Seismic damage and retrofit to California's urban concrete bridge structures

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Seismic Damage and Retrofit to California's Urban Concrete Bridge Structures

Dommages dûs aux séismes et réparation des structures de ponts en Californie

Bebenschäden und Reparatur kalifornischer Betonviadukte

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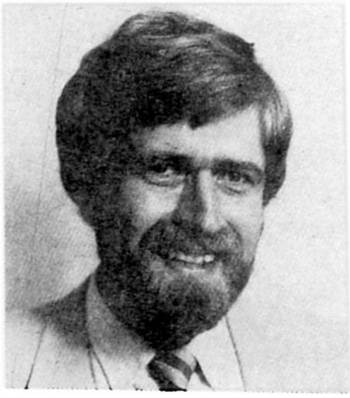

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SUMMARY

The Loma Prieta earthquake of October 1989 has re-emphasized the vulnerability and failure consequences of urban freeway bridges in a major seismic event. An overview of encountered urban bridge damage in recent earthquakes in California, is presented together with retrofit strategies to mitigate seismic bridge hazards in future earthquakes. Photo documentation of encountered damage and implemented temporary and permanent retrofit measures is provided.

RESUME

Le tremblement de terre de Loma Prieta d'octobre 1989 a rappelé la vulnérabilité et les conséquences de la rupture de ponts-routes urbains lors d'un tremblement de terre important. Les dommages encourus par des ponts urbains lors de récents tremblements de terre en Californie sont présentés ainsi que les méthodes de réparation en vue de diminuer les conséquences de futurs tremblements de terre sur les ponts. Une documentation photographique des dommages encourus et des réparations temporaires et définitives est présentée.

ZUSAMMENFASSUNG

Das Loma-Prieta-Erdbeben vom Oktober 1989 führte erneut die Verwundbarkeit und die Folgen eines Einsturzes von Stadtautobahnviadukten vor Augen. Der Beitrag gibt eine Schadenübersicht nach jungeren, kalifornischen Erdbeben an städtischen Brücken und Strategien zu ihrer Ertüchtigung, um die Gefährdung durch zukünftige Beben zuverringern. Schadenmuster und temporäre wie permanente Massnahmen sind durch Bildmaterial dokumentiert.

1. INTRODUCTION

Recent earthquakes in California – San Fernando 1971 (M6.4), Whittier 1987 (M5.9) and Loma Prieta 1989 (M7.1), have repeatedly demonstrated the vulnerability of urban concrete freeway bridges to seismic attack. Ever since the 1971 San Fernando earthquake [1], the need for a major seismic bridge assessment and retrofit program, particularly in California but also in the rest of the United States, was recognized and subsequent seismic events reemphasized the need for accelerated retrofit research and implementation. Caltrans, the California Department of Transportation, developed a three phase bridge retrofit program in 1971 focusing on movement joints, single-column bents and multi-column bent bridge structures.

By the mid-1980's, the Phase I retrofit program of providing seismic restrainers across movement joints was virtually completed and attention turned toward the more difficult problem of improving strength and ductility of bridge columns both in single and multi-column bents. A comprehensive research program was initiated at the University of California, San Diego (UCSD) to develop effective economical and technically feasible means for improving the flexural ductility of plastic hinges in single-column bents. The October 1987 Whittier earthquake shifted the focus to a potentially bigger problem, namely the brittle shear failure in short multi or single-pier bents [2], which comprise a large number of bridge bents in freeway overpasses.

Finally, the Loma Prieta earthquake of October 1989 uncovered problems with double-deck viaduct structures and knee joints in outrigger bents. Caltrans responded with accelerated and significantly expanded and specific retrofit research on single and multi-column bents, double-deck viaducts and outrigger bents, paralleled by implementation of temporary retrofit measures to minimize immediate seismic bridge hazards and followed by a detailed assessment of all 25,000 bridges in California and permanent retrofit designs for over 4,000 bridge structures currently in progress [3].

In the following, an overview of encountered seismic damage to concrete bridge structures in recent California earthquakes is provided together with examples of retrofit implementation. The intent of this photo documentation on urban seismic bridge damage and retrofit is to demonstrate that we are "competing against time" (George Housner, 1990 [4]) with our efforts to mitigate hazards posed by manmade structures in earthquakes.

2. ENCOUNTERED BRIDGE DAMAGE

The 1971 San Fernando earthquake caused significant bridge damage, particularly to newly constructed interstate bridges. Key problems identified ranged from excessive seismic displacements and subsequent unseating of complete bridge spans at movement joints, see Figs. 1a and b, inadequate confinement of flexural plastic hinge regions in columns, see Figs. 1c and d, and Figs. 2a and b, anchorage problems with large diameter ∅ 57 mm (#18) column reinforcement into the footing, see Fig. 2d, brittle shear failure of short columns with insufficient shear reinforcement, see Fig. 1e, and joint failures of knee joints due to the lack of joint shear reinforcement, see Fig. 2c. It is of interest to note that subsequent earthquakes such as Whittier (1987) and Loma Prieta (1989) did not uncover completely new problem areas which were not already identified in San Fernando (1971) but rather reemphasized some of the above mentioned problems.

While design guidelines for new bridge structures were immediately changed to reflect higher seismic force levels, confinement of column concrete particularly in potential plastic hinge regions and increased force and displacement requirements for movement joints, seismic retrofitting of existing bridge structures focussed initially on movement joint restrainers to prevent unseating and span collapse.

The Whittier earthquake (1987) caused significant damage only to one urban concrete bridge structure, the I-5/605 crossing where short piers of a skew multi column-bent bridge structure failed in shear. The large number of existing freeway overheads which feature these short piers, designed and constructed prior to 1971, pose probably the most severe seismic bridge hazard in

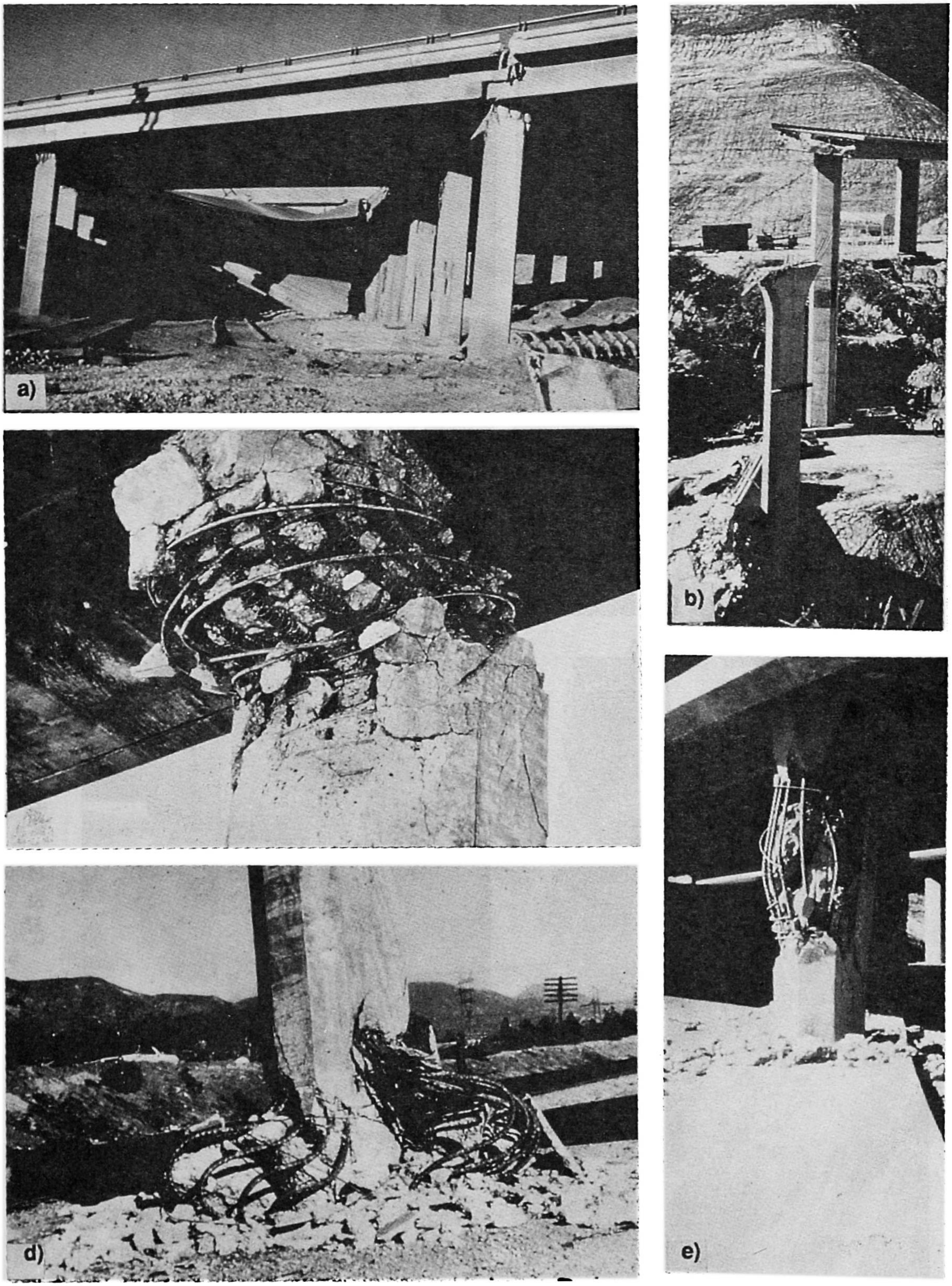


Fig 1. Bridge Damage During the 1971 San Fernando Earthquake

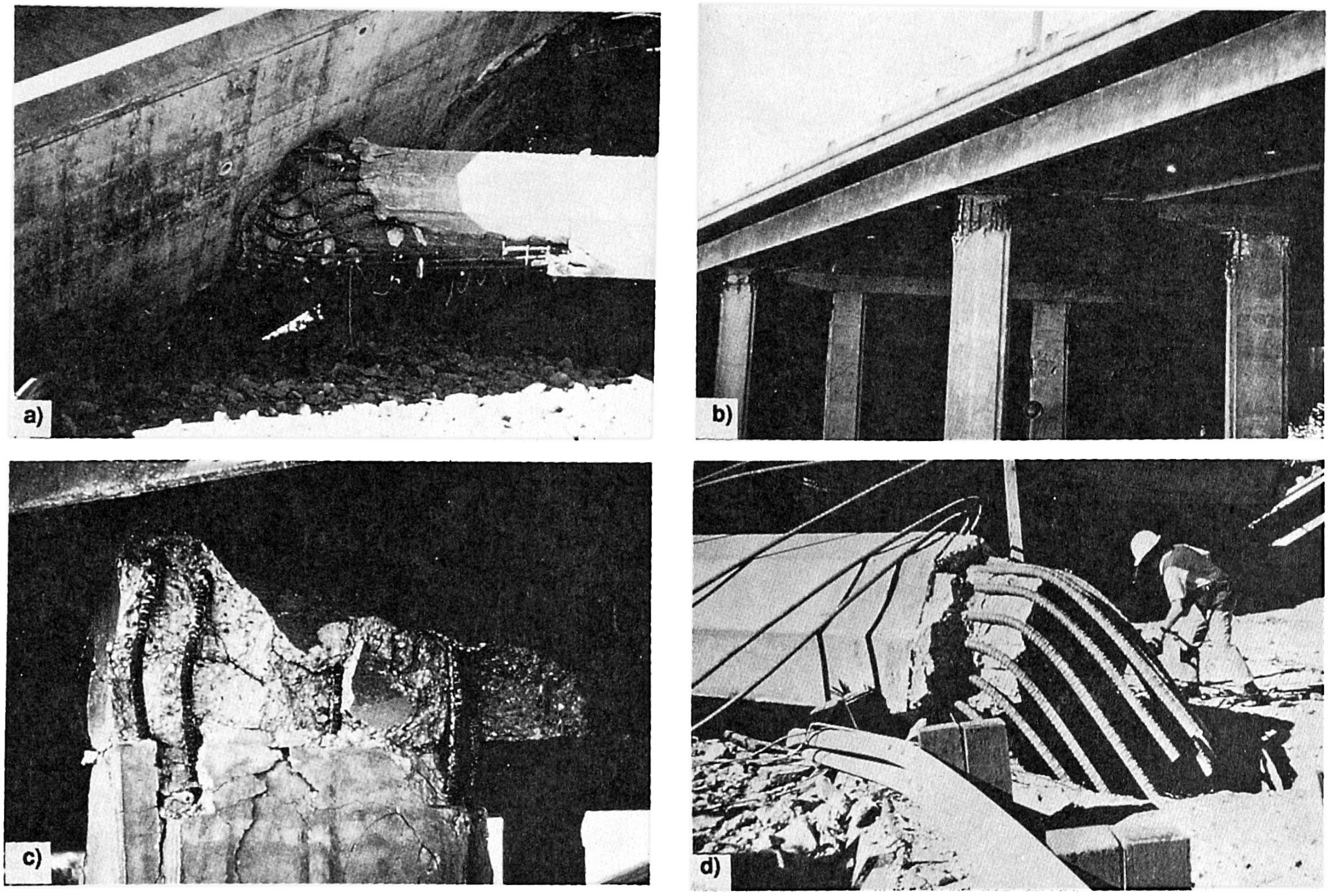


Fig 2. San Fernando Earthquake Bridge Damage (continued)

urban concrete freeway systems since transverse pier reinforcement typically consisted of nominal 12 mm Ø bars @ 300 mm (#4 @ 12 in.) and was not designed for the plastic shear which can be developed by the flexural column capacity, based on current seismic capacity design principles [5].

Finally, Loma Prieta (1989) revisited all previously encountered problems with emphasis on double-deck viaduct structures through the collapse of a 1 km (0.7 mile) long section of the upper deck of the Cypress Viaduct in Oakland, and significant damage to other double-deck viaduct sections in San Francisco.

The collapsed upper deck of the Cypress Viaduct in Oakland is shown in Fig. 3a, featuring columns and pedestals reinforced with 12 mm Ø ties @ 300 mm (#4 @ 12 in.) and joint regions without joint shear reinforcement. Figure 3b depicts a lower cap/column connection with pullout failure of top and bottom cap reinforcement due to inadequate anchorage length and Fig. 3c shows a typical joint failure of the lower cap/column joint region. Typical column shear failure was encountered on Highway 101 – Central Viaduct – see Fig. 3d, and lap-splice failure of column bars in the plastic hinge at the top of the footing was encountered in single-column bents on the West Grand Avenue Connector in Oakland, see Fig. 3e.

Outrigger bents showed problems in flexure and shear in the cap and shear failure of knee joints, see Fig. 4a, due to lack of shear reinforcement, and a fractured 57 mm Ø (#18) bar was encountered in a damaged knee joint on I-980, see Fig. 4b, which can be attributed to large strains introduced during bar bending (6.25%) and possible strain aging effects.

Finally, on struve slough, Figs. 4c and d, the plastic hinge at the column top sheared off and the column offset in the longitudinal bridge direction and punched through the reinforced concrete deck slab.

Additional seismic bridge problems not shown in the figures are liquefaction and associated support displacements at piers and abutments, abutment wing and back wall failures due to superstructure impact, and footing failures due to inadequate flexure, shear and/or joint shear reinforcement.

As a consequence of the damage observed in these earthquakes and analyses of typical structures, the following major problem areas in concrete bridge structures have been identified:

- Inadequate flexural strength of columns and cap beams resulting from design to elastic theory, and from inadequate development of reinforcement.

- Inadequate flexural ductility resulting from insufficient confinement reinforcement in plastic hinge regions, coupled with inadequate detailing.

- Inadequate shear strength of columns resulting from underestimating flexural strength, lack of a capacity design approach and insufficient, poorly detailed transverse reinforcement.

- Inadequate joint shear strength, particularly in column/cap beam connections, and at column/footing connections.

- Inadequate superstructure moment capacity to force plastic hinges into columns under longitudinal response to earthquakes.

- Inadequate footing moment and shear capacity to sustain column plastic moment capacity.

- Inadequate pile capacity (particularly uplift) to sustain column plastic moment capacity.

- Liquefaction potential of foundation material for pile-supported footings.

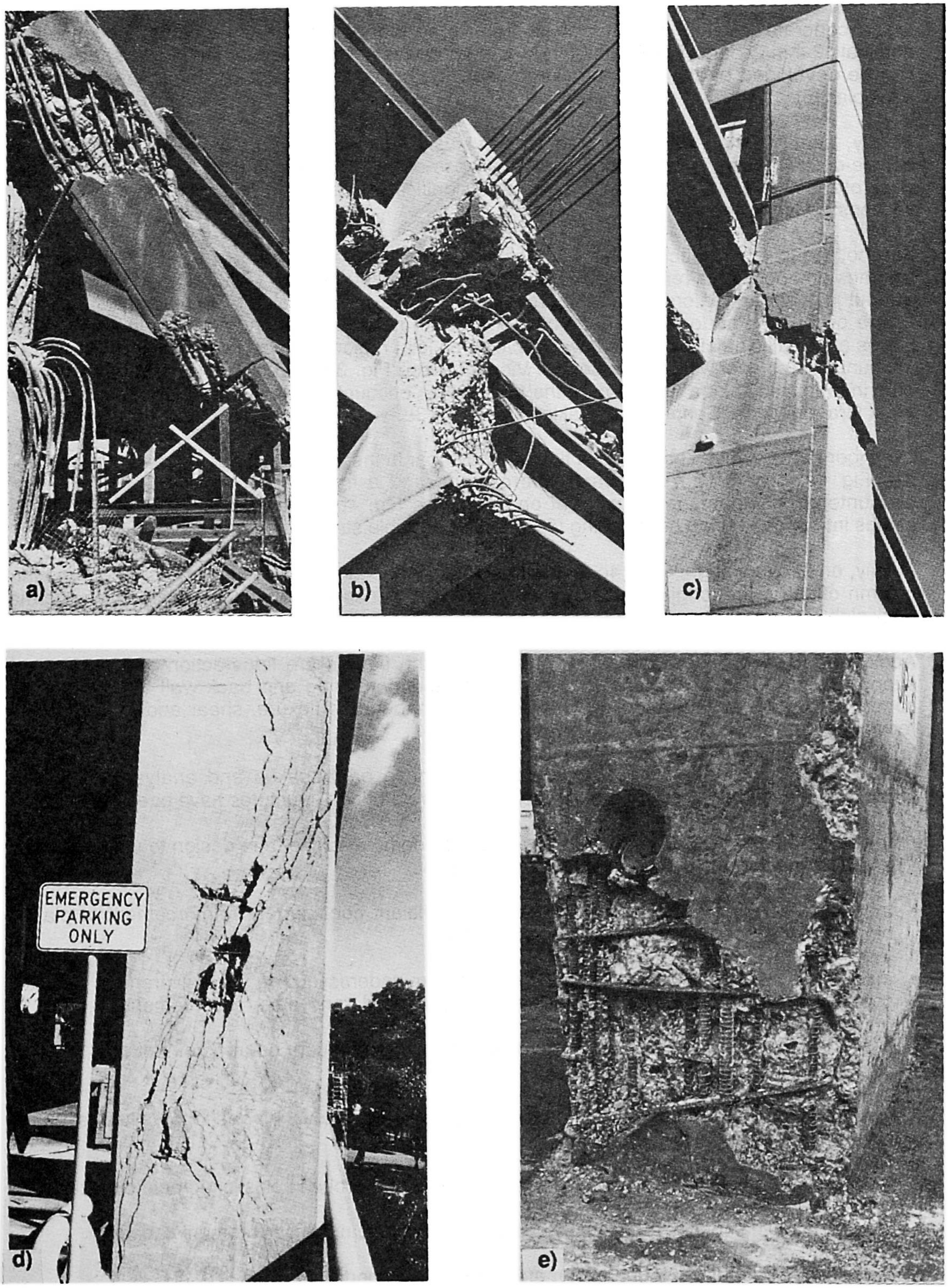


Fig 3. Bridge Damage, Loma Prieta 1989 (M7.1)

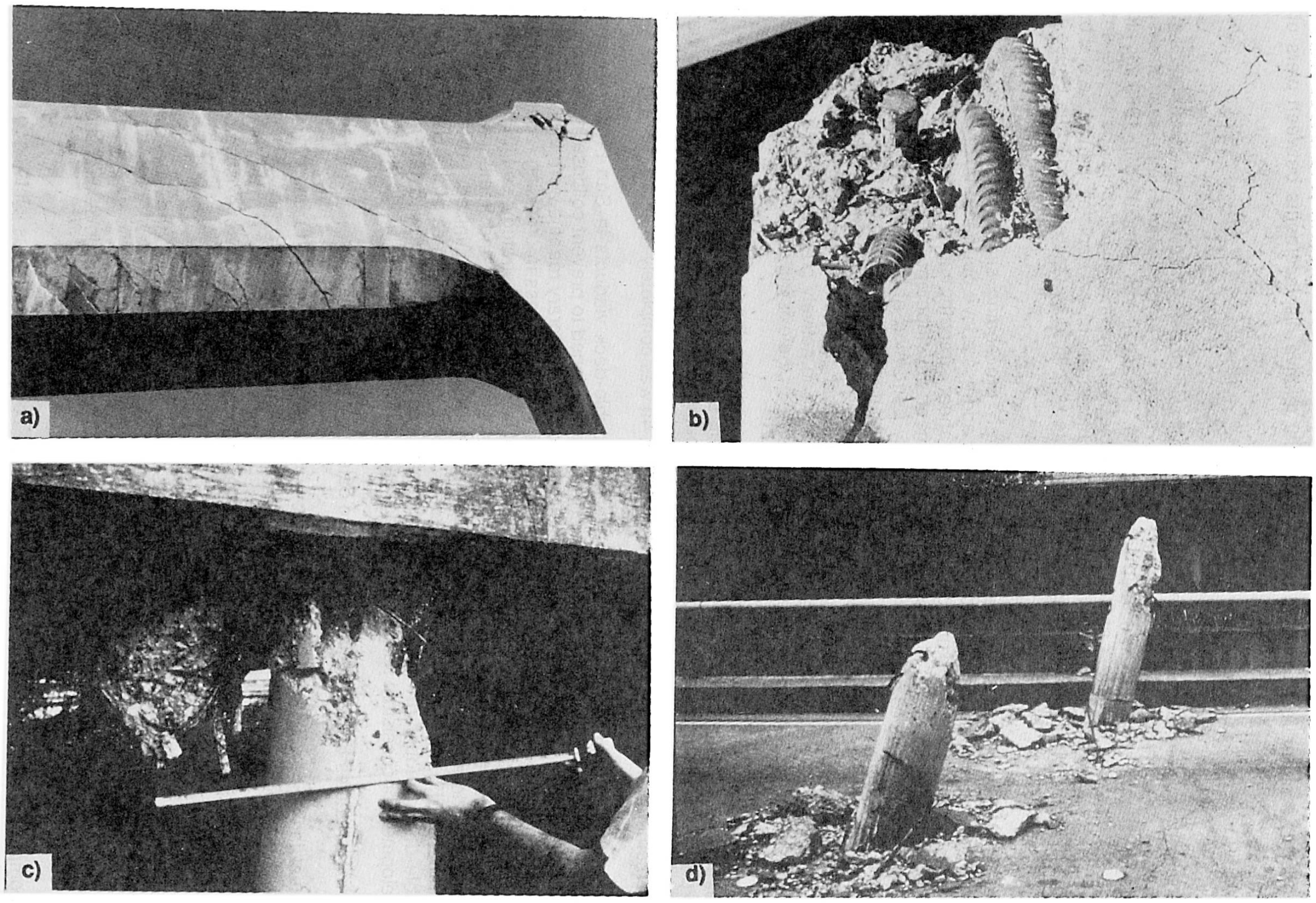


Fig 4. Knee Joint and Plastic Hinge Failure, Loma Prieta 1989

Inadequate structure ductility to sustain potential relative displacements between piers of bridges crossing active faults.

3. RETROFIT IMPLEMENTATION

The Caltrans seismic retrofit program, which began following the 1971 San Fernando earthquake, consists, as outlined above, of three phases, namely (1) movement joint restrainers, (2) single-column bents, and (3) multi-column bents. Phase 1 was completed in 1989 for all bridge structures in California and examples of cable restrainers, whose function is to prevent drop-type failures at expansion joints, hinges and abutment seats, are depicted in Figs. 5a and b. A total of approximately 1,300 bridge structures were retrofitted by Caltrans under the Phase 1 retrofit program.

The Phase 2 and Phase 3 programs are currently proceeding simultaneously and, since Loma Prieta, at an accelerated pace. Both phases address above outlined problems of column flexural strength, column flexural ductility, column shear strength, cap capacities and ductility, superstructure capacities, joint shear, reinforcement development, footing capacities, and abutment capacities. Based on research primarily performed at the University of California, San Diego for Caltrans [3], flexural ductility and shear strength in existing columns and piers can be ensured through partial or full height steel jacketing, see Fig. 5d. Other retrofit measures which are currently being implemented in California for bridge columns consist of composite fiber jackets with glass or carbon fibers in an epoxy matrix and actively prestressed with a Portland cement grout pressurized bladder which is placed between the existing column and the fiberwrap.

A flared pier wall which experienced shear distress during the Loma Prieta earthquake was repaired and retrofitted with a full height steel jacket, see Fig. 5c, for increased shear capacity. The previously discussed joint shear failure in an outrigger knee joint of I-980, see Fig. 4b was repaired by full replacement of the joint concrete, see Fig. 6d, and added joint shear reinforcement, while the outrigger bent shown in Fig. 4a was completely replaced, see Fig. 5e.

Following the Loma Prieta earthquake, several double-deck viaducts in San Francisco were closed to traffic and temporary retrofit strategies were designed to prevent collapse in the case of additional seismic activity in the near future. Some of the temporary retrofits were fully or partially implemented, see Figs. 6a, b and c. However, their ineffectiveness in providing required lateral confinement levels and their lack of global structural seismic retrofit strategy, see [3], prompted a reevaluation of these temporary retrofit schemes and resulted in the immediate design of permanent and final retrofit measures, which are currently being scrutinized, proof tested and implemented [3]. The difficulties encountered during the design process of the San Francisco double-deck viaduct retrofits and other ongoing retrofit projects showed the need for the development of consistent seismic assessment and retrofit strategies for bridge structures.

Retrofit strategies tested and implemented to date in California consist of

- steel jacketing, composite fiber wraps or prestressed wire wraps to enhance the flexural ductility in plastic hinge regions through active or passive confinement
- steel jacketing or composite fiber wraps to increase the shear capacity of existing columns and pier walls
- concrete jackets on knee joints to increase the joint shear area and to allow additional placement of joint shear reinforcement
- reinforced concrete footing overlays to increase the footing capacities in flexure, shear and joint shear
- complete replacement of damaged or inadequate components such as joints or complete bent systems.

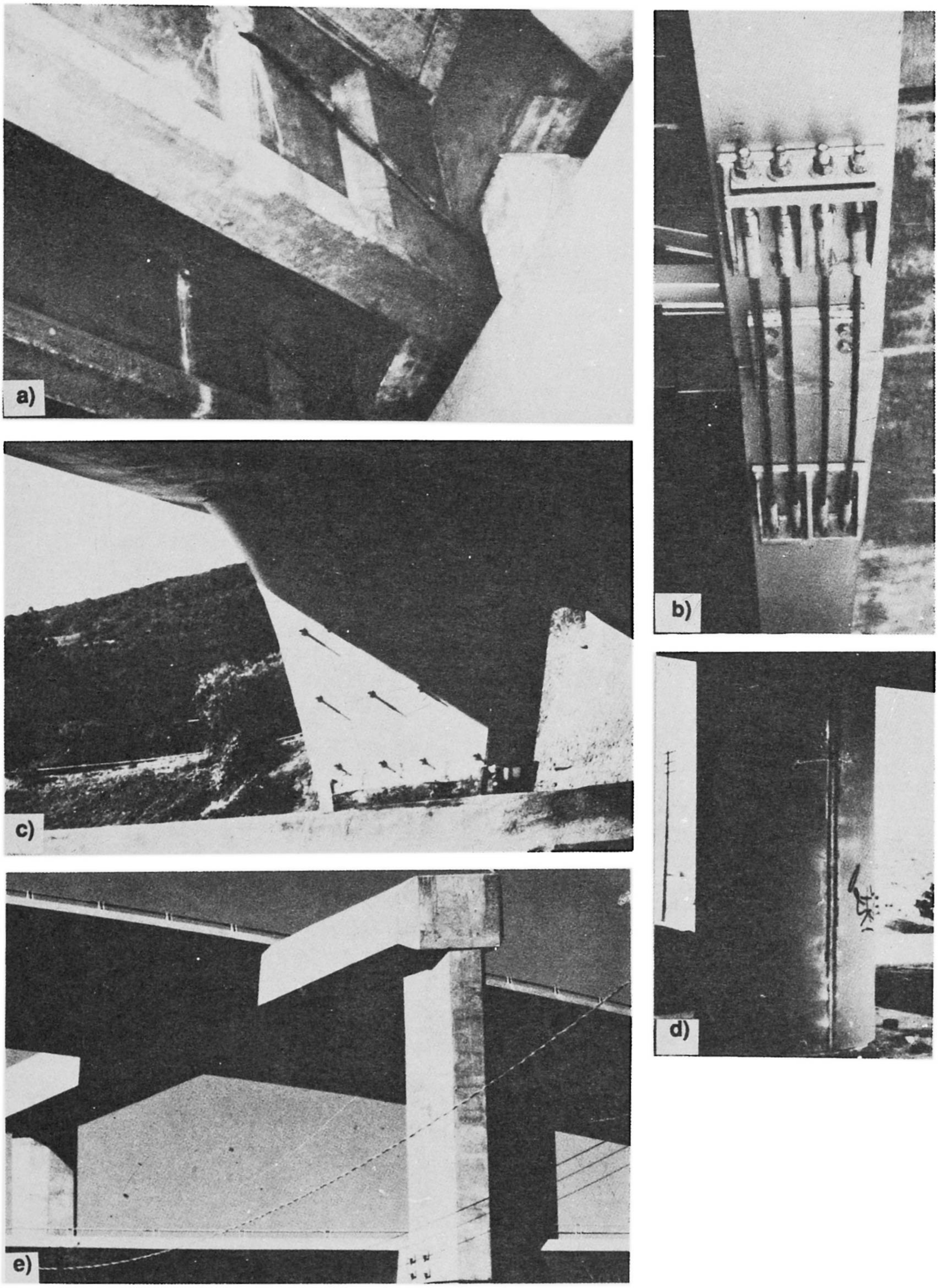
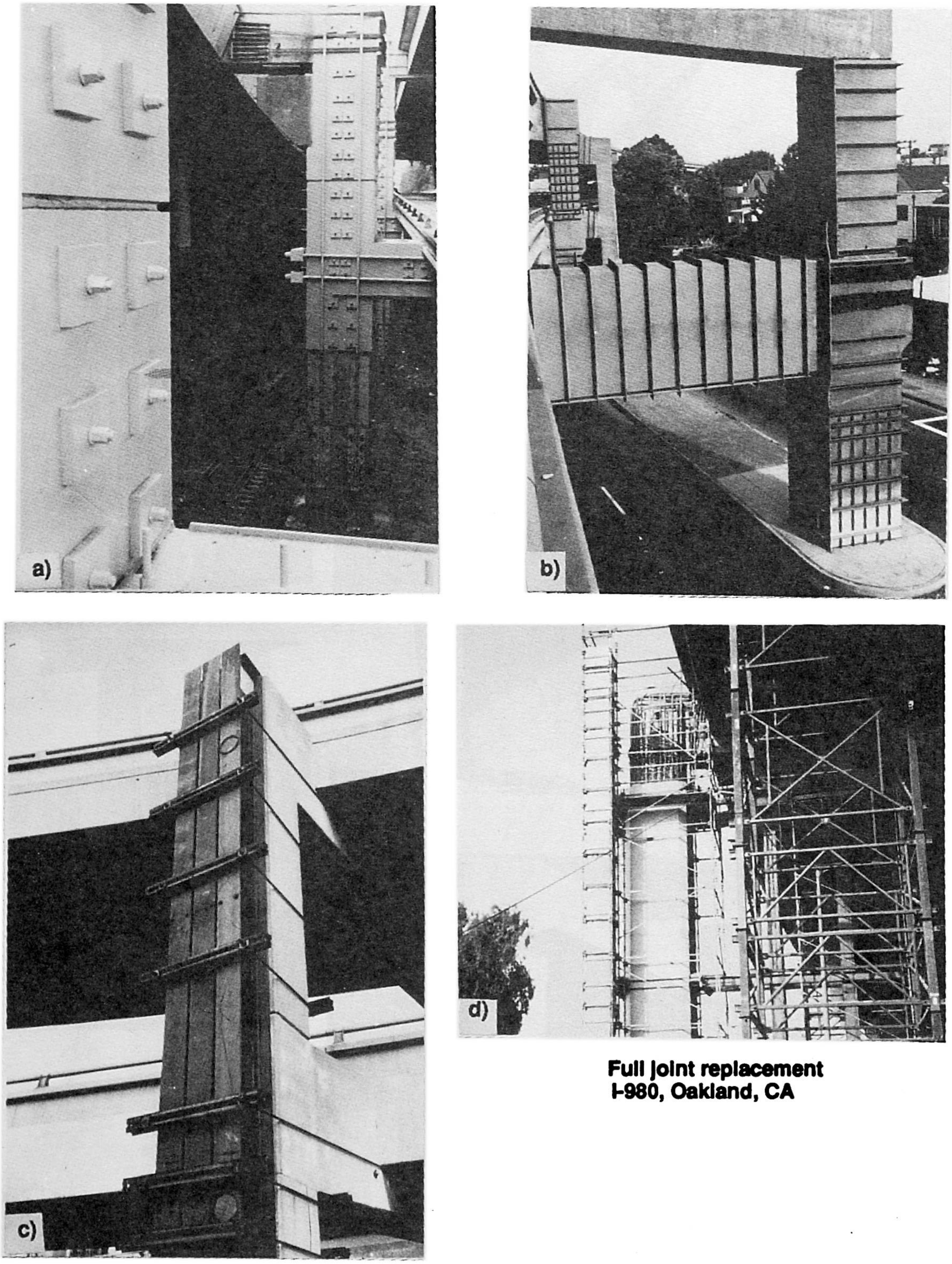


Fig 5. Implemented Permanent Retrofit Measures



Full joint replacement
I-980, Oakland, CA

Fig 6. Temporary and Permanent Retrofit Measures

The underlying retrofit philosophy is to create a structural system which is redundant and which has a ductile global collapse mode through the formation of well defined local ductile mechanisms.

4. CONCLUSIONS

Earthquakes are viewed as natural disasters due to their unpredictable nature and devastating consequences in the form of failures of manmade structures such as buildings, bridges and lifelines. On the example of urban concrete bridges, the vulnerability of manmade structures under seismic attack is demonstrated and measures are outlined toward seismic hazard mitigation of existing structures. The unknown state of existing bridge structures and the enhancement of their seismic performance through retrofitting pose challenging engineering problems which greatly exceed the complexity of seismic design for new structural systems. Significant developments are needed both in research and engineering applications to extend the state-of-the-art of seismic behavior assessment and retrofitting of existing structural systems.

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