DAMAGE TO MEMBRANE ROOF SYSTEMS CAUSED BY THE 1995 HYOUGOKEN-NANBU EARTHQUAKE

KYOJI TANAKA
Tokyo Institute of Technology
Yokohama, Japan

ICHIRO SHIMIZU
Japan Testing Center for Construction Materials
Saitama, Japan

In 1995, the Hyougoken-Nanbu earthquake inflicted severe damage on numerous modern buildings. Ninety-five membrane roof systems on 92 buildings, most of which were still in service though slightly damaged by the earthquake, were investigated. The type and level of membrane damage and the damaged region in roofs were the primary targets of the investigation. Four common types of membrane damage were observed:

- The membranes on collapsed roof decks were completely torn or ruptured.
- Some membranes were ruptured at cracks or joints in decks by rapid extension-contraction movement induced by the earthquake.
- Stiff membranes, such as glass-fiber-reinforced unsaturated polyester resin membranes, were separated from the surfaces of parapets or penthouse walls.
- Some membranes were punctured by the falling, overturning, and sliding of service equipment on roof decks.

The relation between the damage to membranes and to building structures, including decks, will be discussed. Finally, the lessons from the membrane roof system damage caused by the earthquake will be described.

KEYWORDS

Damage, deck, earthquake, membrane, structure, substrate, survey.

INTRODUCTION

The Kyougoken-Nanbu earthquake hit Kobe, the western part of the Osaka metropolitan area, on January 17, 1995. The earthquake, which ranked 7.2 on the Richter magnitude scale, caused the most serious damage suffered by the area in the past half century. The authors did not know of any previous damage to membrane roof systems caused by earthquakes. However, they thought such damage may have occurred with this earthquake because many buildings and houses, including modern buildings, had collapsed, and they realized that they could learn from the earthquake damage. Field surveys were started by members of the Architectural Institute of Japan's (AIJ's) committee on waterproofing systems and members of the Japan Polymeric Roofing Sheet Manufacturers Association (KRK is the Japanese abbreviation). This paper describes the membrane roof system damage observed in the surveys and discusses some lessons obtained from them.

OVERVIEW OF THE INVESTIGATION

Investigated Membrane Roof Systems

Waterproofing membranes are functional finishes designed to prevent the ingress of water. Therefore, it is insignificant that the investigation was extended to the membranes of buildings that were severely collapsed and may not have been able to be used again. The authors focused only on the membranes of buildings that were still used or those that would be used again. In the field surveys, 95 membrane roof systems on 92 buildings were investigated.

Investigation Procedure

Each membrane was visually inspected. Observed damages were recorded using the standard damage investigation sheet prepared by the reconnaissance team of the field surveys. Photographs were taken of membranes as a whole as well as close-ups of the damaged regions. The investigation sheet asked about the following items: type and damage level of building structure, deck, membrane roof system, and membrane, as well as the area of damage.

Details of Investigated Membranes, Structures, and Decks

Membrane roof system.

The membrane systems investigated during the field surveys are shown in Figure 1. If two or more membranes had been applied on a building, they were counted individually. Sheet-applied systems occupied more than half of the investigated roof systems, and the other systems were few. However, it should be noted that Figure 1 does not indicate the market share of each membrane system in this area, because limited membranes were investigated during the surveys.

Building structure

The types of structures are shown in Figure 2. Most of them were reinforced concrete frame structures and steel-encased reinforced concrete frame structures. Fourteen steel frame

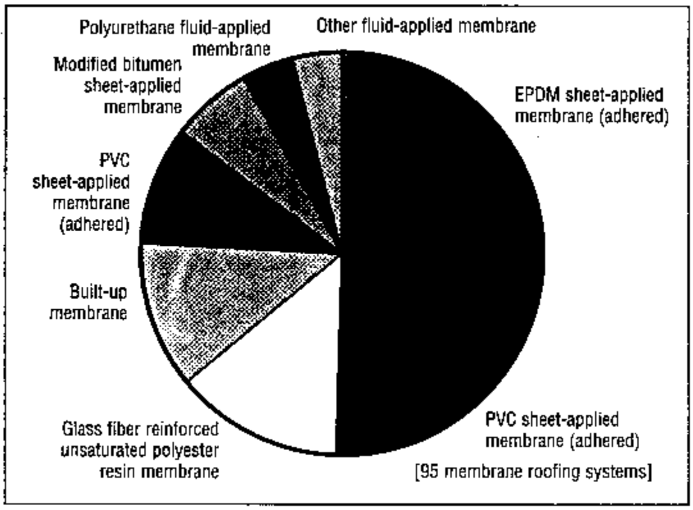


Figure 1. Investigated membrane roof systems.

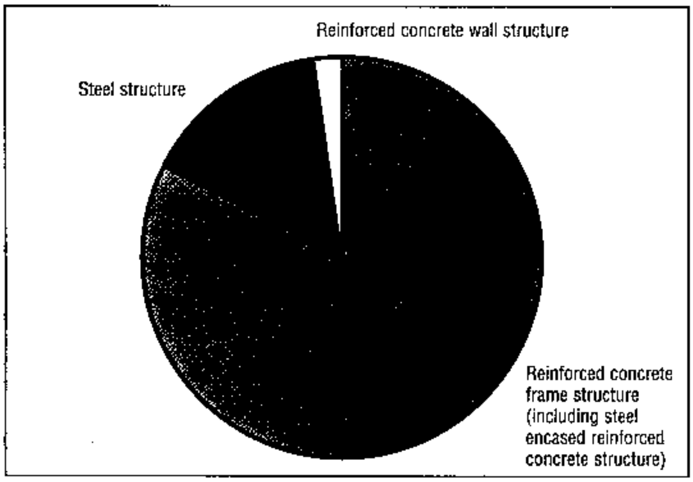


Figure 2. Investigated building structures.

structures and two reinforced concrete wall structures were investigated.

Deck

The types of decks beneath the investigated membranes are shown in Figure 3. Most of them were cast-in-place reinforced concrete decks, 12 were various kinds of precast panel decks, and six were concrete on corrugated steel sheet decks.

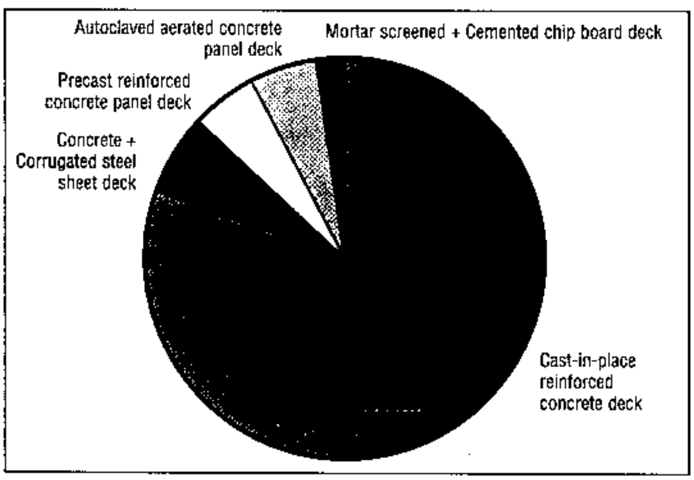


Figure 3. Investigated decks.

MEMBRANE DAMAGE

Rupture of Membrane Caused by Collapse of Deck

Some membranes were ruptured or torn by the collapse of decks. The damage level of these membranes was the most severe.

Photograph 1 shows the roof deck of a reinforced concrete apartment building with a L-shaped plan. The mechanically fastened PVC membrane was torn by the collapse of the deck at the corner of the L-shaped plan.

Photograph 2 shows the rise of a reinforced concrete stairway, which was fixed between two buildings. The glass-fiber-reinforced unsaturated polyester resin membrane coated on it was ruptured by the relative shear movement of the two buildings.

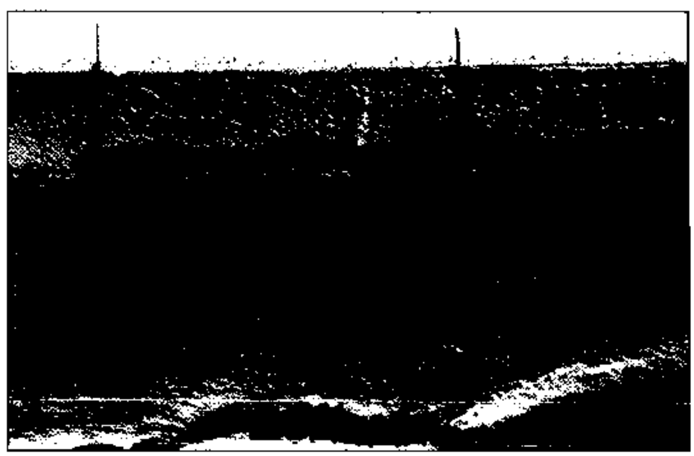
Rupture of Membrane at Crack or Joint

Membranes ruptured because of the movement of cracks, which occurred in screed mortar layers and reinforced concrete slabs, or the movement of joints between roof panels. The ruptures were caused by a larger amplitude of movement than the membranes were designed to handle and by the degradation of the membranes.

Photograph 3 depicts the rupture of a fluid-applied membrane on mortar screed on cement chip boards that were fixed on a steel structure. A long split occurred along the crack of mortar screed.

Photograph 4 shows a glass-fiber-reinforced unsaturated

Photograph 1.



Photograph 2.

Photograph 3.

Photograph 4.

Photograph 5.

polyester resin membrane that was split by the cracking of a reinforced concrete deck. Although the membrane had extremely high mechanical strength compared to the other membranes, it was not able to withstand severe movement.

Photograph 5 shows a PVC membrane adhered to autoclaved aerated concrete panels fixed to a steel structure; the membrane ruptured at the joint of substrate panels. The membrane had already lost flexibility, and the membrane degradation was considered to be an additional cause of the rupture.

Membrane Separation from Substrate

Some membranes separated from their substrate because of adhesive failure. Most of these damages were observed in glass-fiber-reinforced unsaturated polyester resin membranes on vertical surfaces of walls and parapets; vertical elements were severely deformed by the horizontal force induced by the earthquake.

Photograph 6 shows wrinkles that developed in a glass-fiber-reinforced unsaturated polyester resin membrane applied on the wall of a penthouse.

Photograph 7 depicts a glass-fiber-reinforced unsaturated polyester resin membrane that completely separated from the mounted wall of sliding doors. Opening was observed along the end of the membrane.

Rupture by the Falling, Overturning, and Sliding of Equipment

Service equipment is set or fixed on roof decks in many buildings. Some pieces of equipment damaged membranes because of their dynamic behavior induced by the earthquake.

Photograph 8 shows a piece of equipment that fell onto a PVC membrane and punctured it.

Photograph 9 shows a small base for a service pipe that slid and ruptured a polyurethane rubber fluid-applied membrane.

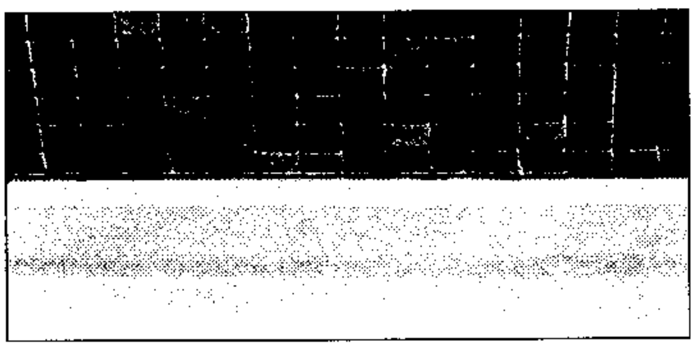
Photograph 10 shows a warehouse with a crane structure. The leaning of the crane tower lifted a stepstone to the tower, tearing off the EPDM sheet membrane covering the stepstone. The damage may have been avoided if the membrane had been laid beneath the stepstone.

Rupture of Membrane by Crack of Coping

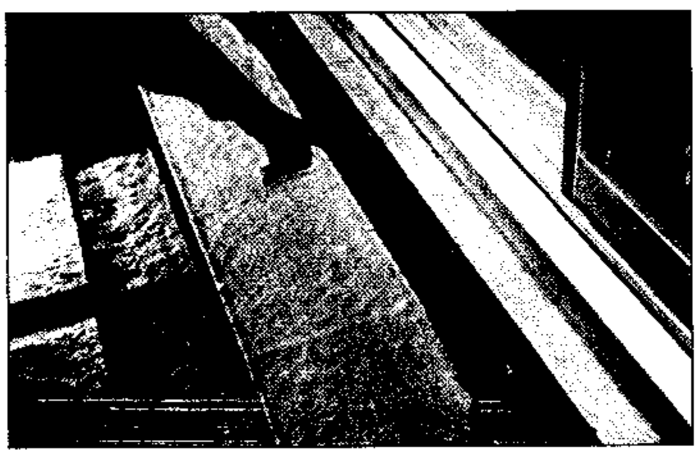
Thin fluid-applied membranes are often used on cement mortar copings to improve watertightness in repair or reroofing projects. These membrane were, however, easily ruptured by the movement of cracks of copings.

Photograph 11 shows a fluid-applied membrane coated on a cement mortar coping; the membrane ruptured at the corner of the coping.

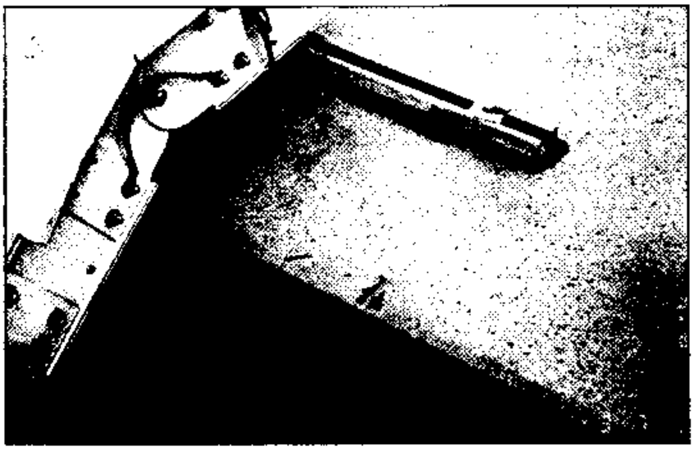
Photograph 12 depicts a fluid-applied membrane that also was ruptured by the crack at the upper surface of a cement mortar coping.



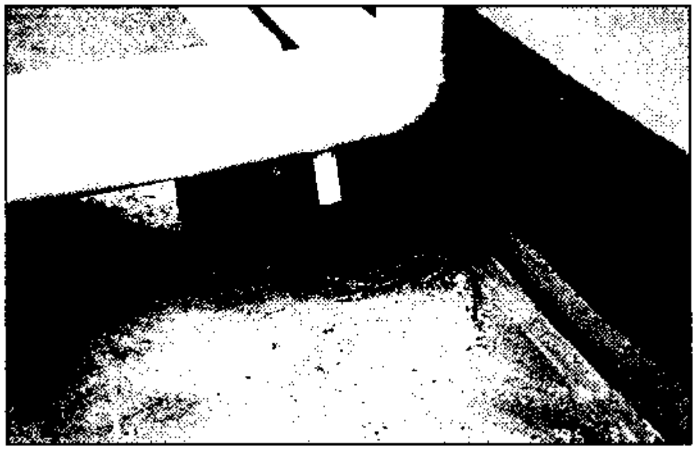
Photograph 6.



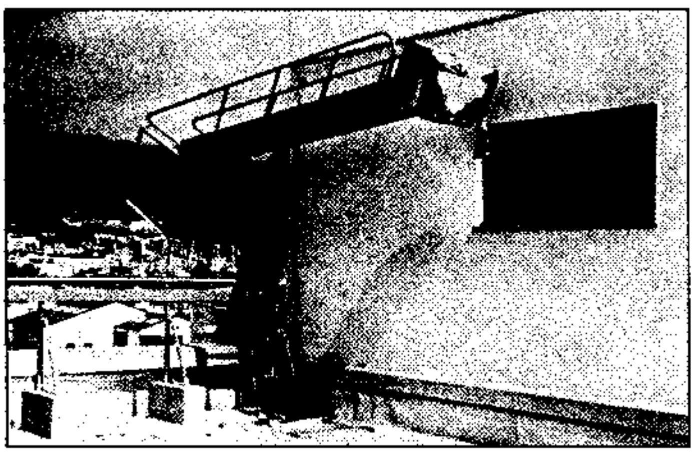
Photograph 7.



Photograph 8.



Photograph 9.

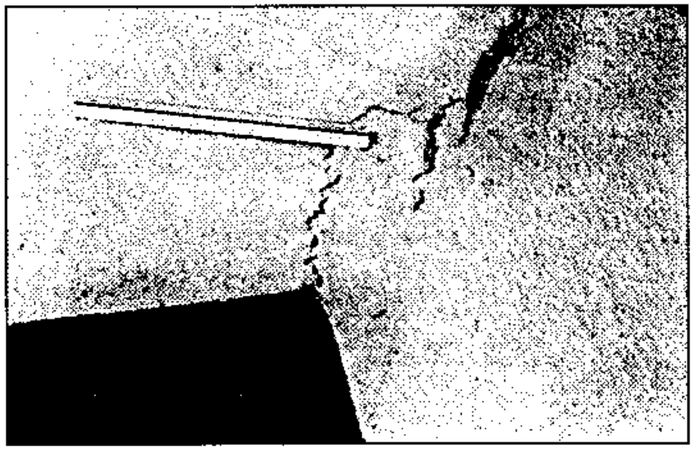


Photograph 10.

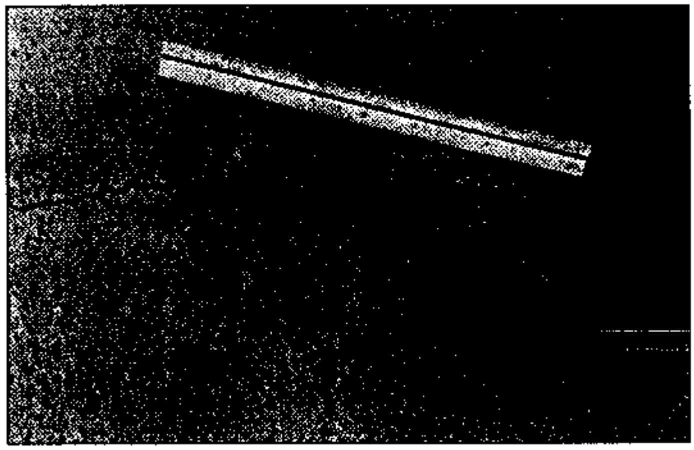
DISCUSSION

Relation Between Membrane Damage and Structural Damage

The upper portion of Figure 4 shows a number of damaged membranes sorted by the level of structural damage; the lower portion shows them as percentages. It is quite natural that the ratio of damaged membranes increases as structural damage level becomes more severe. However, there are many membranes that were not damaged, though their columns, beams, and walls were damaged. This is because the horizontal members, such as roof decks, were shaken as a whole during the earthquake in most buildings. The result was that the horizontal members were not severely deformed and ruptured compared to vertical elements.



Photograph 11.



Photograph 12.

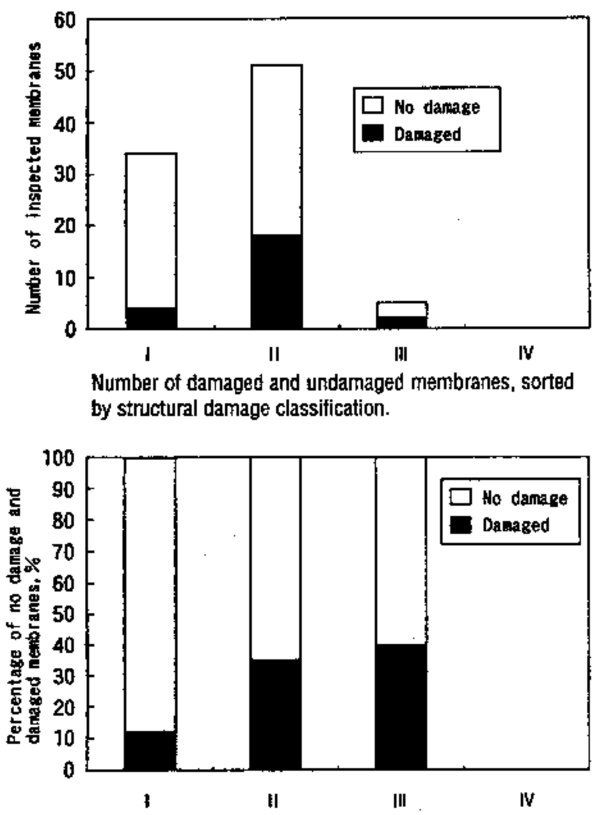
Type and Level of Damage of Membranes

Figure 5 shows the type and level of membrane damage. Severe damage was observed only in the membranes of collapsed decks. The possibility of a large joint movement, as occurred in the earthquake, was not taken into consideration during the design of the membrane roof systems. Therefore, the damage seemed quite reasonable considering the movement capability of the existing membrane roof systems. The earthquake clarified how limited current membrane roof systems are in terms of movement capability.

Type of Damage and Membrane Roof Systems

Table 1 shows the types of damage found in each type of membrane roof system. It does not have statistical meaning, because of the insufficient number of inspected membrane roofing systems. However, some conclusions can be drawn:

- The damage caused by joint movement in the substrate was observed for all types of waterproofing systems.
- All waterproofing systems seemed unable to withstand damage when the deck collapsed. As the table shows, damage was observed only for PVC sheet-applied membrane systems and glass-fiber-reinforced unsaturated polyester



Number of damaged and undamaged membranes, sorted by structural damage classification.

Percent of membrane damage, scored by structural damage classification

I. No structural damage. Architectural damage may be noticeable.
II. Minor structural damage, although the structure may have significant architectural damage.
III. Significant structural damage is visible. Permanent deformation between stories exists but with low possibility of collapse.
IV. A large portion of building frame is damaged, permanent deformation of the structure may cause imminent collapse.

Figure 4. Relation between damage of membrane and damage level of structure.

resin membrane systems. This is because they were mistakenly used for the collapsed decks.

- The separation from substrate was observed only for the glass-fiber-reinforced unsaturated polyester resin membrane systems. The rigid property of the membrane seemed to be the cause of adhesive failure between a membrane and a substrate; the membrane did not inherently follow the substrate deformation.
- The damage caused by the falling, overturning, or sliding of equipment was observed only for EPDM sheet-applied and PVC sheet-applied systems. These systems were damaged because they were not tough enough to withstand severe puncture or tear loads.
- The damage to cement mortar copings was observed only for thin fluid-applied systems. These systems are convenient for waterproofing cement mortar copings; unfortunately, thin membranes were not able to withstand to movement of cracks of cement mortar copings.
- There is a correlation between membrane damage and the type of structural system or deck.

Figure 6 shows the number of membrane failures for each type of structure and deck. The number of membrane damages is prominent in reinforced concrete frame structures, because more than 80 percent of the inspected membranes were applied to these structures. However, the ratio to total number of damages is reduced to about 0.3, because there are a lot of the structures that had undamaged membranes.

As for decks, damaged membranes were also prominent in cast-in-place reinforced concrete decks. However, the ratio to total number of damages also was not very high. The higher ratio is shown for precast panel decks, such as an autoclaved aerated concrete panel and a cement board, particularly in steel frame structures.

Although it could not be proven statistically, it seemed that the combination of precast panel decks fixed to a steel frame structure suffered damage more severe than any other combination of deck and structure.

CONCLUSIONS

Importance of design

It was discovered that membrane damage often resulted from not meeting the fundamental requirements for membrane waterproofing system design, such as an unsuited

Membranes	Causes of damages				
	Collapse of deck	Movement of crack or joint in substrate	Separation from substrate	Falling, over-turning or sliding of equipment	Movement of crack in copying
Built-up		✓			
Modified bitumen sheet-applied		✓			
EPDM sheet-applied (adhered)		✓			
PVC sheet-applied (mechanically fastened)	✓	✓		✓	
PVC sheet-applied (adhered)	✓	✓			
Polyurethane fluid-applied		✓		✓	✓
Glass fiber reinforced unsaturated polyester resin	✓	✓	✓		✓

Table 1. Membranes and causes of damages.

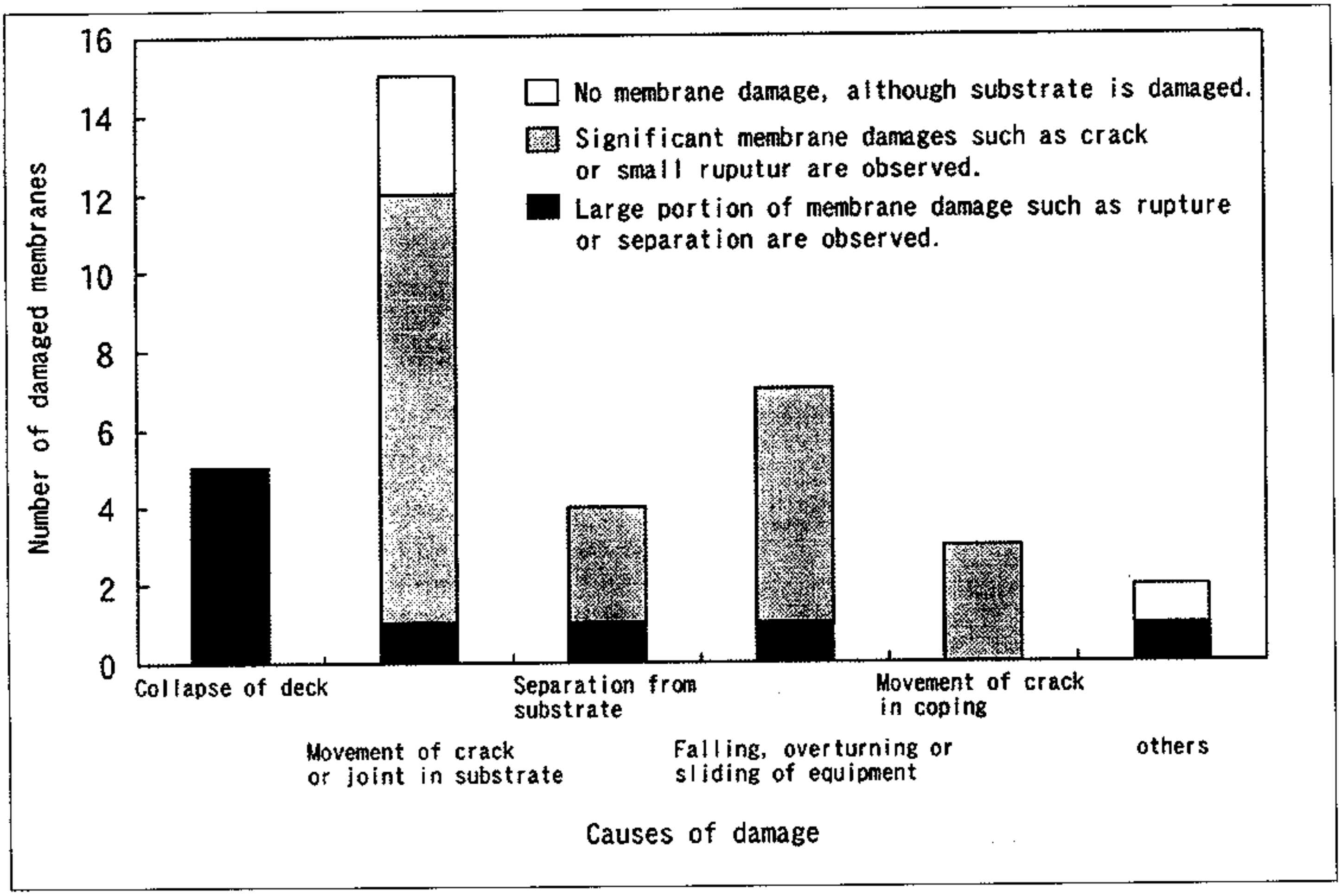


Figure 5. Type and level of damages of membranes.

selection of materials and improper details. It is not easy in practice, particularly in repairing or reroofing projects, to design as textbooks or standard specifications describe. However, there are many damaged membranes that would not have ruptured if they had satisfied basic requirements. The importance of designing a membrane roof system that is truly suited for a given structure and deck should be recognized.

Necessity of Considering Repair or Reroofing when Designing Waterproofing Systems

After studying repairs and reroofed membranes, the authors concluded that design limitations imposed by existing waterproofing systems seemed to have prevented the replacement membrane systems from being designed well. It is necessary to consider future repair and reroofing projects when an original membrane system is being designed.

Cooperation with a Structural Engineer

Most severe membrane damage fell in an area between the scope of responsibility of waterproofing engineers and that of structural engineers. There are some membranes that may have avoided damages if a waterproofing engineer had been knowledgeable about the structural behavior of buildings in earthquakes. For the limited buildings that are expected to have severe and complex behavior in an earthquake, it is necessary to design membrane roof systems in partnership with a structural engineer.

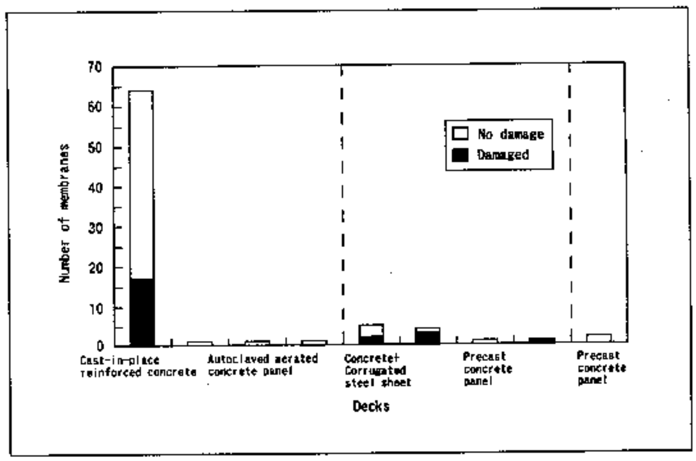


Figure 6. Number of damaged membranes in each type of structure and deck.

ACKNOWLEDGMENT

The investigations were carried out by the members of the AIJ and KRK. The authors would like to express great appreciation to those all who contributed to the surveys, particularly to Mr. Takatsugu Iwai, Mr. Tadashi Ono, and Mr. Takashi Mochizuki for their helpful discussion.