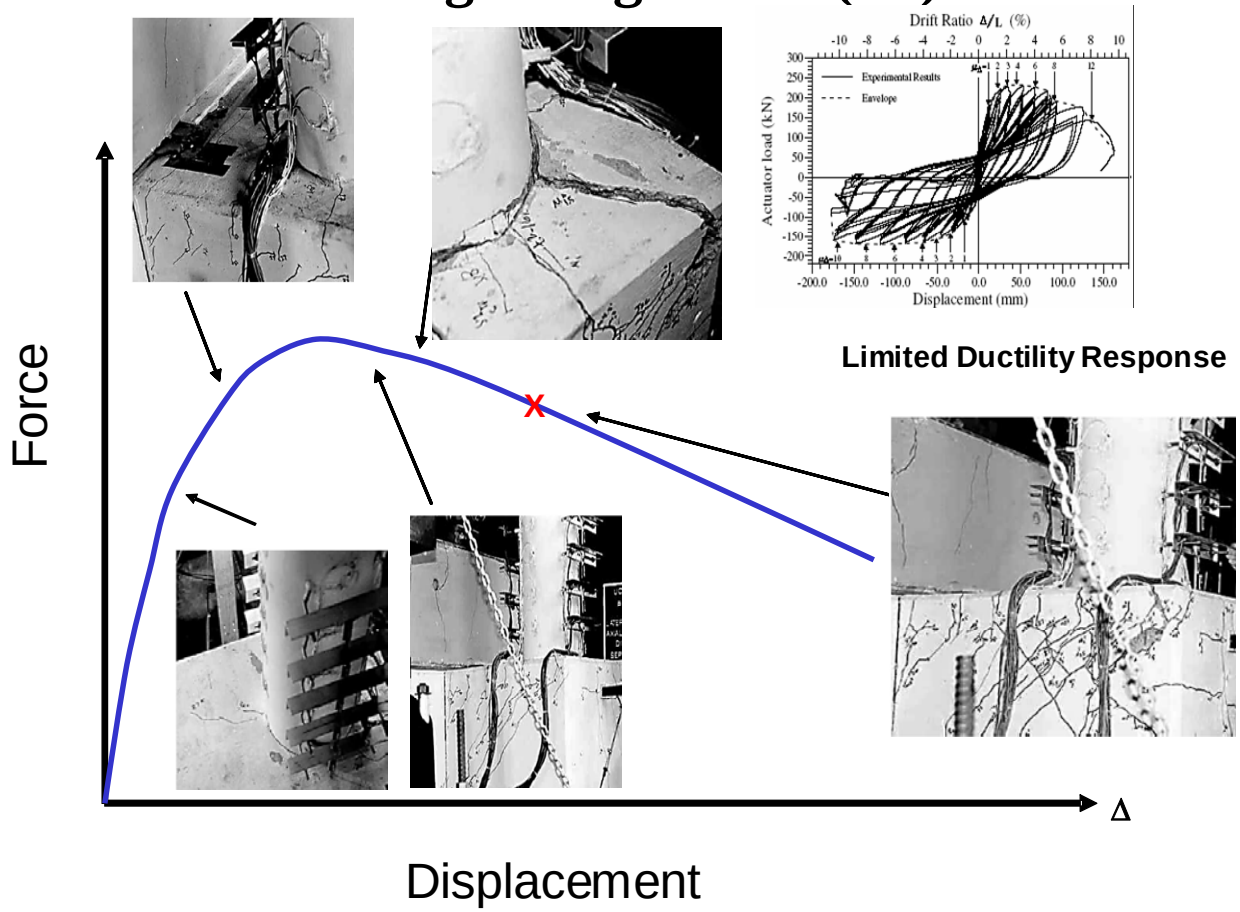


Foundation Performance Curves

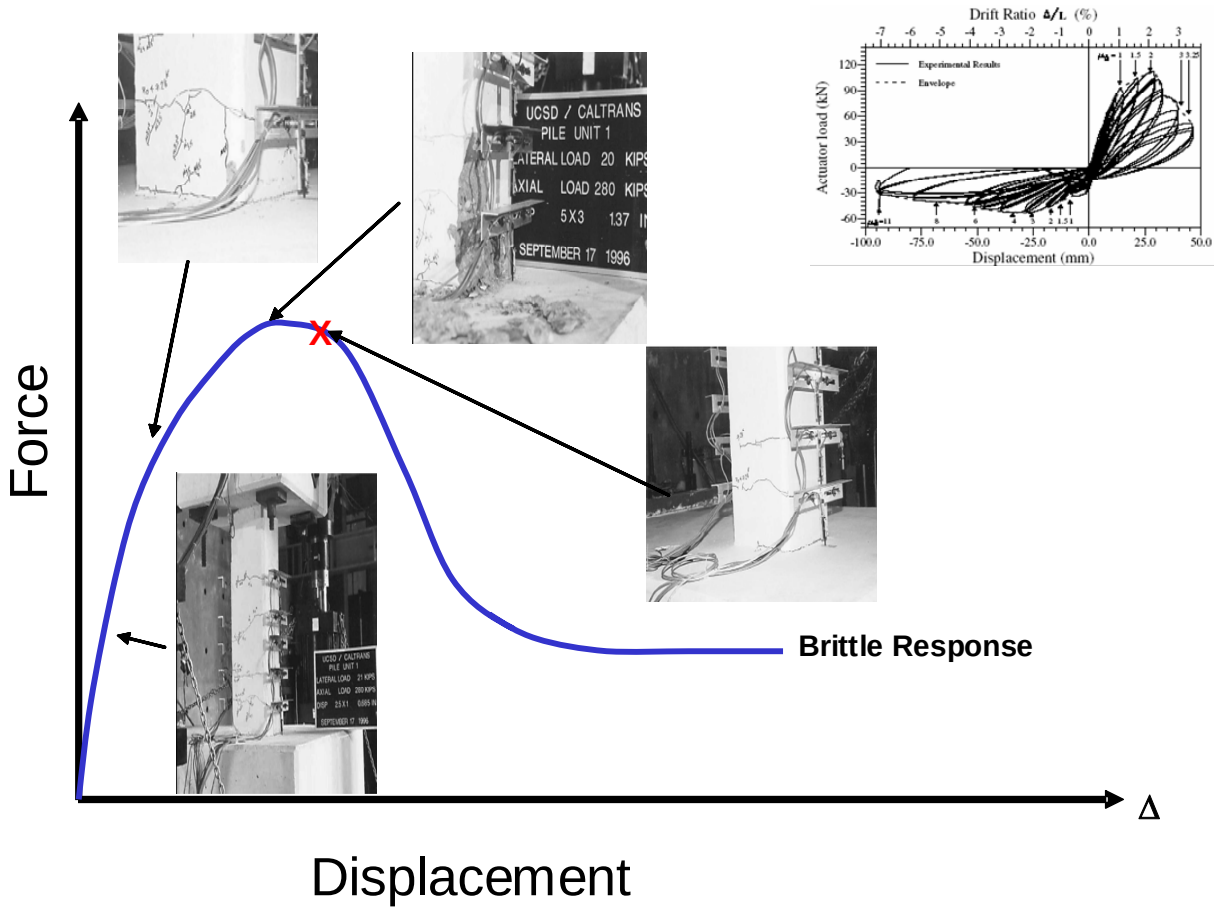
Ductile Curve (F4)



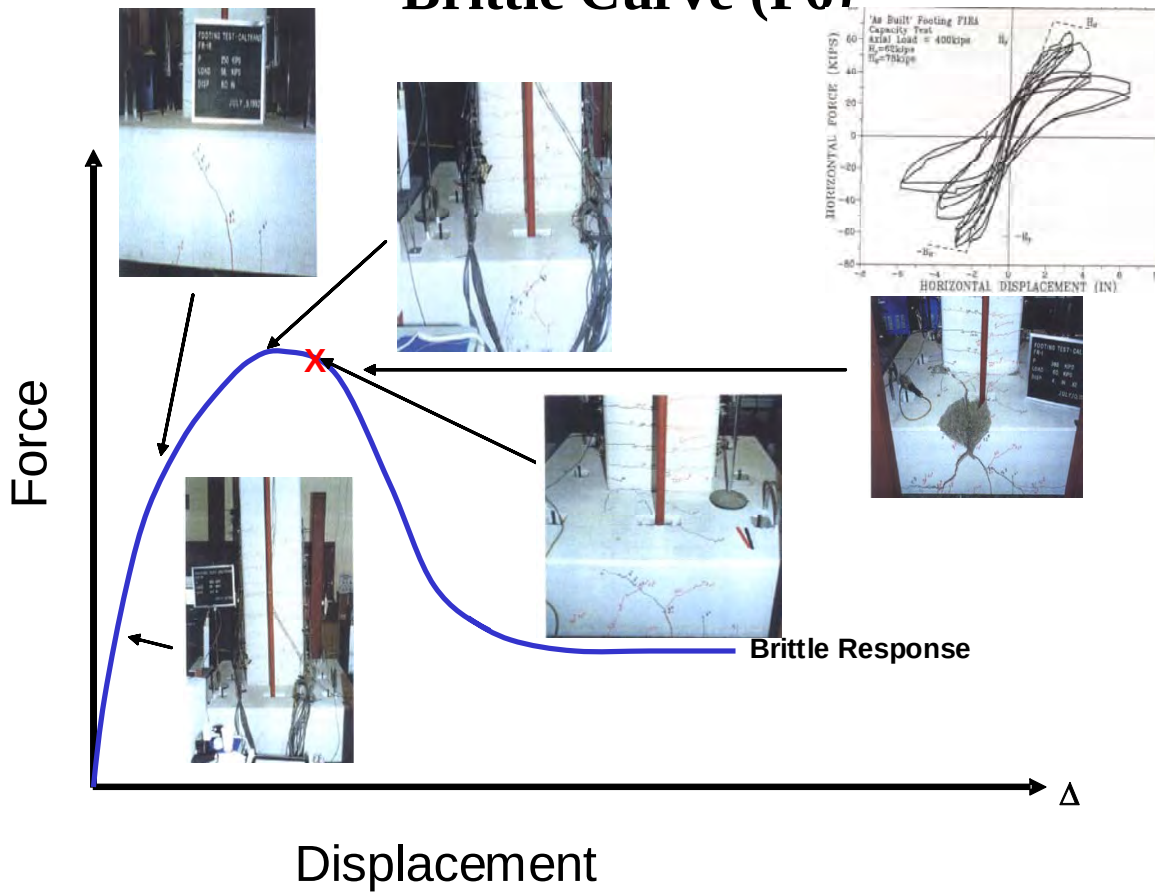
Degrading Curve (F3)



Brittle Curve (F1)

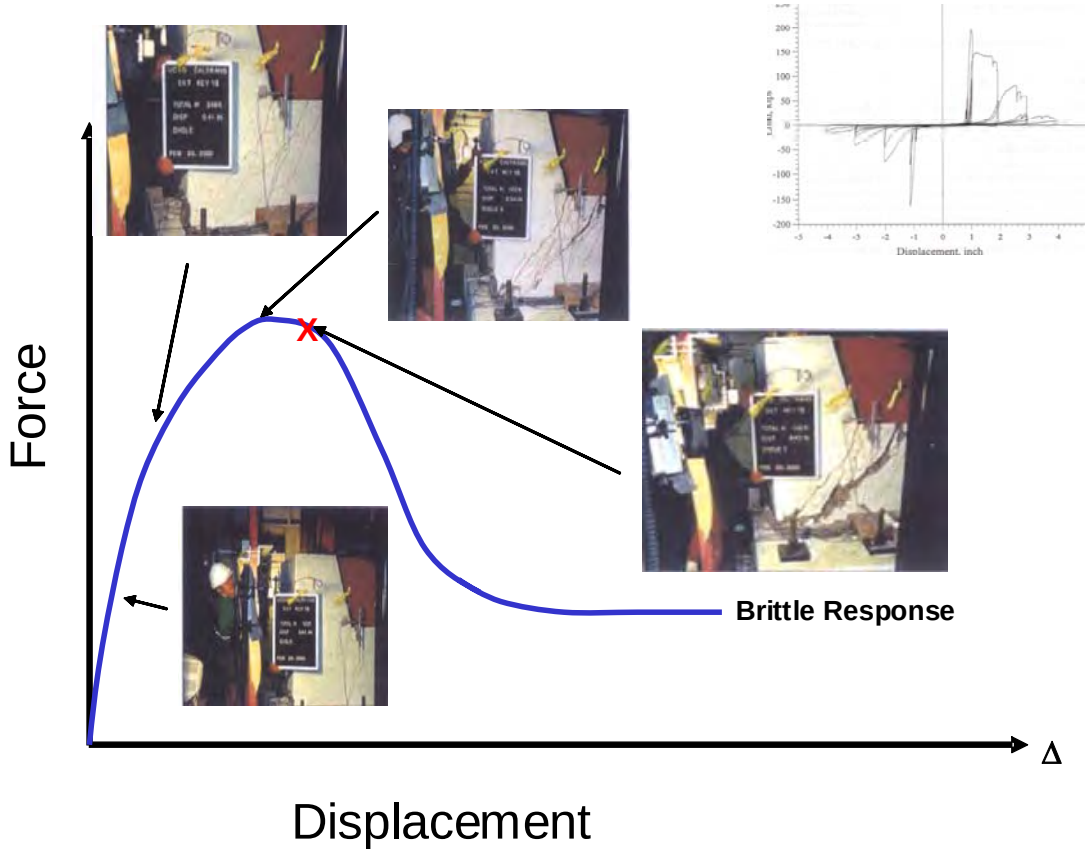


Brittle Curve (F6)



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
F7	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.	F3RR
SK1	Megally, S. H., Silva, P.F., Seible, F., Seismic Response of Sacrificial Shear Keys in Bridge Abutments, Structural Systems Research Project SSRP – 2001/23, University of California, San Diego, La Jolla, CA, May 2002.	1A
SK2	Megally, S. H., Silva, P.F., Seible, F., Seismic Response of Sacrificial Shear Keys in Bridge Abutments, Structural Systems Research Project SSRP – 2001/23, University of California, San Diego, La Jolla, CA, May 2002.	2C
SK3	Megally, S. H., Silva, P.F., Seible, F., Seismic Response of Sacrificial Shear Keys in Bridge Abutments, Structural Systems Research Project SSRP – 2001/23, University of California, San Diego, La Jolla, CA, May 2002.	2D
SK4	Megally, S. H., Silva, P.F., Seible, F., Seismic Response of Sacrificial Shear Keys in Bridge Abutments, Structural Systems Research Project SSRP – 2001/23, University of California, San Diego, La Jolla, CA, May 2002.	1A
SK5	Megally, S. H., Silva, P.F., Seible, F., Seismic Response of Sacrificial Shear Keys in Bridge Abutments, Structural Systems Research Project SSRP – 2001/23, University of California, San Diego, La Jolla, CA, May 2002.	1B
SK6	Megally, S. H., Silva, P.F., Seible, F., Seismic Response of Sacrificial Shear Keys in Bridge Abutments, Structural Systems Research Project SSRP – 2001/23, University of California, San Diego, La Jolla, CA, May 2002.	2B
SK7	Megally, S. H., Silva, P.F., Seible, F., Seismic Response of Sacrificial Shear Keys in Bridge Abutments, Structural Systems Research Project SSRP – 2001/23, University of California, San Diego, La Jolla, CA, May 2002.	3A

R1	Chai, Y., Priestley, M.J.N., Seible, F., Flexural Retrofit of Circular Reinf. Concrete Bridge Columns by Steel Jacketing-Experimental Studies, Structural Systems Research Project SSRP – 91/06, University of California, San Diego, La Jolla, CA, October 1991.	
R2	Silva, P.F., Sritharan, S., Seible, F., Priestley, M.J.N., Full-Scale Test of the Alaska Cast-In-Place Steel Shell Three Column Bridge Bent, Structural Systems Research Project SSRP – 98/13, University of California, San Diego, La Jolla, CA, February 1999.	
R3	Innamorato, D, Seible, F., Hegemier, G., Priestley, M.J.N., Ho, F., Full Scale Test of a Two Column Bridge Bent with Carbon Fiber Jacket Retrofit, Advanced Composite Technology Transfer ACTT-96/10, University of California, San Diego, La Jolla, CA, August 1996.	SMV-I
R4	Innamorato, D, Seible, F., Hegemier, G., Priestley, M.J.N., Ho, F., Full Scale Test of a Two Column Bridge Bent with Carbon Fiber Jacket Retrofit, Advanced Composite Technology Transfer ACTT-96/10, University of California, San Diego, La Jolla, CA, August 1996.	SMV-II
R5	Seible, F., Priestley, M.J.N., Sun, Z.L., San Francisco Flexural Retrofit Validation Tests on Rectangular Columns, Structural Systems Research Project SSRP – 90/07, University of California, San Diego, La Jolla, CA, December 1990.	
R6	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.	R-4
R7	Shmoldas, A., Shleifer, G., Seible, F., Innamorato, D., Carbon Fiber Retrofit of the Arroyo Seco Spandrel Column, Structural Systems Research Project SSRP – 97/13, University of California, San Diego, La Jolla, CA, October 1997.	
R8	Dowell, R., Burgueño, R., Seible, F., Priestley, M.J.N., Mari, A., The Terminal Separation Replacement Structure Prooftest and Retrofit Test, Structural Systems Research Project SSRP – 94/15, University of California, San Diego, La Jolla, CA, October 1994.	Proof Test
R9	Dowell, R., Burgueño, R., Seible, F., Priestley, M.J.N., Mari, A., The Terminal Separation Replacement Structure Prooftest and Retrofit Test, Structural Systems Research Project SSRP – 94/15, University of California, San Diego, La Jolla, CA, October 1994.	
R10	Hewes, J., Priestley, M.J.N., Seismic Design and Performance of Precast Concrete Segmental Bridge Columns, Structural Systems Research Project SSRP – 2001/25, University of California, San Diego, La Jolla, CA, June 2002.	JH1-T1

R11	Hewes, J., Priestley, M.J.N., Seismic Design and Performance of Precast Concrete Segmental Bridge Columns, Structural Systems Research Project SSRP – 2001/25, University of California, San Diego, La Jolla, CA, June 2002.	JH2-T1
SM1	Seible, F., Priestley, M.J.N., Latham, C., Silva, P., Full-Scale Bridge Column/Superstructure Connection Tests under Simulated Longitudinal Seismic Loads, Structural Systems Research Project SSRP – 94/14, University of California, San Diego, La Jolla, CA, June 1994.	
SM2	Sritharan, S., Priestley, M.J.N., Seible, F., Seismic Response of Column/Cap Beam Tee Connections w/Cap Beam Prestressing, Structural Systems Research Project SSRP – 96/09, University of California, San Diego, La Jolla, CA, December 1996.	IC1
SM3	Sritharan, S., Priestley, M.J.N., Seible, F., Seismic Response of Column/Cap Beam Tee Connections w/Cap Beam Prestressing, Structural Systems Research Project SSRP – 96/09, University of California, San Diego, La Jolla, CA, December 1996.	IC2
SM4	Sritharan, S., Priestley, M.J.N., Seible, F., Seismic Response of Column/Cap Beam Tee Connections w/Cap Beam Prestressing, Structural Systems Research Project SSRP – 96/09, University of California, San Diego, La Jolla, CA, December 1996.	IC3
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)
SM8	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 4 (PT-S)
SM9	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.	

SM10	Schoettler, M., Restrepo, J., Seible, F., BART Aerial Guideway Bent Proof Test, Structural Systems Research Project SSRP – 2002/13, University of California, San Diego, La Jolla, CA, October 2002.	
SM11	Priestley, M.J.N., Seible, F., Anderson, D., Proof Test of a Retrofit Concept for the San Francisco Double-Deck Viaducts, Structural Systems Research Project SSRP – 92/03, University of California, San Diego, La Jolla, CA, July 1992.	
SM12	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.	Bulb Tee
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
SM14	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.	Bulb Tee Super
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