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Repair of Three Long Span Steel Bridges Damaged During the 1995 Hyogo-ken Nanbu (Kobe) Earthquake

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ABSTRACT

The 1995 Hyogo-ken Nanbu (Kobe) earthquake was the world's first experience with an earthquake that caused moderate damage to long-span bridges. This paper reviews damage and describes techniques used to repair three major steel bridges along the Wangan Route (Bayshore Route) in Kobe: the 485 m Higashi-Kobe Bridge, the 217 m Rokko Island Bridge, and the 252 m Nishinomiya Port Bridge. These bridges had been in service for less than three years. Failure of bearings and seismic restrainers were principal initiators of the damage to these bridges. Significant constraints on repair of these bridges included confined working space and requirements for maintaining maritime navigational clearances. Repairs utilized heavy-lift floating cranes (up to 4,100 ton capacity) and various capacities of jacks to realign the spans. In one case reconstruction of a collapsed span was required, with lifting weight a prime concern. The back-to-service time for these three bridges ranged from three to nine months.

INTRODUCTION

The January 17, 1995 Hyogoken-Nanbu earthquake caused extensive damage to the urban infrastructure in and around Kobe, Japan. Most of the serious damage was to older structures that, by virtue of their age, had little or no seismic resistant design features. Damage to older bridges was similar in many respects to what occurred in previous earthquakes such as Northridge and Loma Prieta. Of considerable surprise however, was the damage sustained by three long-span bridges less than three years old. Although not nearly as severe or extensive as the damage to older bridges, damage to these new bridges had a severe impact on the transportation system in Kobe in the months following the earthquake. A detailed account of damage to steel bridges is given by Bruneau, Wilson and Tremblay (1996).

This paper focuses on the repair of three long-span steel bridges along the Wangan Route, a toll expressway opened just nine months before the earthquake on reclaimed land along the waterfront between Rokko Island in Kobe and Osaka to the east. The three bridges examined in this paper are: the Higashi-Kobe Bridge, the Nishinomiya Port Bridge, and the Rokko Island Bridge.

STRATEGY AND SCHEDULE FOR BRIDGE REPAIR AFTER THE 1995 EARTHQUAKE

With one exception, all major land-based transportation routes through Kobe were damaged and out-of-service after the earthquake. This cut all land transportation between eastern and western regions of Japan. The exception was a surface road on one National Route Highway, but this was severely restricted because of the collapse of a 600 m portion of the Hanshin Expressway on top of the eastbound lanes. Since damage on the Wangan Route was less severe than on the Hanshin Expressway the decision was made to proceed immediately with repair, with the objective of re-opening the Wangan Route (and hence providing a major transportation link east to Osaka) as soon as possible. This route was re-opened in stages, with the complete route (except the link to Rokko Island) back in service on July 1, 1995, 5-1/2 months after the earthquake. Damage on the other major route, the older Route 3 Hanshin Expressway, was much more severe and required complete reconstruction at many locations (it was re-opened September 30, 1996).

The three major bridges on the Wangan Route which are the subject of this paper were repaired to essentially the same state as before the earthquake. The reasons for this were the urgency to re-establish the expressway link to Osaka, and because it could not be determined within a short time frame what changes should be done to improve seismic resistance of these new structures that had just been built to current standards (the few changes to the original designs that were made are noted in later sections). Work is ongoing on development of retrofit strategies for the Wangan Route. On the

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Hanshin Expressway, new design criteria and techniques (both seismic and non-seismic) were applied to the repair and reconstruction.

HIGASHI-KOBE BRIDGE

Description of Bridge and Damage

The Higashi-Kobe Bridge (Figure 1) is a three-span (200 + 485 + 200 m; deck width 13.5 m) continuous all-steel double-deck cable-stayed bridge. The bridge was opened to traffic in 1992. A unique feature of the seismic design is that the main girder was allowed free longitudinal movement at all piers and towers (no bearings were used), to achieve a long sway period (approximately 4.4 sec). Two pendulum supports were provided at all piers to provide this longitudinal freedom. Oil vane dampers were used at the end piers for longitudinal displacement control of the girder during an earthquake. Wind shoes on the piers and towers were used to transfer transverse wind loads.

The significant damage to this bridge occurred at west pier P187 (Figures 1 & 2) where the connections between the girder and the two pendulum tension supports, wind shoe, and two oil dampers were all severed. The large pendulum shoe plates (keeper plates) holding the pin in the upper eye of the pendulum were bent away from the pendulum as a result of transverse motions of the girder, and the bolts on the wind shoe and oil dampers failed in a combination of tension and shear at extremely large deformations. The tension in the cables lifted the end of the girder at P187 by approximately 0.5 m. On P187 there was shear-induced buckling in the cross-beams and compression buckling in one leg. Shear-induced buckling also occurred in the cross-beams of P186 and P182 and on some of the approach piers. The wind shoe at P182 was also damaged, as were earthquake restrainers on the approach span at P187.

Repair

Repairs to the pendulum supports required extensive work. The bent shoe plates were first cut from the girder, and the pendulum support arm was cut just below the upper eye (Figure 2). This was done to facilitate removal of the damaged part of the pendulum from the pier, as there was limited clearance between the pier top and girder, and also because the original field connection on the pendulum arm was near the lower eye. These parts, along with the 0.5 m diameter pins, were removed for shop inspection, repair and reassembly. The two pendulum supports at P187 were restored by lowering the girder using 130 tons of counterweight (trucks parked on the deck) and 8 x 100 ton jacks. The reassembled components were then reconnected to the pendulum arms using new bolted splices (Figure 2).

Wind shoes on P182 and P187 were temporarily repaired with new bolts increased in size and strength as much as possible. Cracking in one of the shoes was repaired with welding. The wind shoes were eventually replaced with new shoes designed for higher seismic force levels. The oil dampers at P187 were damaged beyond repair and were replaced with new ones of the same design.

Buckling in the leg of P187 was repaired by welding T-shaped rib plate reinforcement on the outside surface of the leg, extending about 1 m on either side of the buckled area. Cover plates were installed over the rib reinforcement. Where major shear buckling had occurred in the pier cross-beams this was repaired by replacing the web steel. Repair of less minor shear buckling was done by heating the buckled plates and adding additional reinforcement. Finally, cable tensions were checked. The bridge was re-opened in April 1995.

ROKKO ISLAND BRIDGE

Description of Bridge and Damage

The Rokko Island Bridge (Figure 3), completed in 1992, is a 217 m double-deck steel arch bridge with a width varying from 16.3 m (Kobe City side) to 26.7 m (Rokko Island side). The weight of the arch span was 9,200 tons.

The Rokko Island end of the arch at P214 was displaced transversely (to the east) by 3.1 m (Figure 4) destroying the bearings at this end of the bridge. This left the south end of the east arch unsupported by the pier. The north end pier P213 was twisted as a result of this lateral displacement. The approach spans were dragged eastward by the displacement of the arch and contacted the upper deck columns on the approach pier. Buckling occurred in the upper lateral bracing between the two arch ribs. Shear-induced buckling was observed in the cross beams of several approach piers and on

P214, similar to that observed on the Higashi-Kobe Bridge. There were also failures of the earthquake restrainers and expansion joints at P214 due to the large transverse displacement of the end of the arch span. Large ground settlements were observed around the south approach piers due to movement of the quay walls.

Repair

To realign the arch span, the south double deck approach spans between P214 and P215 were temporarily removed (Figure 3). There was not sufficient vertical clearance under the cross-beam to lift the end of the span with jacks, and so two floating cranes were used; a 4,100 ton crane lifting at the damaged end, and a 3,500 ton crane lifting at the centre (Figure 4). These cranes were used for lifting only. Transverse realignment was completed using a system of 200 ton jacks and tendons on top of P214, jacking against the bearing supports and pulling on the ends of the arch ribs (Figure 4). New bearings of the same design as the originals were installed. Lateral stoppers were added to the bearing mounts, a modification to the original design. The upper and lower cross-beams were repaired as well as the top lateral bracing. After all this work was completed the approach spans were re-erected. The bridge was re-opened in October 1995.

NISHINOMIYA PORT BRIDGE

Description of Bridge and Damage

The Nishinomiya Port Bridge (Figure 5) is a 252 m cable arch bridge with a single level steel deck with width that varies from 27.3 m to 31.2 m. The total weight of the arch span was 12,000 tons. The approach spans immediately to the east, between P97 and P99 were simply supported box girders composite with a concrete deck. All other approach spans were continuous construction. The bridge was completed in 1993.

At the west (Kobe) end of the bridge at P100 the cast bearings supporting the arch span were fractured (Figure 5). At the east end, the 52 m approach span slipped off its bearings at P99 and collapsed. This was caused by the main arch span being pulled westward at the same time as the east arch pier rotated about its base as a result of liquefaction and lateral-spreading induced deformations at the base of the pier immediately adjacent to the quay walls along the port entrance channel. This resulted in 17 cm of permanent movement of the top of P99 towards the channel (west). Two single-bolt restrainers were provided at P99 between each of the three approach box-girders and the cross-beam of the arch span. However, the restrainer connecting plates tore out and there was insufficient seat width to accommodate the displacement at the top of P99. In addition to Bruneau, Wilson and Tremblay (1996), detailed descriptions of the damage and damage mechanisms are also given by Ministry of Construction (1995).

Repair

Repair of this structure required work on both the arch span and the eastern approach span. Nishinomiya Port Channel is a busy navigation passage and work that required obstructing this channel was done at night. This included used of floating cranes positioned in the channel to access the collapsed approach span on the east side.

At P100, six 1,200 ton jacks were used to temporarily stabilize the end of the span while the damaged bearing assembly was replaced. Fabrication of a new bearing took approximately 2-1/2 months, a time shorter than usual because the company still had the mold from production of the original bearing. Tensions in all the cables were also checked.

Replacement of the collapsed approach span was more problematic. The span was too heavy (1,900 tons) to be lifted out in one piece by floating cranes. Consequently, the concrete deck was cut into blocks weighing approximately 200 tons and removed. After the deck had been removed each of the three steel box girders were removed in one piece by a 3,600 ton floating crane. The new span was shop-constructed as a steel deck box girder span to minimize lifting weight. This was placed in a single lift using Japan's largest floating crane having a 4,100 ton capacity (Figure 5). As part of the repair, the seat width on P99 for the approach span was increased from 110 cm to 170 cm. Seismic restrainers of the same bolted slotted plate design as the originals were used again to connect each box girder (two restrainers per girder) to the arch span. The bridge was re-opened in April 1995.

LESSONS FROM THE REPAIR PROCESS

The repair processes used on three large modern steel bridges have been described. Some of the lessons that have come out of this experience include:

1. In all three bridges there was severe damage to the bridge bearings (or girder-to-pier connections).
2. Because of the severe damage to bearings/connections much of the repair work had to be done in restricted work space that limited the options and equipment that could be used.
3. The availability of heavy lift cranes (up to 4,100 tons capacity) was key to the repair process in two of the three bridges.
4. Multiple jacks of various capacities (100 tons to 1,200 tons) were used to both stabilize damaged bearings, and to assist in realignment of the bridges.
5. Bearings for large bridges are specialty items and the time to fabricate new bearings can be a critical element in returning a bridge to complete service.
6. Two of the bridges were returned to service three months of the earthquake, and the third bridge was opened after nine months. This was accomplished at a time when there were severe demands on all resources to cope with the effects of the earthquake in other areas of Kobe.

CONCLUSIONS

The 1995 Hyogoken-Nanbu earthquake was the world's first experience with a large earthquake that caused damage to new long-span steel bridges. Descriptions of the methods used to repair the bridges, the equipment necessary for the repairs, and the time frames of putting the bridges back into service, all serve as useful lessons in preparing for and coping with post-earthquake repair of moderately damaged long-span bridges.

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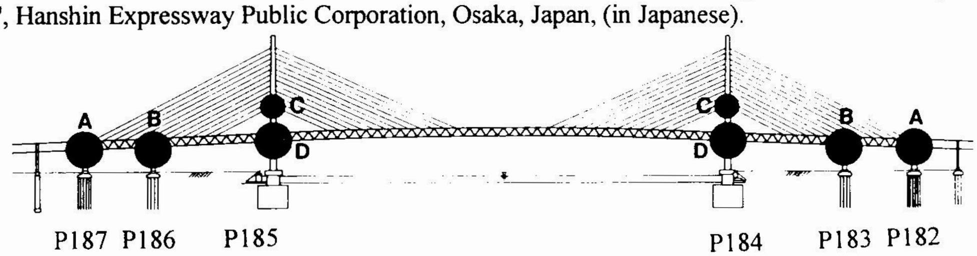
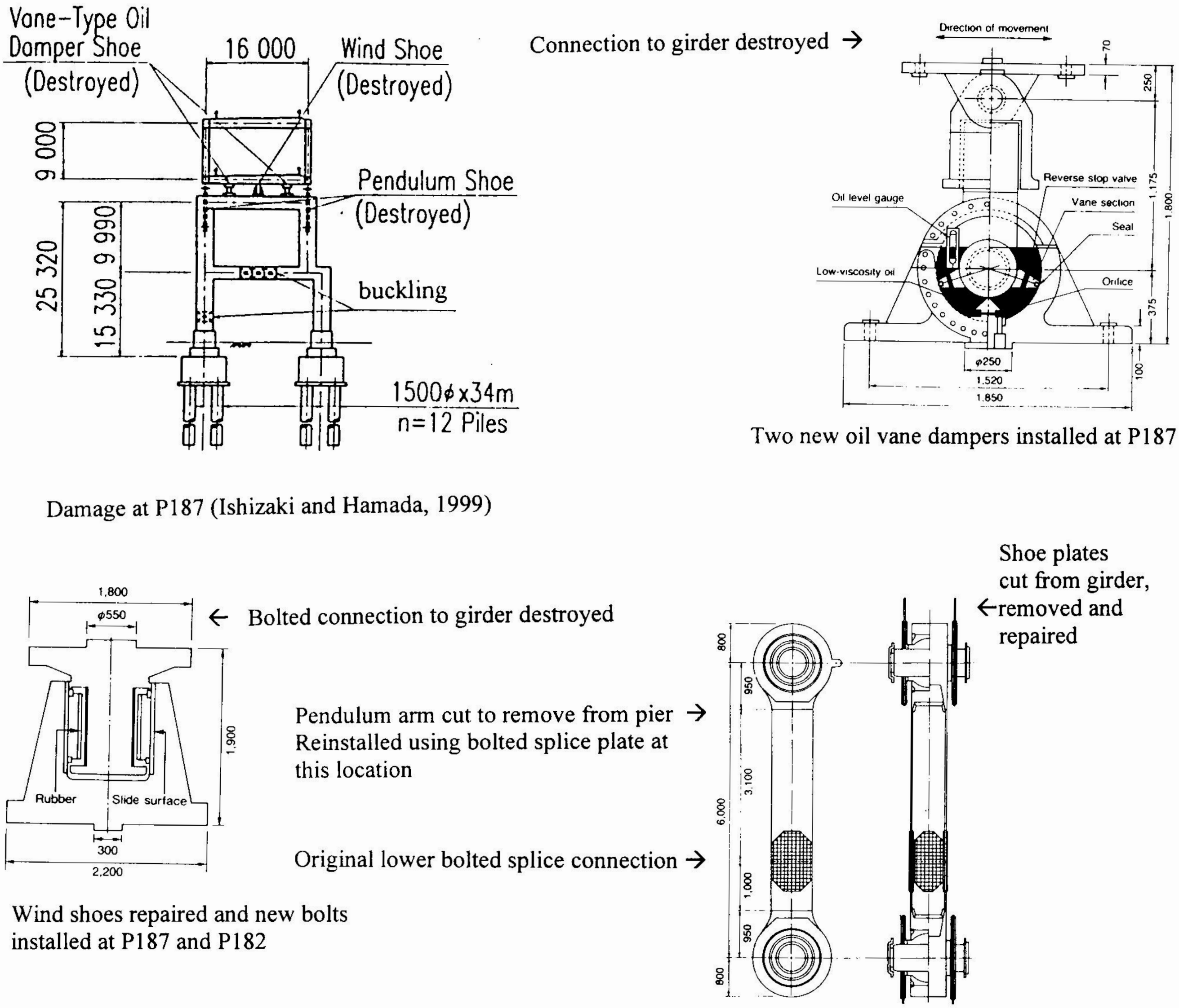


Figure 1 The Higashi Kobe Bridge (200 + 485 + 200 m spans): pendulum supports at A,B; wind shoes at A,B,D; oil vane dampers at A (Hanshin Expressway Public Corporation).



Damage at P187 (Ishizaki and Hamada, 1999)

Two new oil vane dampers installed at P187

Wind shoes repaired and new bolts installed at P187 and P182

Repairs to pendulum supports at P187

Figure 2 Damage and repairs to Higashi Kobe Bridge at P187 (Ishizaki and Hamada, 1999; Hanshin Expressway Public Corporation)

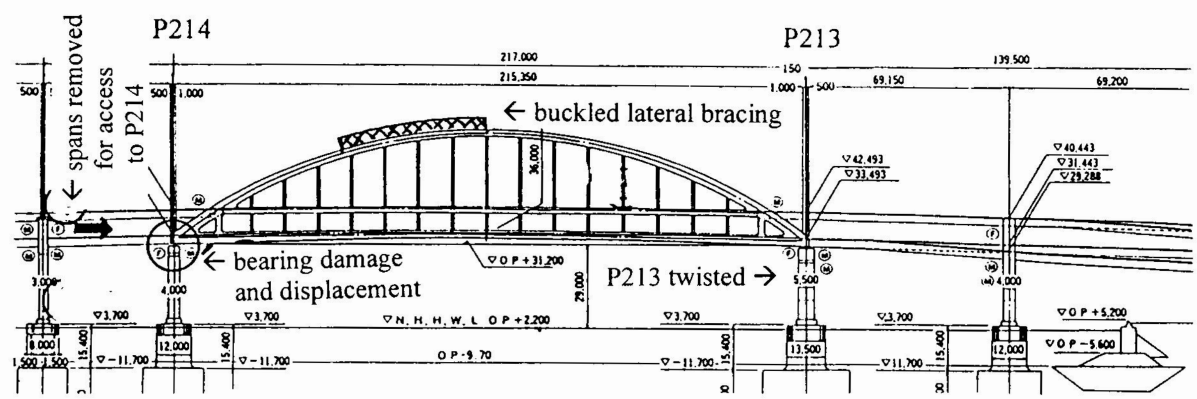
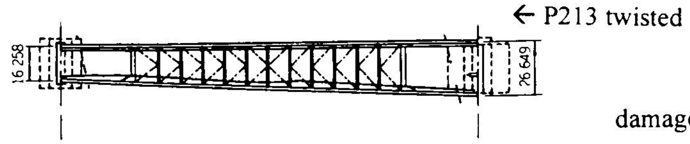
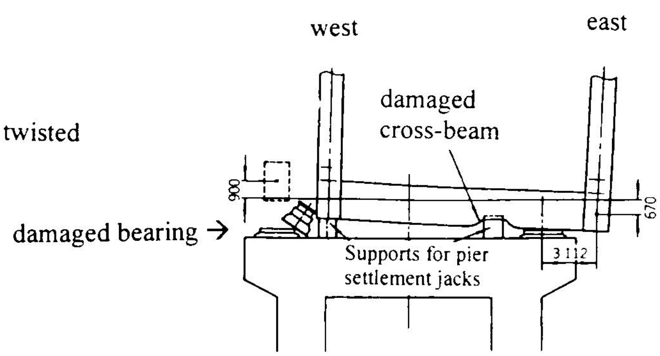


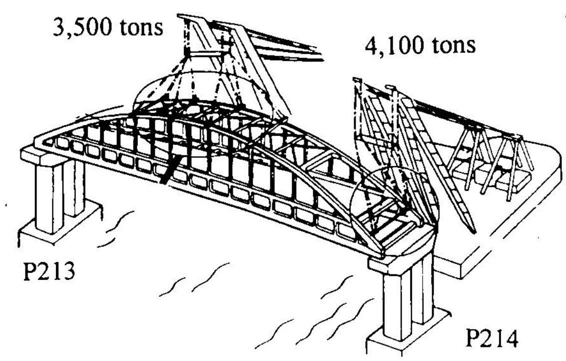
Figure 3 The Rokko Island Bridge (Ishizaki and Hamada, 1999)



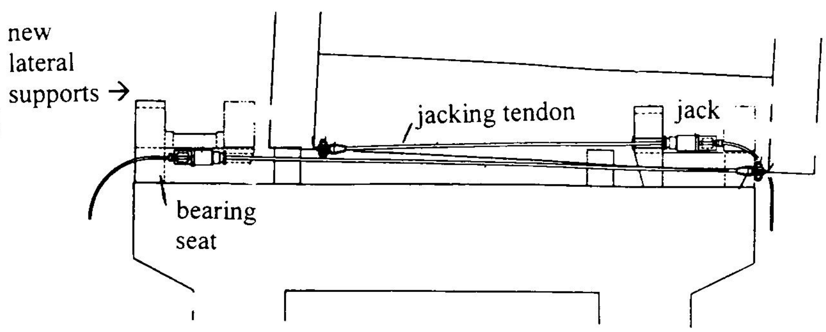
Plan view of Rokko Island Bridge



3.1 m eastward displacement of arch at P214

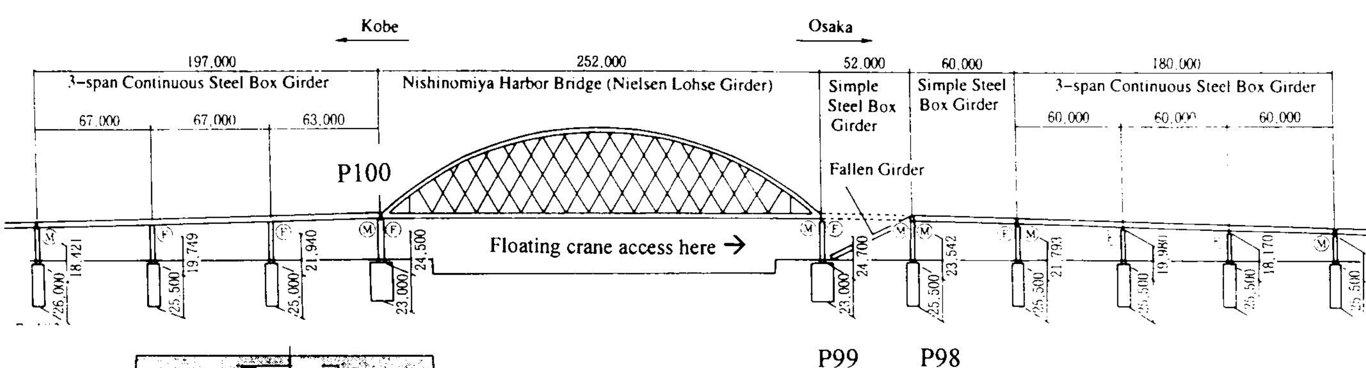


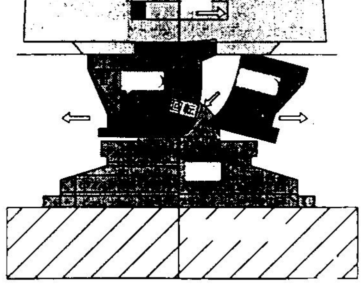
Lifting with two floating cranes



Jack arrangement for arch realignment at P214
(view with approach spans removed)

Figure 4 Damage and repairs to the Rokko Island Bridge (Yonekura et al., 1996)





Fractured bearing at P100

Figure 5 The Nishinomiya Port Bridge (Ministry of Construction, 1995)