SHAKING TABLE TEST ON SEISMIC BEHAVIOR OF TOMBSTONE WITH AND WITHOUT REINFORCEMENT

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ABSTRACT:

Recently, many types of reinforcement have been developed to prevent tombstone from overturning. 3-dimensional shaking table tests of full-scale tombstone models were conducted to investigate the seismic behavior and overturning mechanism of the tombstones and the effect of reinforcement. Full scale Japanese-type and European-type tombstone models without any reinforcement and tombstones with bonding, adhesive and interlocking reinforcement were tested. Effectiveness of reinforcement measures was discussed based on the pictures and acceleration measurements. The conclusions obtained from the experiment are summarized as follows, 1) The main reason for damage of Japanese-type tombstones without reinforcement during the earthquake is overturning by rocking vibration, 2) The main reason for damage of European-type tombstones without reinforcement during the earthquake is dropping from base stone caused by large displacement of sliding, 3) Japanese-type tombstones were overturned by strong motion in compliance with JMA seismic intensity of 6+. European-type tombstones were overturned by strong motion in compliance with JMA seismic intensity of 7, 4) Reinforcement measures by gluing, adhesion or interlocking of tombstones are effective for mitigating the seismic disaster to tombstones.

KEYWORDS: tombstone, shaking table test, overturning, reinforcement, strong motion

1. INTRODUCTION

In Japan, tombstones are prone to be overturned easily because they have a simple structure of being only piled up without any reinforcement. During the 1995 Hyogoken-Nambu Earthquake, many tombstones were overturned and damaged. After the earthquake, because of the increase of the awareness for disaster mitigation, various kinds of reinforcement measures for preventing from overturning of tombstone have been developed and applied in practice, such as gluing with a bonding agent between tombstones, adhesion with an adhesive agent, interlocking with steel bars in the holes of tombstones. However, there remain many un-reinforced tombstones, mainly built before the 1995 Hyogoken-Nambu Earthquake. Dynamic behavior of a tombstone during an earthquake is very complicated; it is thought that the shaking table test on full-scale tombstone models is one of the reliable ways to study the dynamic behavior and effectiveness of seismic retrofitting measure for tombstones. In this research, three-dimensional shaking table tests on full scale tombstone models were conducted in order to investigate the behavior of tombstones during strong motion and the effect of reinforcement measure (Furukawa et al., 2006, 2008a, 2008b, Kiyono et al., 2007, Miwa et al., 2007). At first, Japanese type and Western type tombstone without reinforcement were tested to clarify the characteristics of normal tombstone with seismic intensity of 6-, 6+ and 7 in compliance with JMA Intensity scale. Next, tombstones with reinforcement by gluing, adhesion or interlocking with steel bar were tested to study the effectiveness of the reinforcement measures.

2. MODELS OF TOMBSTONES

2.1 Tombstone without reinforcement

2.1.1 Japanese type tombstones

Figure 1 shows the models of tombstone. Table 1 shows the size and mass for each part of the models. The type of tombstone used widely in Tokyo area was selected as the typical Japanese tombstone. The first, second, third and fourth stones from the top are known as "Saoishi", "Jodai", "Chudai" and "Shibadai", respectively. "Saoishi", "Jodai" and "Chudai" were installed in such a way the center of the gravity was in a straight line with a vertical axis of symmetry.

2.1.2 Western type tombstones

In this type of tombstone, the top stone is known as "Saoishi", followed by "Jodai" and bottom as "Shibadai" respectively. The stones were installed with a vertical axis of symmetry.

2.2 Tombstones with reinforcement by gluing and adhesion

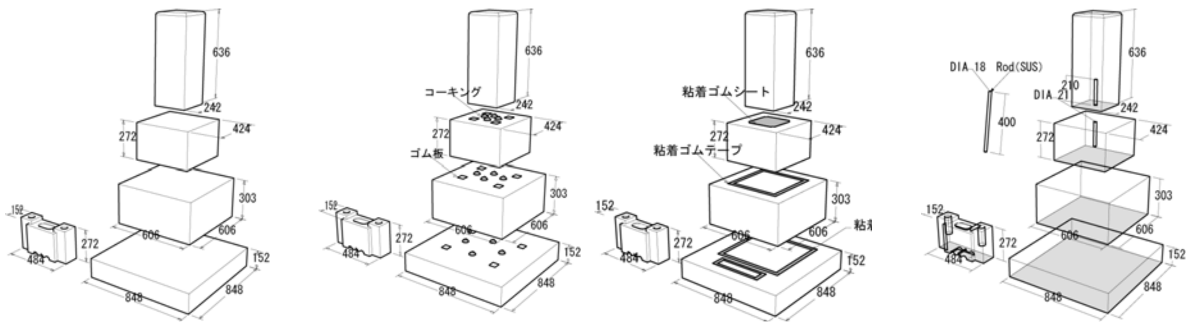
Both bonding agent and adhesive agent are commonly used for joining separated objects or materials. Bonding agent has low initial liquid viscosity.After joining, the liquid hardens gradually and yields high bonding strength. On the other hand, adhesive agent is a semi solid with initially high viscosity and low elasticity modulus. It's characteristics dose not change after joining. In other words, the process of hardening is not essential for adhesive agent.
Gluing measure is to join the stones by elastic bonding agent. This method is widely used as retrofitting measure for tombstones. Elastic bonding agent like denatured silicone has proper material strength comparing with the strength of stone. Adhesive measure is to join the stones by adhesive agent, like butyl gum with shock and energy absorption characteristics. It is to be mentioned that both measures have issues pertinent to degradation of joining agent (bonding agent or adhesive agent).

2.3 Tombstones with reinforcement by interlocking using steel bar

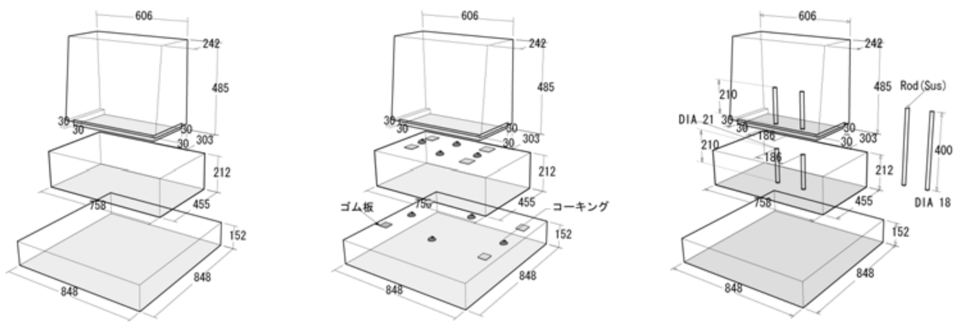
The interlocking reinforcement measure using steel bar is carried out by drilling holes at the bottom of the top stone "Saoishi" and at the surface of the second stone "Jodai", followed by inserting a steel bar, before joining the two stones with the steel bar. One steel bar is inserted without bonding with mortar or bonding agent. Moreover, there is no reinforcement between "Jodai" and "Chudai" as well as between "Chudai" and "Shibadai". The interlocking reinforcement measure has been widely used. The seismic behavior of three types of tombstones with different interlocking reinforcement measures, namely one with a long and thick steel bar, one with a short and thin steel bar, one with two short and thin steel bars, were compared. For Model 6, the diameter and depth of hole were 21 mm and 210 mm, respectively. Besides, the diameter and length of the steel bar were 18 mm and 400 mm, respectively . For Model 7 and Model 8, the diameter and depth of hole were 12 mm and 80 mm, respectively. Furthermore, the diameter and length of the steel bar were 10 mm and 150 mm, respectively. There were two steel bars in Model 8, and the distance between the two holes was approximately 115 mm. The locations of the holes for the steel bar on the bottom surface of 'Saoishi' are shown in Figure 2.

2.4 Input motion

In order to investigate the vibration characteristics of tombstones which have different natural frequencies, artificial strong motion in horizontal directions were simulated by using amplitude of the response spectra in compliance with the seismic design of highway bridges (Japan Road Association, 2002), which has flat amplitude in major frequencies, and phase characteristics of the earthquake record obtained by JMA Kobe during the 1995 Hyogoken-Nambu Earthquake. Besides, vertical motion was simulated by adopting the spectra data for evaluating earthquake reistance of communication equipments (NTT, 1998) and the phase characteristics of the earthquake record obtained by JMA Kobe during the 1995 Hyogoken-Nambu Earthquake. Acceleration response spectra and waveforms are shown in Figure 3. Strong motion in compliance with JMA Intensity 6-, 6+ and 7 were simulated by using these artificial strong motions, by multiplying with the same proportionality constant in three directions. Maximum values of these strong motions are shown in Table 2. These strong motions are known as "6-", "6+" and "7" hereafter in this paper.



a) Japanese type tombstone without reinforcement
b) Japanese type tombstone with reinforcement by gluing measure
c) Japanese type tombstone with reinforcement by adhesion measure
d) Japanese type tombstone with reinforcement by Interlocking using steel bar



e) Western type tombstone without reinforcement
e) Western type tombstone with reinforcement by gluing measure
f) Western type tombstone with reinforcement by Interlocking using steel bar

Figure 1 Tombstone models for Shaking table test

Table 1 Tombstone Models for Shaking Table Test (unit: mm)

Model	Type	Reinforced measure	Steel bar size	Steel bar number	Saoishi	Jodai	Chudai	Shibadai	Mizubachi
1	Japanese	No reinforcement	-	-	W242×D242×H636 Mass 108kg	W424×D424×H273 Mass 142kg	W606×D606×H303 Mass 322kg	W848×D848×H152 Mass 315kg	W484×D152×H272 Mass 46kg
2		Gluing	-	-					
3		Adhesion	-	-					
4		Interlocking	d18 L400	1					
5		Interlocking	d10 L150	1					
6		Interlocking	d10 L150	2					
7	Western	No reinforcement	-	-	W606×D303×H485 Mass 211.1kg	W758×D455×H212 Mass 197.8kg	-	W848×D848×H152 Mass 315kg	-
8		Gluing	-	-					
9		Interlocking	d18 L400	2					

(d: diameter, L: length, W: width, D: depth, H: height)

Figure 2 Location of the holes for the steel bar on the bottom surface of ‘Saoishi’

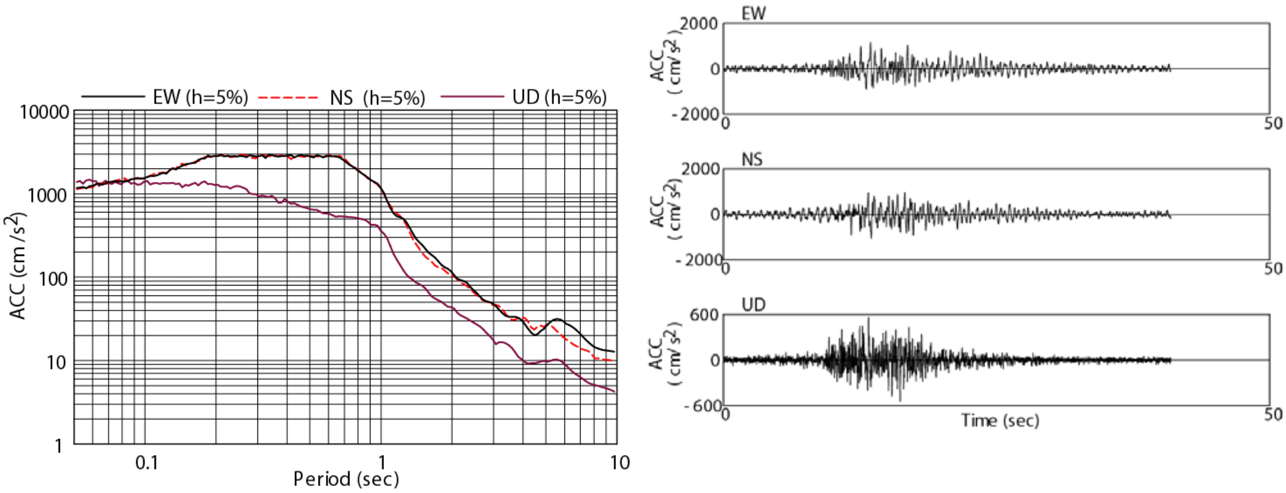


Figure 3 Acceleration response spectra and waveforms of Input motion for the test

Table 2 Maximum acceleration for each seismic intensity (m/s^2)

JMA Intensity	x	y	z
6-	5.53	4.84	2.79
6+	8.94	8.18	4.68
7	1.170	1.049	7.33

Table 3 Result of shaking table test

Model	Type	Reinforced measure	Steel bar size	Steel bar number	6-	6+	7
1	Japanese	No reinforcement	-	-	B	D	D
2		Gluing	-	-	A	A	A
3		Adhesion	-	-	A	A	A
4		Interlocking	d18 L400	1	B	B	E
5		Interlocking	d10 L150	1	B	C	E
6		Interlocking	d10 L150	2	B	C	E
7	Western	No reinforcement	-	-	B	B	D
8		Gluing	-	-	A	A	A
9		Interlocking	d18 L400	2	B	B	B

A: No Damage, B: Displaced, C: Displaced, “Mizubachi” was overturned,
D: “Saoishi” was overturned or dropped, E: ”Saoishi” was overturned with “Jodai”

3. RESULTS OF SHAKING TABLE TESTS

3.1 Summary

The behaviors of tombstones were recorded in the form of animations by digital cameras. Table 3 shows the results of the shaking table test. Model 1, with no reinforcement, slid during "6-", and overturned during "6+". The models reinforced with gluing agent or adhesion agent did not overturn even at "7". The model reinforced with interlocking measure restrained from overturning during "6+", but the top stone "Saoishi" and the second stone "Jodai" were overturned as one unit during "7".

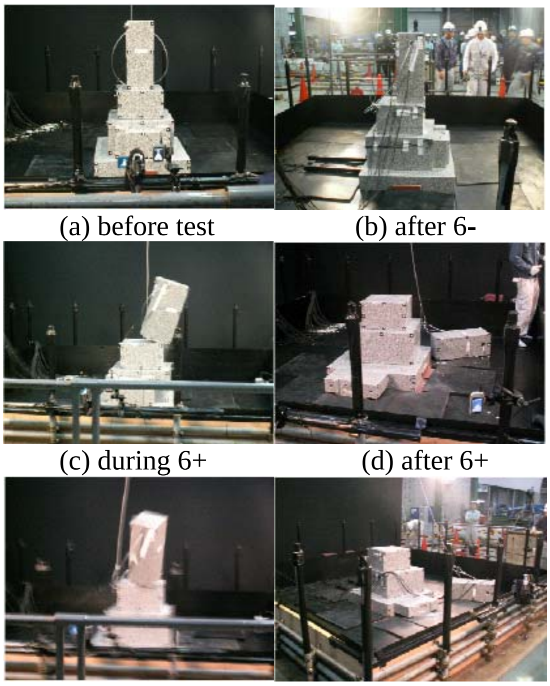
3.2 Behaviors of tombstone during strong motion

3.2.1 Japanese type tombstone without reinforcement

Figure 4 shows the condition of the Japanese type tombstone model without reinforcement during the shaking table tests. Typical behavior during "6-" was rocking of "Saoishi" and displacements in association with rocking. "Saoishi" was not overturned, but was displaced to the edge of "Jodai". "Jodai" and "chudai" were found rotated slightly. During "6+", "Saoishi" was rocked hard, and was displaced to the edge of "Jodai". The model was finally overturned after 22 second from the start of shaking. During "7", "Saoishi" was rocked very intensely and was overturned after 21 second from the start of shaking. For this model, the rocking of "Saoishi", which has high height to width ratio, was predominant. As a result, the rocking caused overturning of the stone.

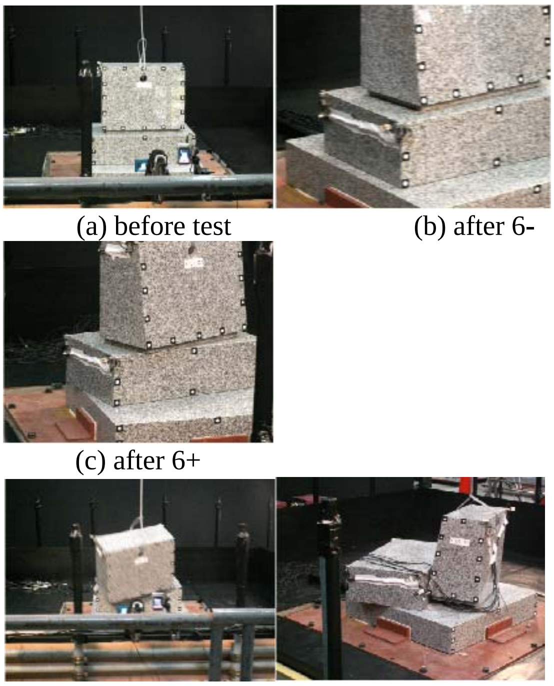
3.2.2 Western type tombstone without reinforcement

Figure 5 shows the condition of the Western type tombstone model without reinforcement during the shaking table tests. "Saoishi" and "Jodai" rotated in horizontal plane during '6-'. The stones rotated largely during "6+". "Saoishi" slid and dropped after 26 second from the start of shaking. As for the Western type tombstone without reinforcement, typical behavior was observed in the form of large movements of "Saoishi" by slide, which eventually caused dropping. Because the height to width ratio of the Western type tombstone was smaller than that of the Japanese type tombstone, rocking was not predominant and did not result in overturning of this type of tombstone.



(a) before test (b) after 6-
(c) during 6+ (d) after 6+
(e) during 7 (15senonds) (f) after 7

Figure 4 Test results of Japanese type tombstones without reinforcement



(a) before test (b) after 6-
(c) after 6+
(d) during 7 (25second) (e) after 7

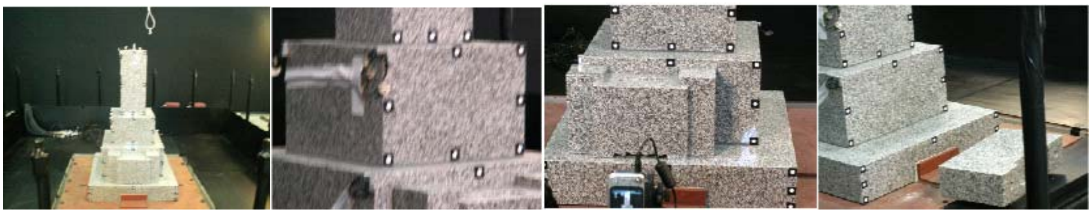
Figure 5 Test results of Western type tombstones without reinforcement

3.2.3 Gluing measure

Figure 6 shows the condition of the tombstone models with reinforcement by gluing during the shaking table tests. Gluing measure exhibited its effect on the seismic behaviors of tombstone models. For the Japanese type tombstone models, movement did not occur even at '7', although the side stone, known as "Mizubachi" moved or was overturned because there was no bonding applied. As for the Western type tombstone models, movement was not observed even at "7"for all parts. This confirmed the effectiveness of the gluing measure.

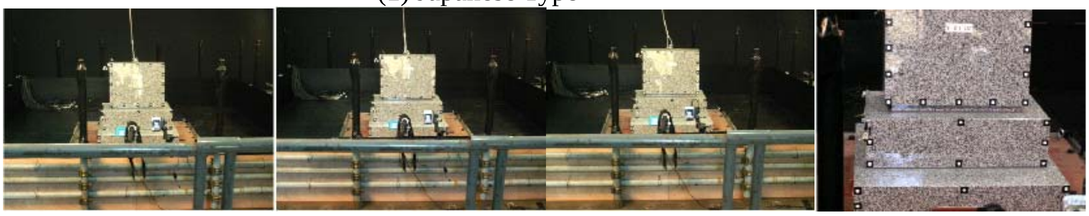
3.2.4 Adhesive measure

Figure 7 shows the condition of the tombstone model with reinforcement by adhesion during the shaking table tests. Adhesive measure also yielded effect its effect on the seismic behaviors of the tombstone models. Tombstone parts including "Mizubachi", which was adhered in this case, did not recorded any movement even at "7",



(a) before test (b) after 6- (c) after 6+ (d) after 7

(1) Japanese Type



(a) before test (b) after 6- (c) after 6+ (d) after 7

(2) Western Type

Figure 6 Test results of tombstones with reinforcement by gluing

(a) before test (b) after 6- (c) after 6+ (d) after 7

Figure 7 Test results of tombstones with reinforcement by adhesion

3.2.5 Interlocking measure using steel bar (Japanese type tombstone models)

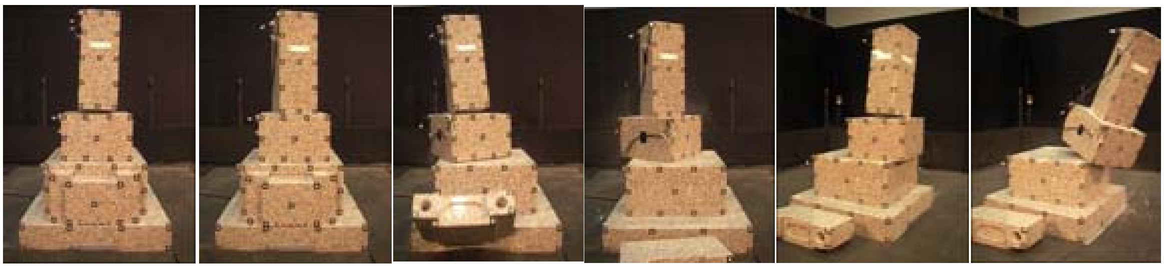
Figure 8 shows the condition of the Japanese type tombstone model with reinforcement by interlocking measure using steel bar during the shaking table tests. Steel bar was used for joining "Saoishi" and "Jodai" in order to prevent rocking, sliding and overturning of "Saoishi". Through joining, the two stones moved as one unit, and therefore, the center of gravity became lower than the case in which "Saoishi" was able to move independently. Rocking was prevented by low center of gravity. Large friction was expected because of the increase in weight by joining the two stones,. Moreover, it was also expected that this kind of joint is able to prevent sliding. However, this joint was found not effcective at "7". During "7", "Saoishi" interlocked with "Jodai" by a steel bar

was overturned as a unit. This suggested the necessity to reinforce between "Jodai" and "Chudai", and between "Chudai" and "Shibadai" at the same time.
It was found that steel bars with a larger diameter and a longer length as in Model 6 restrained rotational movement, which did not happen for steel bars with a smaller diameter and a shorter length. Relative movement between "Saoishi" and "Jodai" was predominant in Models 7 and 8, both of which small steel bars were used. Relative movement should be reduced because such a motion causes a more considerable damageto the tombstones. It is reckoned that steel bars of large diameters and long lengths, e.g. that used in Model 6, should be used for this reinforced measure, concerning the simplicity in execution.

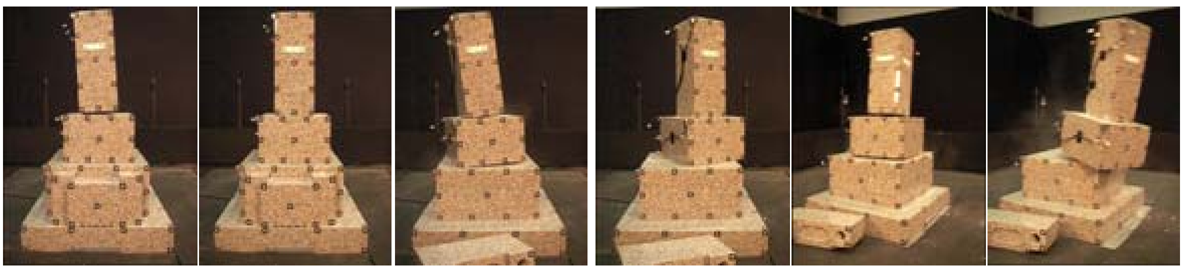
3.2.6 Interlocking measure using steel bar (Western type tombstone models)

Figure 9 shows the condition of the Western type tombstone model with reinforcement by interlocking measure using steel bar during the shaking table tests. "Saoisi" interlocked with "Jodai" by using a steel bar slid on "Shibadai" during all seismic intensities. During "7", "Saoisi" and "Jodai" moved as one unit to the edge of "Shibadai". It is supposed that these stones would be overturned in the same way as the Japanese type tombstone models, if the duration of strong motion becomes slightly longer or the intensity of the motion becomes slightly larger. Therefore, it is necessary to apply reinforce measure between "Jodai" and "Shibadai".

(a) during 6- (b) after 6- (c) during 6+ (d) after 6+ (e) during 7 (f) after 7
(1) Model 4 (1 long steel bar)



(a) during 6- (b) after 6- (c) during 6+ (d) after 6+ (e) during 7 (f) after 7
(2) Model 5 (1 short steel bar)



(a) during 6- (b) after 6- (c) during 6+ (d) after 6+ (e) during 7 (f) after 7
(3) Model 5 (2 short steel bar)

Figure 8 Test results of Interlocking measure using steel bar (Japanese type tombstone models)

(a) before test (b) after 6- (c) after 6+ (d) after 7

Figure 9 Test results of Interlocking measure using steel bar (Western type tombstone models)

4. CONCLUSIONS

The conclusions obtained from this research are summarized as follows:
1) The main reason for damage of Japanese type tombstones without reinforcement during the earthquake is overturning of "Saoishi" by rocking vibration.
2) The main reason for damage of European type tombstones without reinforcement during the earthquake is dropping from base stone caused by large displacement of sliding.
3) Japanese type tombstones were overturned by strong motion in compliance with JMA seismic intensity of 6+. European type tombstones were overturned by strong motion in compliance with JMA seismic intensity of 7.
4) Reinforcement measures by gluing, adhesion of tombstones are effective for mitigating the seismic disaster to tombstones. Both gluing and adhesion measures have issues pertaining to degradation of joining agent.
5) Interlocking measure using steel bars is effective for strong motion up to '6+'. However, "Saoishi" interlocked with "Jodai" by a steel bar was overturned as one unit during '7'. It is therefore necessary to reinforce between "Jodai" and "Chudai", and between "Chudai" and "Shibadai" at the same time.
6) It is reckoned that steel bars with larger diameters and longer lengths like that applied in Model 6 should be used for this reinforced measure, concerning the simplicity in execution.

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