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SEISMIC PERFORMANCE AND REPAIR OF MAJOR STEEL BRIDGES ON THE HANSHIN EXPRESSWAY, JAPAN

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ABSTRACT

The Hanshin Earthquake hit Osaka, Kobe and the Hanshin area, at a cost of more than 6,300 lives. The infrastructure, especially the urban expressways, suffered very serious damage. Hanshin Expressway Routes 3 and 5 are elevated structures using mostly concrete or steel piers and superstructures. On Route 3, eighteen prestressed concrete bridge spans collapsed totally and ten spans of steel girders fell off their cap beams at four places along the route. Steel piers showed virtually every kind of distress possible, the damage to some 15% of them being classified as higher than category B (severely damaged). On Route 5, longer-span steel bridges like the cable-stayed Higashi-Kobe Bridge and arched Rokko Island Bridge also suffered damage. In this paper the damage statistics of Hanshin Expressways are reported with emphasis on steel bridges. Some of the restoration techniques used for ordinary bridges and longer-span bridges are also mentioned, which are designed to meet the Restoration Guidelines issued by the Ministry of Construction especially for damaged highway bridges. Also mentioned are new types of bridge structures such as steel concrete hybrid piers and base isolated rigid frame piers where the main girders are integrated with the cap beams.

KEYWORDS

Hanshin Earthquake; Hanshin Expressway Routes 3 and 5; Hybrid pier; Base isolated pier; Higashi-Kobe Bridge; Rokko Island Bridge; Base isolator; Cable restrainer

INTRODUCTION

The Great Hanshin Earthquake hit Osaka, Kobe and other cities in the Hanshin area at dawn on January 17, 1995 (Fig. 1). The epicenter was under the sea just north of Awajishima Island, the earthquake being caused by a series of movements of active faults running from the northern part of Awajishima Island up through the Hanshin area. The earthquake cost more than 6,300 lives, and damaged or totally destroyed some 200,000 houses. The infrastructure and life-lines were also badly hit. Kobe's port facilities were almost totally destroyed, and on the rail network all four lines connecting Kobe and Osaka, including the Shinkansen, ceased through operations for three or more months. Some elevated sections of the lines collapsed and stations were also destroyed by the strong ground motion. Water, gas, electricity and telephones were cut all over the Hanshin area, affecting more than 1.3 million households. Bridges were also badly affected by the earthquake. Two of the trunk toll expressways, the Meishin route (Kobe to Nagoya) and the Chugoku route (Osaka to Fukuoka), were forced to close or limit the volume of traffic over the Hanshin section for some six months. Some elevated sections of national highway Route

2 were also seriously damaged, still being restored as of January 1996.

The severest damage to bridge structures could be found on Hanshin Expressways Routes 3 and 5 (Fig. 1) which connect Osaka and Kobe and are all elevated structures mostly with concrete or steel columns and superstructures; 635 meters of the Fukae section of Route 3 was toppled (Photo 1). At the Nishinomiya section of Route 5, a steel box girder 52 m long and 27 m wide fell to the ground. Route 3 runs through an urban area where the earthquake intensity registered 7 on the Japanese Scale of Earthquake Damage Intensity, with a probable maximum ground acceleration of more than 600 gals. On the other hand, Route 5 runs through man-made islands around Osaka Bay; it was designed to a relatively new standard and suffered less damage than Route 3.

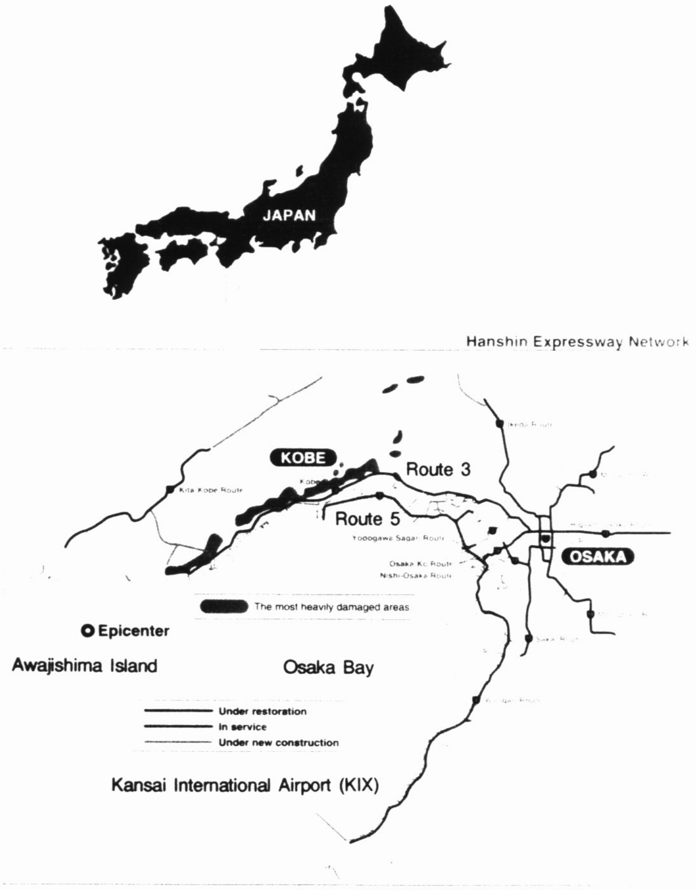

Fig. 1 Epicenter and Hanshin Expressway network

Photo 1 Collapsed portion of Route 3

This paper presents the damage suffered by bridge structures mainly on Hanshin Expressway Routes 3 & 5, together with the repair techniques for repairable bridges and new types of structures which will replace severely damaged bridges.

GENERAL DESCRIPTION OF BRIDGE DAMAGES IN HANSHIN EXPRESSWAY

The Hanshin Expressway network in the Osaka-Kobe area had 13 routes covering 200 km in service at the time of the earthquake. Every route suffered its share of damage, but Routes 3 and 5 suffered most, and 27.7 km of Route 3 was still out of service as of January 1996. The damage statistics of these two routes are shown in Table 1 (Committee on Restoration, 1995a), divided into bridge components. Damage levels As, A, B, C, & D mean collapsed or near collapse; and very severely, severely, moderately damaged and structurally sound respectively. Route 3 was constructed between thirty and twenty years ago with a seismic coefficient of mostly 0.2, coming into service section by section. Route 5, on the other had, was opened to traffic in 1994, with a structural design conforming to the upgraded earthquake-resistant design codes of 1980. "As" on Route 3 includes 18 spans of prestressed concrete bridge which tipped over because supporting concrete columns broke at ground level; two spans of simply-supported steel girders which fell off their pier caps because of the unexpectedly large displacement of the girders that may have been caused by the collision of adjacent girders on the pier cap in addition to the plastic displacement of piers during the earthquake; steel girders of a triple-span continuous system which buckled (not because of direct earthquake shaking but following the settlement caused by the failure of supporting columns); and steel columns which could not support the dead load of their box girder superstructures and were literally torn apart because the local buckling occurring to the plate(s) during the quake and the resulting deformation was so large that corner welds cracked (Photos 2 & 3). On top of these, many reinforced concrete piers suffered serious damage. The "As" damage on Route 5 is the approach span to the Nishinomiya Harbor Bridge, which collapsed. There are no other As's or A's for piers and girders on Route 5. This is quite a contrast with Route 3. Possible reasons may be that Route 5 conforms to the updated design codes or that the input acceleration for Route 5 was not so high as that of Route 3, or a combination of both. Table 2 shows the damage levels and locations of steel girders for both routes. Most damage was found at the ends of the girders, namely at the spot where external forces would have been transferred through bearings and longitudinal seismic restrainers. At these points the bearings, longitudinal restrainers, girders or all three suffered serious damage. The steel bearings of the two routes did not show much difference in performance and suffered seriously. But, as shown in Table 3, which includes not only Hanshin Expressway bridges but also other highway bridges, rubber bearings performed well compared with steel ones.

Table 1 Damage statistics on Routes 3 and 5

			Damage Classifications					
Route	Portion		As	A	B	C	D	Total
No. 3	Piers	Steel	3 (2%)	8 (5%)	12 (7%)	112 (69%)	28 (17%)	163 (100%)
		RC	64 (7%)	78 (8%)	102 (11%)	225 (24%)	474 (50%)	943 (100%)
	Bearings		—	371 (18%)	274 (13%)	383 (18%)	1090 (51%)	2118 (100%)
	Girders		26 (2%)	67 (5%)	243 (19%)	215 (16%)	753 (58%)	1304 (100%)
No. 5	Piers	Steel	0 (0%)	0 (0%)	13 (9%)	21 (15%)	109 (76%)	143 (100%)
		RC	0 (0%)	0 (0%)	1 (0%)	22 (11%)	179 (89%)	202 (100%)
	Bearings		—	30 (5%)	72 (12%)	196 (34%)	286 (49%)	584 (100%)
	Girders		1 (0%)	0 (0%)	8 (2%)	28 (6%)	425 (92%)	462 (100%)
Total	Piers	Steel	3 (1%)	8 (3%)	25 (8%)	133 (43%)	137 (45%)	306 (100%)
		RC	64 (6%)	78 (7%)	103 (9%)	247 (22%)	653 (57%)	1145 (100%)
	Bearings		—	401 (15%)	346 (13%)	579 (21%)	1376 (51%)	2702 (100%)
	Girders		27 (2%)	67 (4%)	251 (14%)	243 (14%)	1178 (67%)	1766 (100%)

Photo 2 Buckled box girder

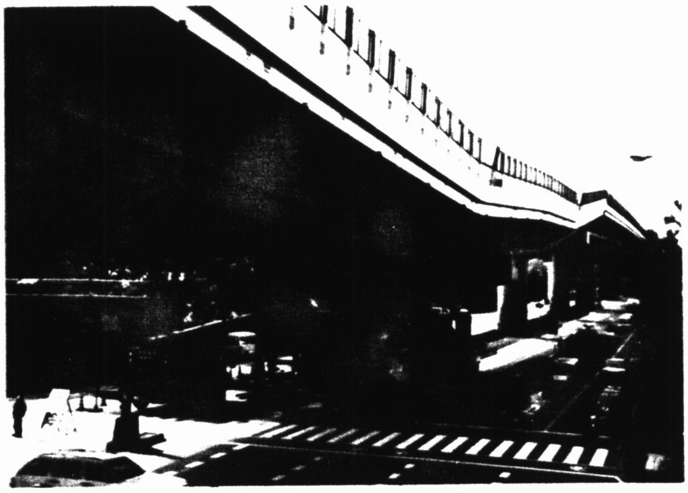

Photo 3 Collapsed steel pier

Table 2 Location of damage in steel girders (spans)

Damaged location	Damage classifications				Total
	As and A	B	C	D	
Bearings	112 (7%)	142 (8%)	62 (4%)	1364 (81%)	1680 (100%)
Restrainers	4 (0%)	24 (2%)	38 (3%)	1317 (95%)	1383 (100%)
Centers of a girders	1 (0%)	5 (0%)	2 (0%)	1672 (100%)	1680 (100%)
Ends of girders with web gaps	26 (14%)	29 (16%)	12 (6%)	120 (64%)	187 (100%)
Total	143 (3%)	200 (4%)	14 (2%)	4473 (91%)	4930 (100%)

Table 3 Performance comparison between steel and rubber bearings (lines)

Bearing materials	Damage classifications				Total
	As and A	B	C	D	
Steel bearings	986 (21%)	603 (13%)	681 (14%)	2503 (52%)	4773 (100%)
Rubber bearings	0 (0%)	6 (2%)	19 (8%)	219 (90%)	244 (100%)
Total	986 (20%)	609 (12%)	700 (14%)	2722 (54%)	5017 (100%)

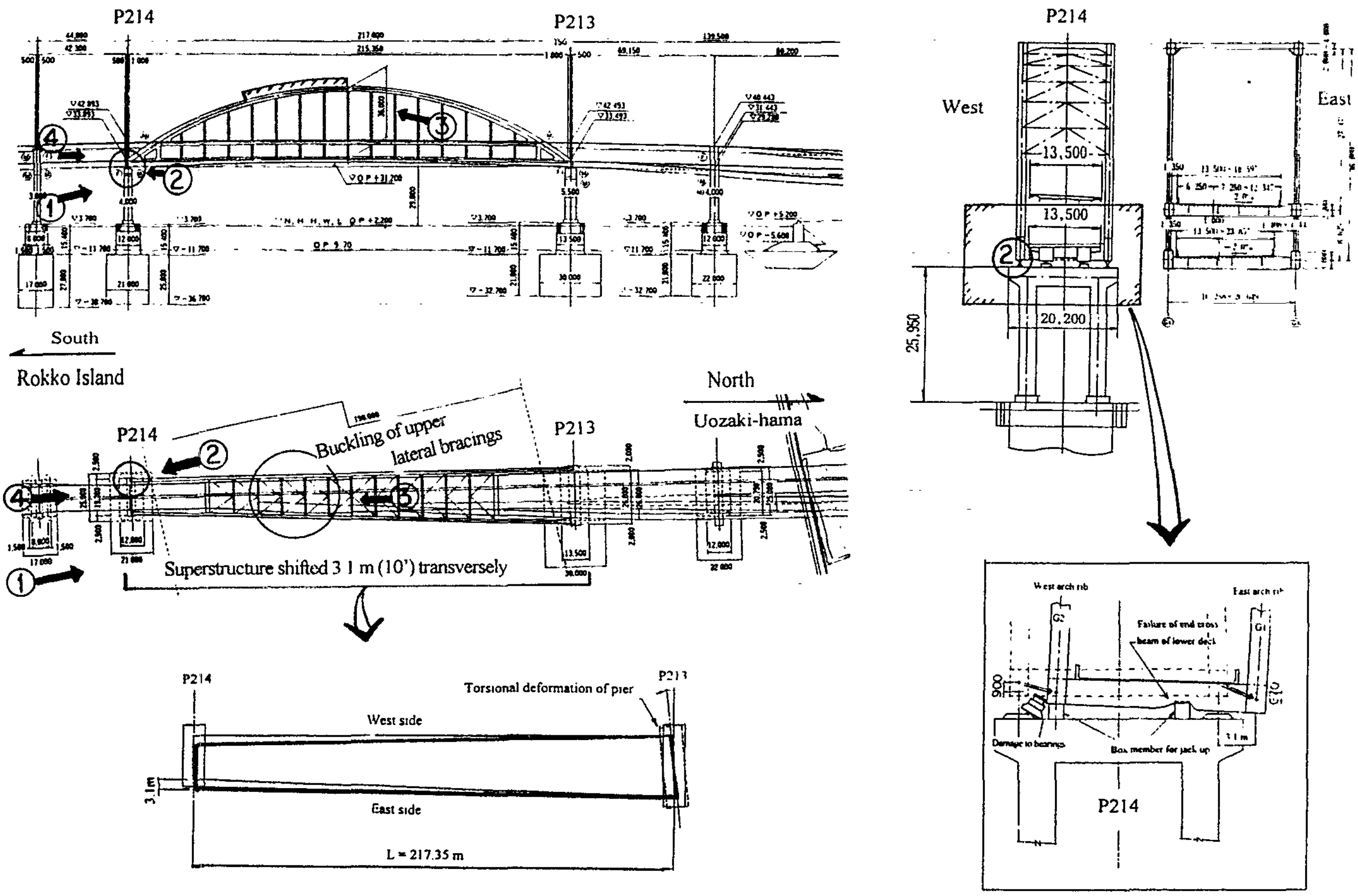

Fig. 2 Rokko Island Bridge

DAMAGE IN LONGER-SPAN STEEL BRIDGES ON ROUTE 5

Rokko Island Bridge

This is a Lohse double-deck arch bridge with a span of 252 m as shown in Fig. 2. This arch bridge shifted transversely to the east by 3.1 m on the south end pier (P214) in response to the earthquake and fell off its pivot bearing, damaging the end cross beams. Lateral bracing members, which connect two arches near the top of the arches, also buckled. The following is the repair procedure for the bridge.

a) Temporary removal of the approach spans (P214–P215).
b) Installation of temporary supports for the main span.
c) Lifting up the main span (9,170 tons) with two floating cranes (capacities 3,500 and 4,100 tons).
d) Shifting the main span back to its original position, but 6″ higher for the exchange of bearings.
e) Repair of end cross beams, top lateral bracings, the box member to allow the main span to be jacked up and the pier cap.
f) Installation of new bearings and jacking the main span back down.
g) Re-erection of the approach spans.

Higashi-Kobe Bridge

This is a double-decked three-span continuous cable-stayed bridge with a center span of 485 m and side spans of 200 m as shown in Fig. 3. The stiffening truss girder of this bridge is suspended only by stay cables and this system makes the period of vibration longer in the longitudinal direction. This reduces the response acceleration of the bridge in that direction. But in the transverse direction the girder is restrained by wind shoes which are installed on the lower beams of the towers and the cap beams of the end piers. The transverse restrainers at the west end pier broke during the quake and could not hold the girder in place. Also installed at the end pier were two inverse pendulum type shoes to resist the lifting-up force of the girder and vane-type oil dampers against excessive longitudinal displacement under normal traffic conditions.

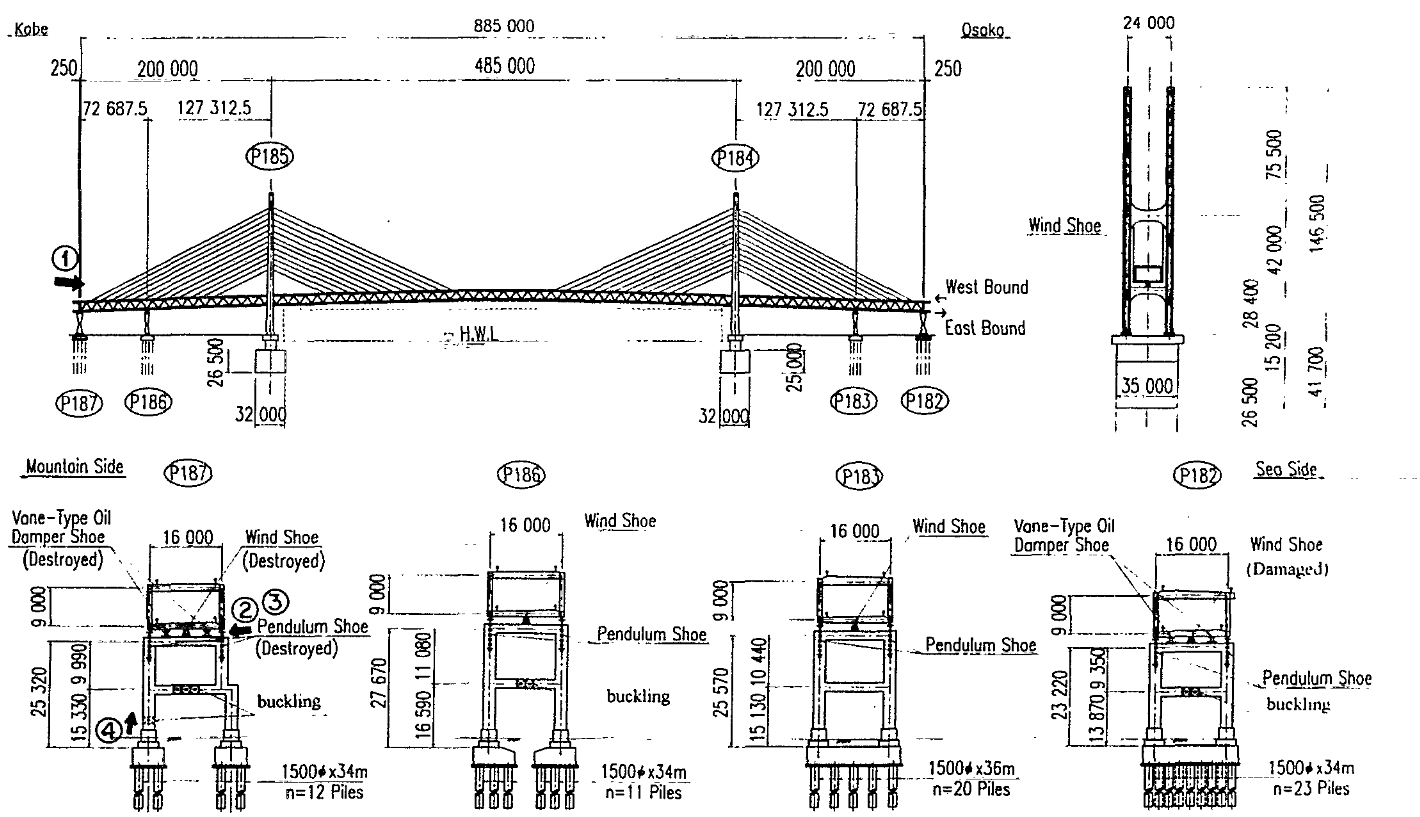

Fig. 3 Higashi-Kobe Bridge

These devices were badly damaged by the large longitudinal and unexpected transverse displacement of the girder, with the girder springing up some 50 cm at the end piers. Two-story frame-type steel piers suffered serious local buckling in the lower column and diagonal wrinkles due to the shear in the cap beam.

When retrofitting these damaged devices and members the earthquake waves recorded at the site were used. Wind shoes were redesigned and manufactured especially for larger transverse forces. Inverse pendulum shoes were partly replaced and the oil dampers were completely replaced. Buckled beams and columns were partially replaced or reinforced by adding new cover plates or stiffeners after heating the deformed plates back into plane.

Shin-Ashiyagawa Bridge and Shin-Shukugawa Bridge

These two are cantilevered steel box girder bridges. The end piers of these bridges stand on very young reclaimed land. The foundations of these piers were forced to move about 1 m toward the center of the river with severe ground deformation due to lateral spreading caused by liquefaction. The ends of the girders came within centimeters of being unseated. In these cases measures to widen the pier caps were adopted together with stronger restrainers.

REPAIR AND RETROFIT OF STEEL BRIDGE MEMBERS

Typical damage to steel members of bridges is illustrated in Figs. 4 and 5. The steel girders which are classified As or A are to be replaced by new ones with steel deck plates instead of concrete slabs, which are designed to the latest building codes for steel girders (although there is not much difference from the old ones). Girders classified B and less are to be repaired by heat treatment, partial replacement of webs and flanges and by welding cracks. In both cases cross beams at the end of the bridge were reinforced from a knee type to a full-depth web. Steel piers, bearings and restrainers are to be repaired and retrofitted according to the Restoration Guidelines for Roadway Bridges Damaged by the Earthquake, issued by the Ministry of Construction (Committee on Restoration, 1995b), which requires that restored bridges should be ductile enough to perform well for an earthquake of the same magnitude as the Hanshin. Special emphasis is put on improving the ductility of piers: namely, concrete piers should have a lot more transverse reinforcement and steel piers should have their lateral deformation capabilities improved, for example, by having concrete poured inside.

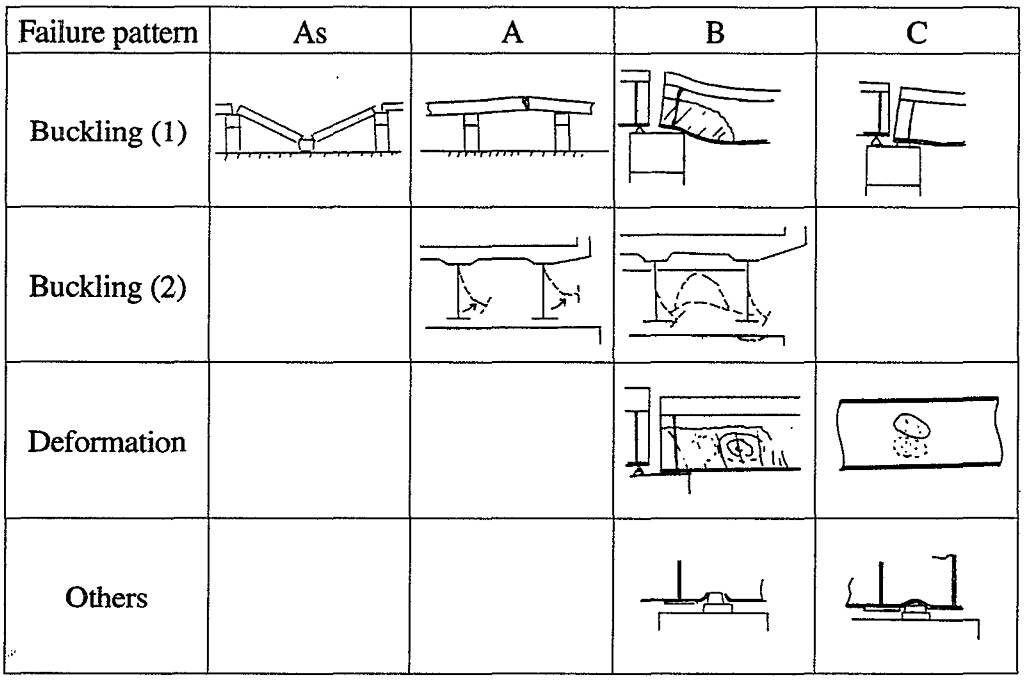

Fig. 4 Damage classification of steel girders

Failure pattern	As	A	B	C
Buckling		df>0.03lb	0.03lb>df>0.01lb	0.01lb>df
Cracking (Around manholes)		Crack propagation	Long crack	Short crack
Paint flaking		With crack	Paint flaking at important part	Paint flaking
Joint		Over 10% bolt loss	Less than 10% loss	Paint flaking

Fig. 5 Damage classification of steel girders

As for bearings and restrainers, the Guidelines recommend that base isolators and rubber bearings are preferred and that restrainers should be more shock-absorbent, more ductile and strong enough to prevent girders from falling off pier caps. On Route 3 we are replacing steel bearings with rubber bearings, pouring concrete in (repaired) steel piers and installing cable restrainers which connect adjoining girders (Fig. 6). On Route 5, repair work to restore damaged members is now finished except for foundations and retrofitting work.

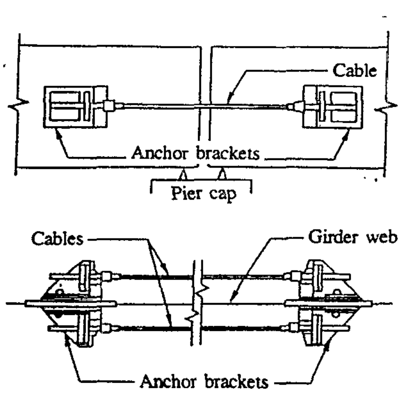

Fig. 6 Longitudinal cable restrainer

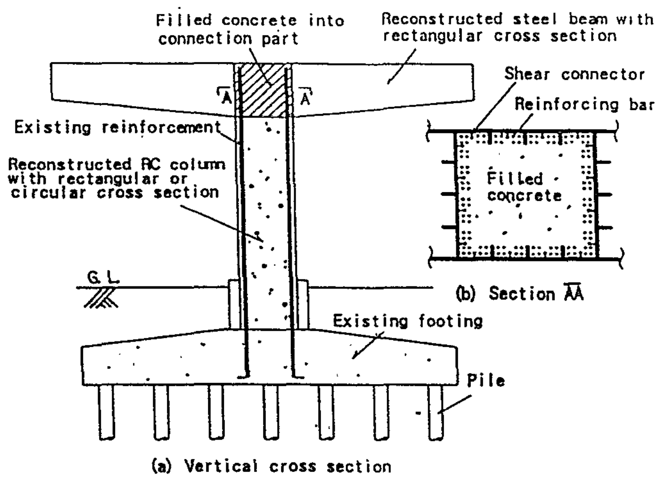

Fig. 7 Hybrid pier with concrete column and steel cap beam

NEW TYPES OF BRIDGE STRUCTURES

In retrofitting Route 3 a couple of new types of constructions and structures were adopted to reduce the construction period and to achieve better seismic performance.