STRUCTURAL PERFORMANCE OF DETERIORATED HISTORICAL RC BUILDINGS AT GUNKANJIMA-ISLAND

K. Kabayama[1]

[1] Shibaura Institute of Technology, Tokyo, Japan, kaba@sic.shibaura-it.ac.jp

Abstract: *The industrial remains on Gunkanjima (officially called Hashima) in Nagasaki City, Japan were registered as a World Cultural Heritage in 2015. Most of buildings remaining on the island are RC structures. They are deteriorating with the passage of time, and it is necessary to take measures to preserve them as cultural assets. Therefore, a survey was conducted on the structural performance of abandoned and deteriorated RC buildings.*

The deterioration grade of each structural member (columns, seismic walls and beams) was investigated for the major buildings on the island in order to evaluate the structural performance considering deterioration. Trained investigators visually judged the deterioration grade (six levels from 0 to 5) of each member. The deterioration grade of the members was aggregated in each floor of the building, and the R_L *value (the remaining ratio of axial force holding capacity) and the* R_E *value (the remaining ratio of seismic capacity) were calculated as indicators of structural performance considering deterioration. It was confirmed that the* R_L *and* R_E *values fluctuate according to the age and location of buildings*

The Building No. 3 is a four-story RC housing complex built on a hill in the centre of the island in 1959. The authors conduct a survey of the building every year from 2015 for follow-up observation. As of 2022, the R_L *value of the building remained above 95%, while the minimum* R_E *value was around 70%. It was revealed that the deterioration of beams progressed more markedly than that of columns and seismic walls, especially on high floors.*

The structural performance is declining due to the gradual deterioration of the structural members in RC buildings on Gunkanjima. The effective measures such as repair and retrofitting are urgently required in order to preserve those historically and culturally valuable buildings.

1. Preface

The industrial remains of Gunkanjima (officially called Hashima) in Nagasaki City, Japan were registered as a component of the World Cultural Heritage "Sites of Japan's Meiji Industrial Revolution: Iron and Steel, Shipbuilding and Coal Mining" in July 2015. In order to maintain the unique atmosphere and scenery of this island, it is necessary to conserve the buildings that remain on the island. Figure 1 shows a silhouette of Gunkanjima's appearance taken from the sea. In Japanese, "Gunkan" means battleship, and "jima" means island. As shown in the figure, the island looks like a battleship, so it has been called by this common name.

Gunkanjima was an island used for mining coal, and at the peak period, over 5,000 people lived on the island. The coal mine was closed in 1974, and the island remained uninhabited for a long time. Most of buildings remaining on the island are RC structures. Wooden and steel buildings had been destroyed by the harsh natural environment. Figure 2 shows the layout of the major buildings and facilities remaining on the island.

Those buildings have deteriorated over the years, and it is necessary to take measures to preserve them as cultural assets. Therefore, a survey on the structural performance of residential facilities that had been left behind and deteriorated was conducted starting in September 2015. The main investigators were experts belonging to the Architectural Institute of Japan, which was commissioned by Nagasaki City, the administrator of Gunkanjima.

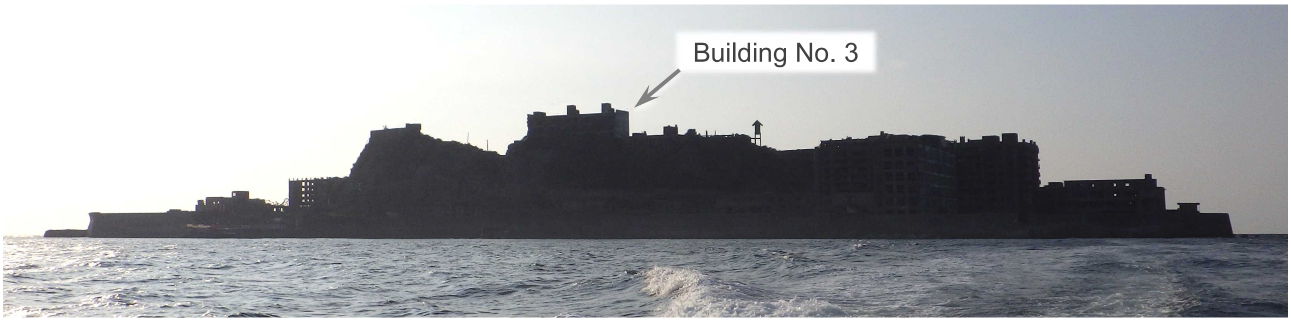


Figure 1. Silhouette of Gunkanjima (officially called Hashima)

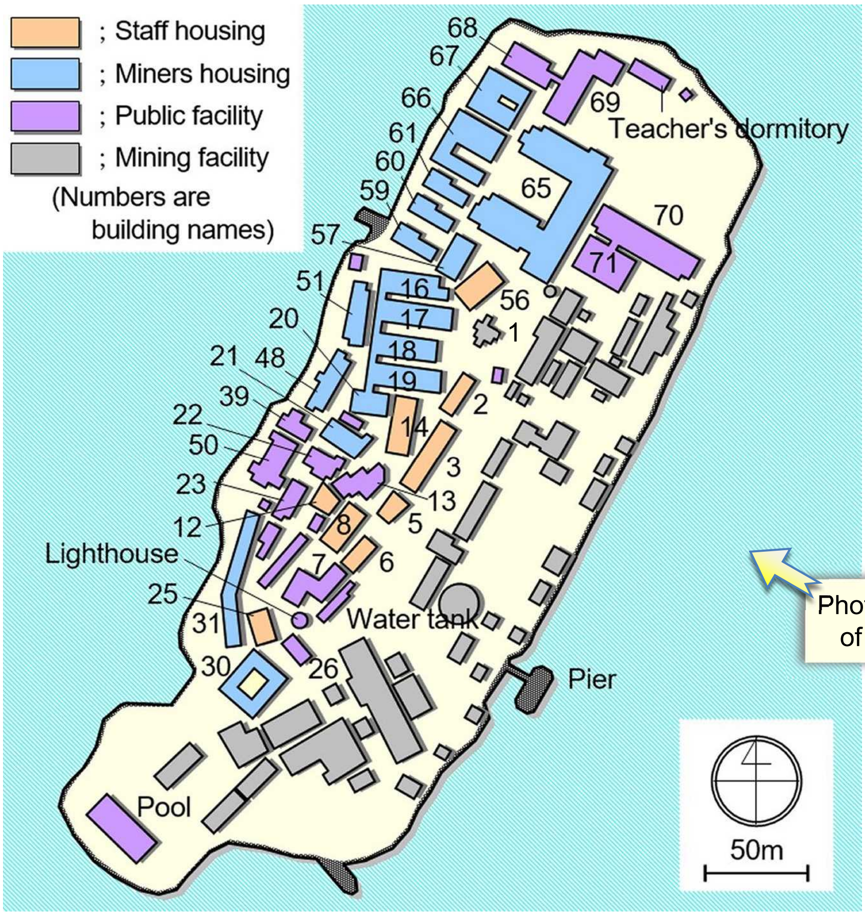


Figure 2. Layout of major buildings and facilities on Gunkanjima

2. Structural Performance Survey

2.1. Buildings to be investigated

The major residential facilities remaining on the island are listed in Table 1. Most of them were included in the survey conducted in September 2015. As shown in the table, the oldest building was Building No. 30, built in 1916, and the newest building was Building No. 71, built in 1970. Most of them were residential buildings, but also included public facilities such as a school and a hospital.

Table 1. Remaining major residential facilities (Surveyed in September 2015)

Building No.	Structure	Built year	Usage	min R_L (%)	min R_E (%)
1	RC-1F	1936	Shrine	---	---
2	RC-3F	1950	Housing for staff	---	83
3	RC-4F	1959	Executive staff housing	98	86
8	RC+W-3F	1919	Staff housing & communal bath	72	17
13	RC-4F	1967	Public housing	95	79
14	RC-5F	1941	Housing for staff	59	51
16	RC-9F	1918	Housing for miners	73	24
17	RC-9F	1918	ditto	79	20
18	RC-9F	1918	ditto	81	50
19	RC-9F	1922	ditto	82	56
20	RC-6F	1922	ditto	77	51
21	RC-5F	1954	Miners housing & police station	78	26
22	RC-5F	1953	Town office	90	25
25	RC-5F	1931	Housing for staff	66	6
30	RC-7F	1916	Housing for miners	44	3
31	RC-6F	1957	Miners housing & communal bath	78	7
39	RC-3F	1964	Community center	92	56
48	RC-5F+B1	1955	Housing for miners	77	19
50	RC+brick-2F	1927	Movie theatre	78	26
51	RC-8F	1961	Miners housing & store	84	52
56	RC-3F	1939	Housing for staff	85	52
57	RC-4F	1939	Miners housing & store	42	4
59	RC-5F	1953	Housing for miners	77	27
60	RC-5F	1953	Miners housing & shop	83	25
61	RC-5F	1953	Miners housing & communal bath	77	27
65-north	RC-9F+B1	1945	Housing for miners	81	9
65-east	RC-10F+B1	1949	ditto	87	20
65-south	RC-10F	1958	ditto	92	65
66	RC-4F+B1	1940	Dormitory for miners	76	28
67	RC-4F	1950	Dormitory for single miners	37	---
68	RC-2F	1958	Isolation ward	97	73
69	RC-4F	1958	Hospital	77	22
70	RC+S-7F	1958	Elementary and junior high school	92	66
71	RC-2F	1970	Gym	82	25
Dormitory	RC-2F	1958	Teacher's dormitory	46	---
Water tank	RC-1F+PH	1957	Water storage tank	76	7

2.2. Survey for the deterioration grade of structural member

The deterioration grade of each structural member (columns, seismic walls and beams) was investigated in the most of buildings shown in Table 1 in order to evaluate the structural performance considering deterioration. As shown in Table 2, the deterioration grade of structural member was in six levels from 0 to V, and was defined by the committee in charge of the Architectural Institute of Japan, Kishimoto (2016). Depending on the deterioration grade, the reduction factor of long-term performance and seismic performance was determined as shown in the table.

Structural members were classified into column, wall without column, wall with a column, wall with both side columns, and beam. Trained investigators visually judged the deterioration grade (six levels from 0 to V) of each structural member for each building. Figure 3 shows an example of a beam with the deterioration grade IV and a column with the deterioration grade V.

2.3. The structural performance remaining ratio, R_L & R_E

The structural performance remaining ratio was devised based on the idea that the deterioration grade of the member affects the structural performance of the building. The remaining ratio of axial force holding capacity considering deterioration "R_L" was calculated using Equation (1), and the remaining ratio of seismic capacity considering deterioration "R_E" was calculated using Equation (2). The concept of the calculation method for R_L and R_E was based on the remaining ratio of seismic capacity "R" for the damaged building by an earthquake (JBDPA 2001). Therefore, R_L and R_E represented the ratio of the retained performance after deterioration to the initial retained performance. R_L was calculated for each floor in terms of long-term performance, while R_E was calculated in each direction of each floor in terms of seismic performance.

The remaining ratio of axial force holding capacity considering deterioration "R_L"

$$R_L = \frac{\sum A_{Lj}}{A_{Lorg}} \cdot 100\ (\%) \tag{1}$$

$$A_{Lorg} = N_{CL} + N_{W0}$$

$$A_{Lj} = [N_{CLj} + N_{W0j}] \cdot \eta_L$$

For the considering floor, N_{CL} ; total number of columns (Ignore the wall part of the column that has the wall attached), N_{W0} ; number of wall without column, j ; deterioration grade (from 0 to V), N_{CLj} ; number of column (the j - grade), N_{W0j} ; number of wall without column (the j - grade), η_L ; reduction factor for long-term (shown in the Table 2).

The remaining ratio of seismic capacity considering deterioration "R_E"

$$R_E = \frac{\sum A_{Ej}}{A_{Eorg}} \cdot 100\ (\%) \tag{2}$$

$$A_{Eorg} = N_{CE} + N_{W0} + N_{W1} \cdot 2 + N_{W2} \cdot 6$$

$$A_{Ej} = [N_{CEj} + N_{W0j} + N_{W1j} \cdot 2 + N_{W2j} \cdot 6] \cdot \eta_E$$

For the considering direction of the floor, N_{CE} ; total number of columns, N_{W0} ; number of wall without column, N_{W1} ; number of wall with a column, N_{W2} ; number of wall with both side columns, j ; deterioration grade (from 0 to V), N_{CEj} ; number of column (the j - grade), N_{W0j} ; number of wall without column (the j - grade), N_{W1j} ; number of wall with a column (the j - grade), N_{W2j} ; number of wall with both side columns (the j - grade), η_E ; reduction factor for seismic performance (shown in the Table 2).

In the calculation of R_L, only the deterioration grade of columns and walls without column was adopted, while the deterioration grade of beams was not considered. In the calculation of R_E, if the deterioration grade of a vertical member was lower than a beam attached in the considering direction, it was read as the deterioration grade of the beam, Kishimoto (2016).

Table 2. The deterioration grade and reduction factor of structural member

Deterioration grade	**State of deterioration**	**Reduction factor**	
		Long-term η_L	**Seismic perform. η_E**
0	No deterioration (retain original performance)	1.00	1.00
I	Slight deterioration, the crack width is less than 1mm.	0.95	0.95
II	Reinforcement is corroded and is slightly separated from concrete.	0.90	0.80
III	Large crack have occurred in cover concrete. But there are almost no cross-sectional defects in reinforcement. (Vertical members are available on one side and both sides.)	0.90	one 0.65 both 0.33
IV	Cover concrete has fallen off, and reinforcement and concrete are partially separated. But the cross-sectional area of reinforcement is more than 70%. (Vertical members are available on one side and both sides.)	one 0.90 both 0.80	one 0.25 both 0.10
V	Core concrete is missing, and reinforcement and concrete are completely separated. The cross-sectional area of reinforcement is less than 70%.	0.30	0.00

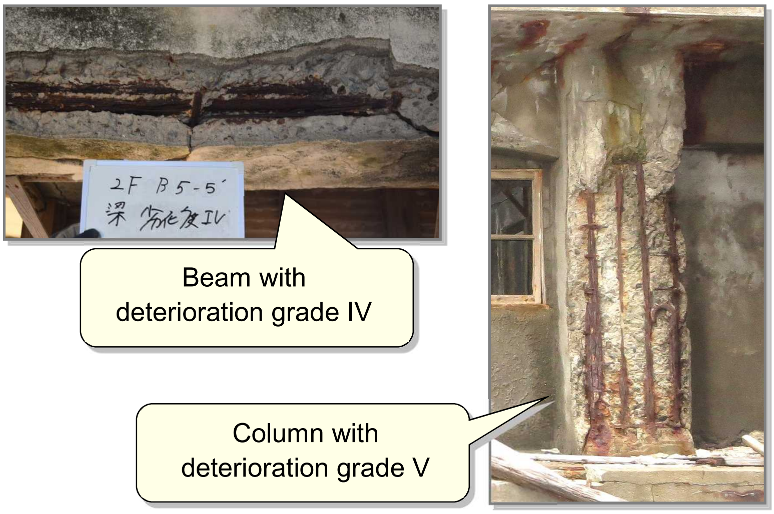


Figure 3. Example of the deterioration grade of structural member

The minimum values of R_L and R_E calculated for the buildings surveyed in September 2015 are listed in the Table 2. Buildings No.30, No.57, and No.67 have a low R_L of approximately 40%. On the other hand, the R_E value of Building No.30 was the lowest at 3%.

Figure 4 shows the relationship between the built year and the minimum values of R_L and R_E for each building. Each regression line is drawn in the figure. Although it can be confirmed from the figure that both R_L and R_E have a positive correlation with the built year, the variation is large, and it is assumed that other factors such as location on the island and construction status also have a large influence.

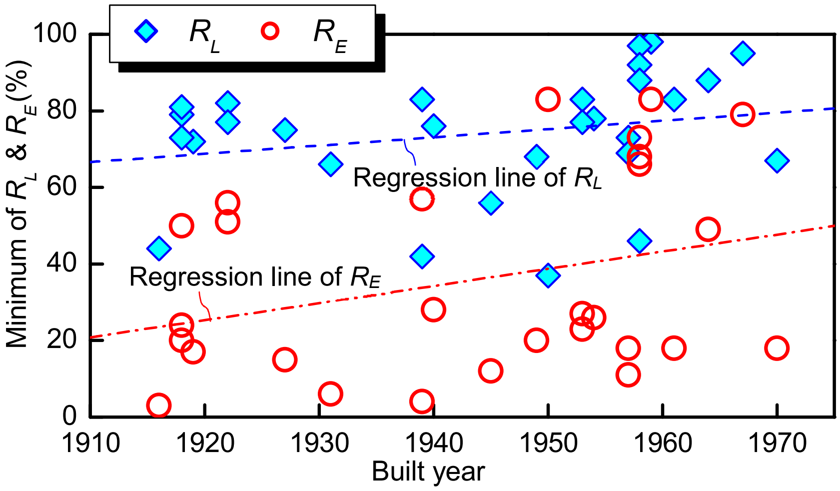


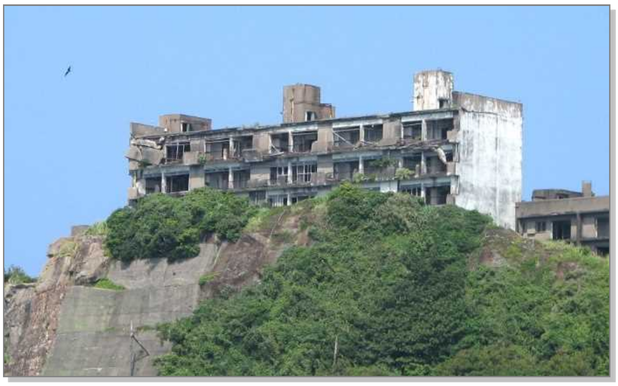
Figure 4. Relationship between built year and minimum values of R_L and R_E

3. Case Study of Building No. 3

3.1. Information on Building No. 3 of Gunkanjima

The Building No. 3 is a four-story RC housing complex built on a hill in the centre of the island in 1959. As illustrated in Figure 1, this building has a strong presence on the island. Figure 5 shows the east facade and specifications of the building. The Building No. 3, a symbolic item on Gunkanjima, has been selected as a priority for conservation consideration by Nagasaki City, the island's administrator.

The floor plan, elevation, and structural information for Building No. 3 were determined through a field survey while referring to the original design drawings at the construction. Figure 6 shows the standard floor plan and frame elevation of longitudinal direction.

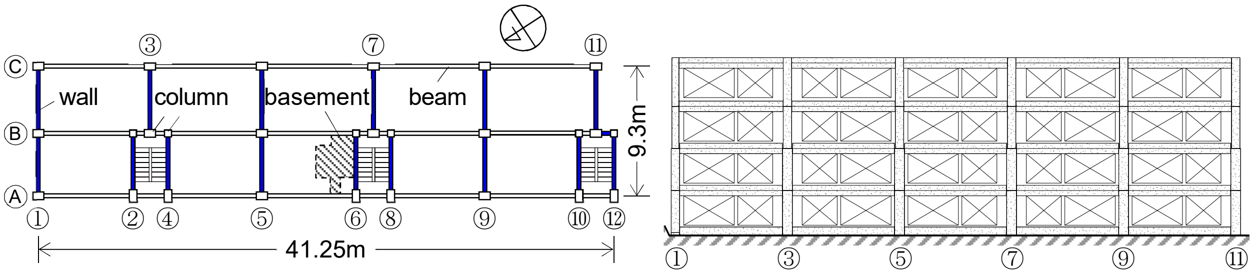


The east facade of Building No. 3

--- Specifications of Building No. 3 ---

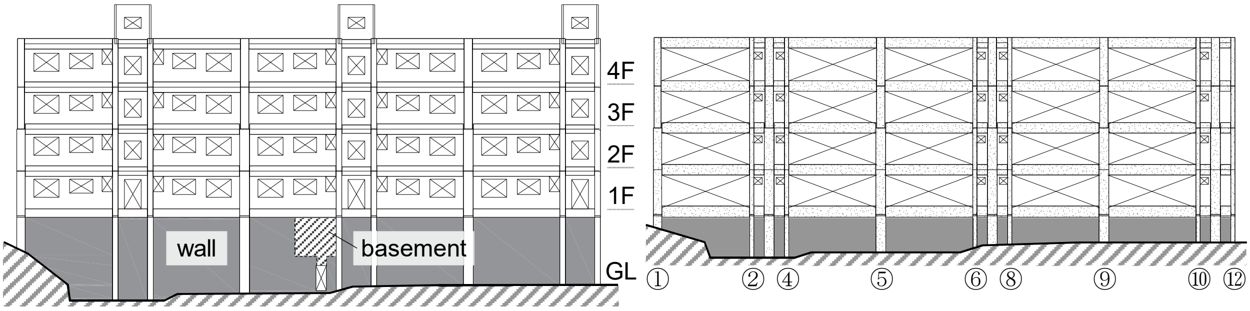
- Apartment complex for executives of the coal mining company.
- A four-story reinforced concrete building with a small basement, and it was built in 1959.
- Built on a sloping cliff, and directly supported by the bedrock.
- Concrete strength was 18.4 N/mm^2 in a 2016 survey.
- The reinforcement was round steel, and the yield strength was estimated to be 294 N/mm^2.

Figure 5. Exterior photo and specifications of Building No. 3



Standard floor plan

Elevation of the Frame-C



Elevation of the Frame-A

Elevation of the Frame-B

Figure 6. Floor plan and frame elevation of Building No. 3

3.2. Investigation of deterioration status in Building No. 3

The authors have been conducting a survey on the deterioration grade of structural member in building No. 3 every year since 2015. As an example of the survey results, Figure 7 shows the deterioration grade of columns and beams confirmed in the survey conducted in November 2022, comparing the 1st and 4th floors. It can be found that there are more parts with a higher grade of deterioration on the 4th floor than on the 1st floor from this figure. On each floor, the deterioration grade tends to be higher in the beams than in the columns. It can be confirmed that for both columns and beams, there are differences in the deterioration grade depending on the position of the member.

In order to understand the progress of the deterioration grade for each structural member, Figure 8 was created. This figure represents the situation in which the ratio of the number of members related to the deterioration grade changes from 2015 to 2022, in each floor, about seismic walls, columns, and beams (longitudinal direction). It can be recognized from this figure that the deterioration has progressed more remarkably in the beams than in seismic walls and columns. Note that the same tendency applies to the beams in the transverse direction as in the longitudinal direction. The beams are gradually deteriorating on each floor, with the ratio of the deterioration grade IV and V increasing on the third and fourth floors. That is considered as a worrying situation. On the other hand, although the deterioration grade of seismic walls and columns is milder than that of the beams, it can be found that the deterioration is progressing gradually.

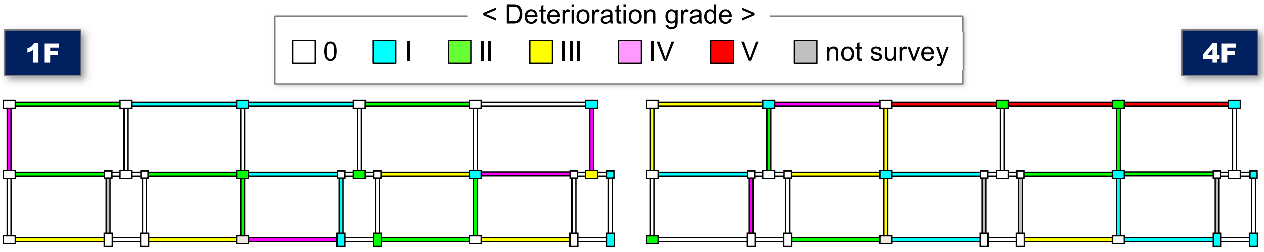


Figure 7. The deterioration grade of column and beam (Survey in November 2022)

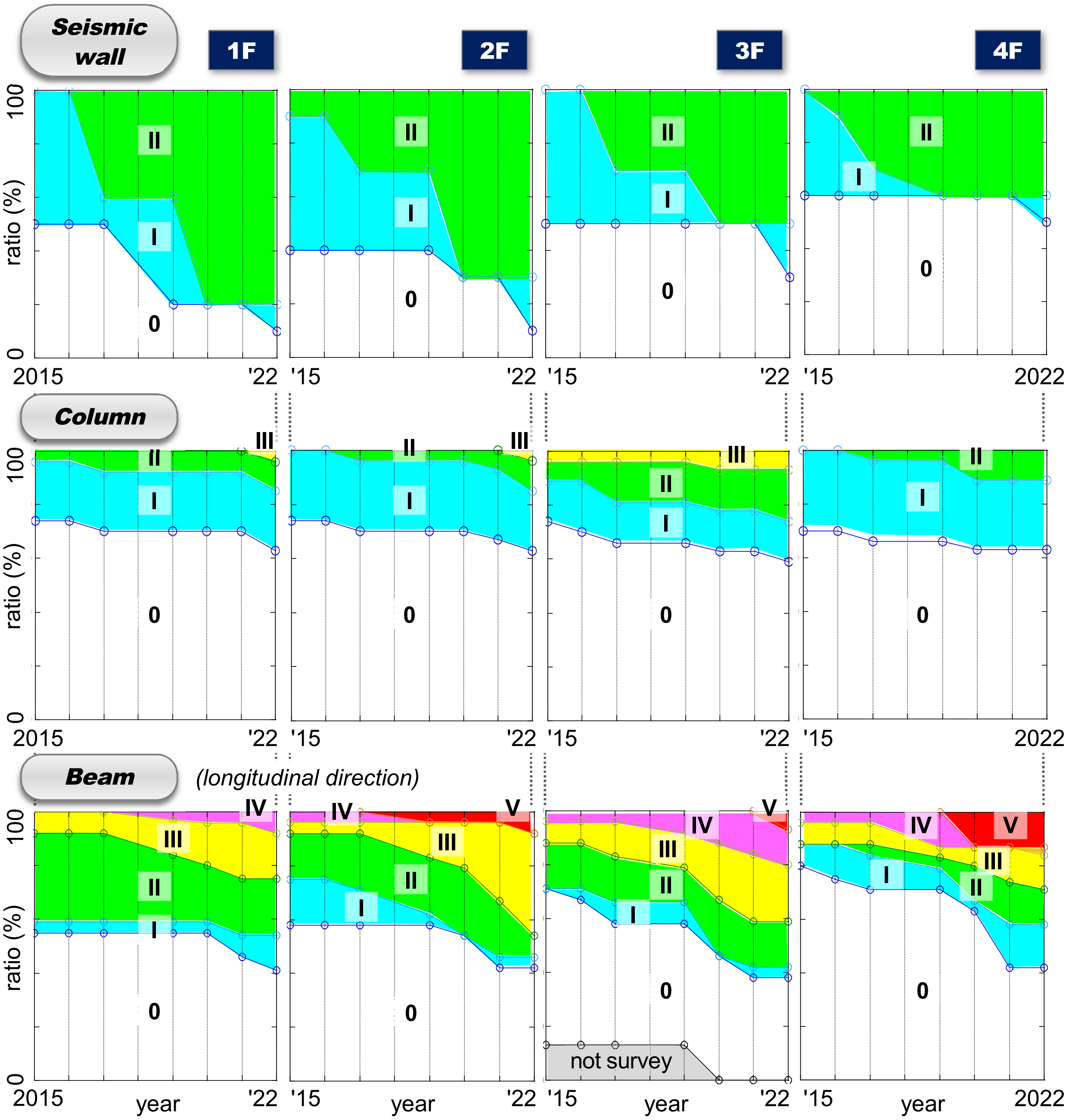


Figure 8. Progress in the deterioration grade of structural member types

3.3. Distribution of structural performance remaining ratio, R_L & R_E of Building No. 3

Figure 9 shows the distribution of structural performance remaining ratio (R_L and R_E) in each floor of the Building No. 3, comparing 2015 and 2022. According to the calculation method described in the Section 2.3, the R_L value was determined once for each floor, and the R_E value was determined for each direction of the floor, as shown in this figure.

There was little difference in the distribution of R_L between floors, with a decline of approximately 1% for all floors from 2015 to 2022. On the other hand, the R_E value showed a large decrease in both directions, reaching values of around 10-25%. While the R_L value is mainly calculated based on the deterioration grade of columns, the R_E calculation also takes into account the deterioration grade of beams. The reason for the large decrease in the R_E value was that the deterioration of beams progressed remarkably, as shown in Figure 8.

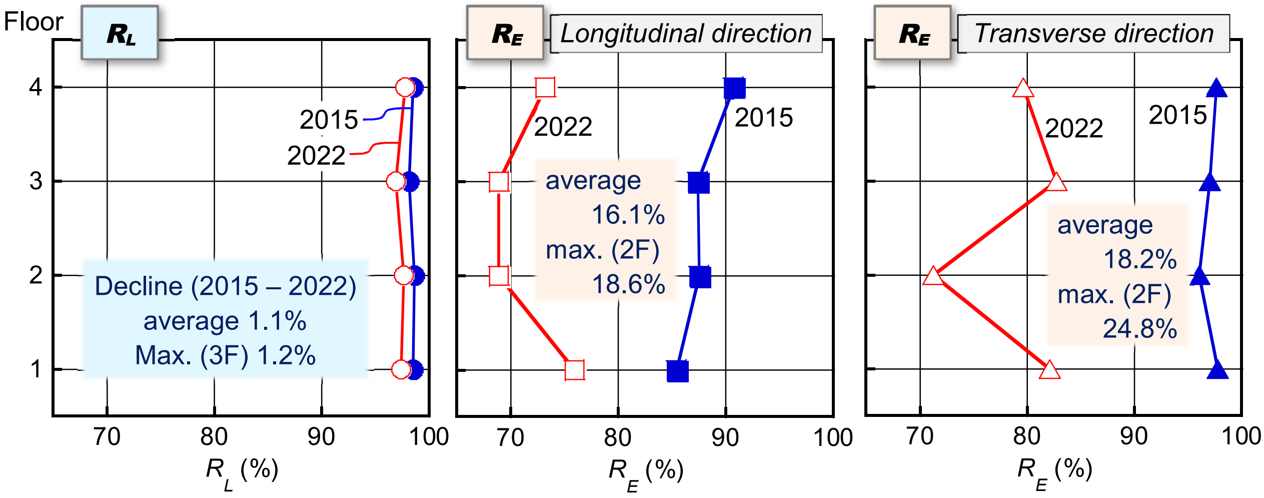
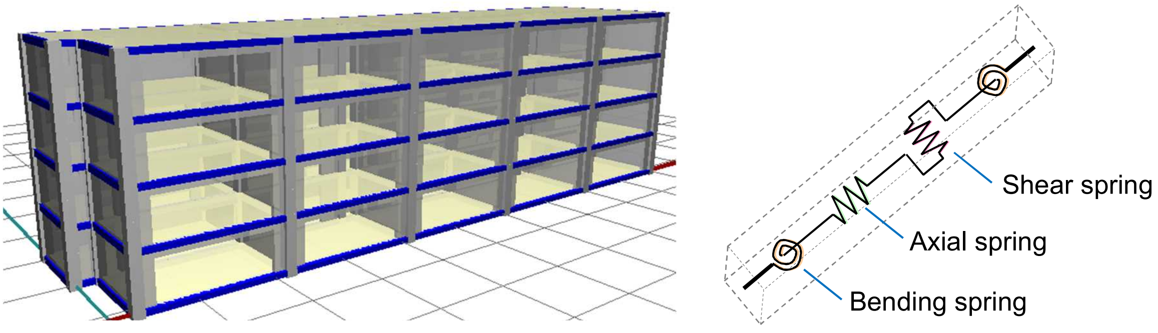


Figure 9. Distribution and decline of structural performance remaining ratio, R_L & R_E

3.4. Performance evaluation by pushover analysis

The 3-dimensional frame model of the Building No. 3 shown in Figure 10 was constructed by the authors in order to analytically evaluate the structural performance. In the analytical model shown in the figure, the mass was set at the floor position, and supported by pins under the foundation beam. The external lateral force distribution shape was kept constant, and the pushover analysis was performed using load increments. The structural members such as columns and beams were replaced with a spring model consisting of bending springs, shear springs, and axial springs as shown in the figure. The axial spring was an elastic behaviour type, while the bending spring and shear spring were set as tri-linear model types. Note that the reduction in bearing force due to shear failure was not taken into consideration. As a method for considering deterioration, the slope changing points of bending springs and shear springs were lowered by multiplying the reduction factor (shown in Table 2) according to the deterioration grade of the members, Nakahara (2019).



3-D frame model of building   Spring model of structural member

Figure 10. 3-D frame model of the Building No. 3 for pushover analysis

Figure 11 shows the analysis results for a case with no deterioration, which is assumed at the time of construction, and a case that reflects the deterioration in 2022. It represents the relationship between the shear force and the story drift angle of each story when a lateral force is loaded in the longitudinal direction. Considering deterioration of members, the shear force on the first story was reduced by approximately 4% at a story drift angle of 0.005 rad. The effects of column shear failure was not taken into account in this analysis, so improvements should be needed in the future.

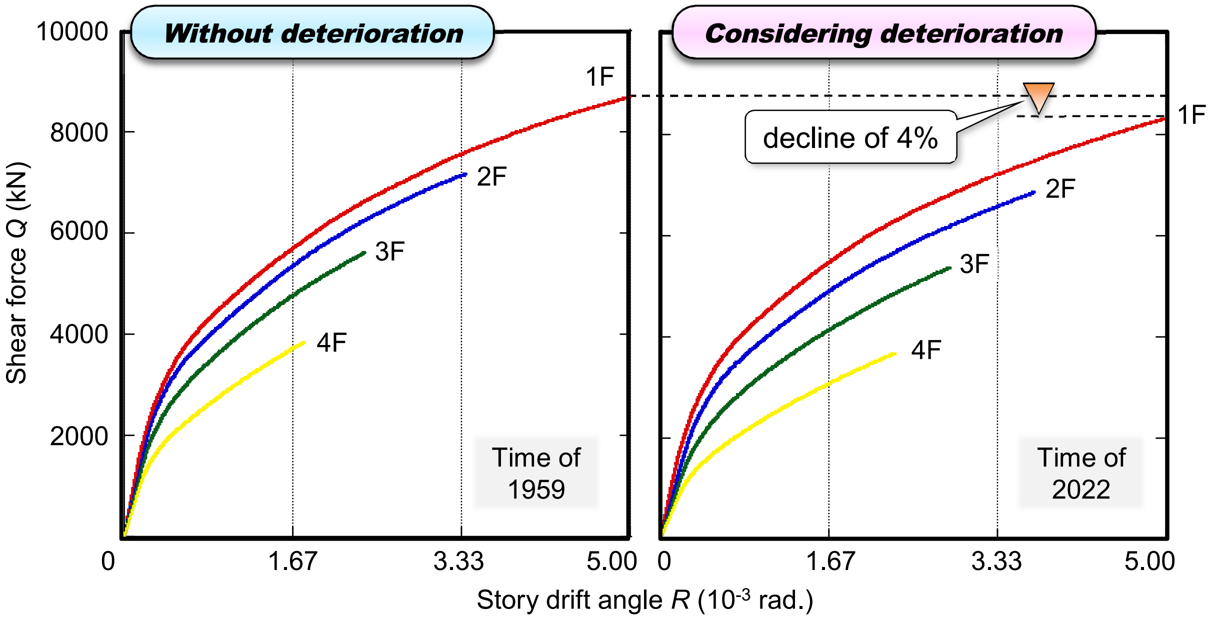


Figure 11. Hysteresis curve obtained from pushover analysis in longitudinal direction

4. Conclusion

In order to maintain the historical value of Gunkanjima, which is a world cultural heritage site, consideration must be given to preserve the remaining buildings on the island. The facilities existing on the island are reinforced concrete buildings, and it was confirmed that their structural performance has declined due to deterioration caused by the harsh natural environment. In the Building No. 3, located at the top of the island symbolically, the beams had deteriorated more noticeably than the columns and seismic walls. As a result, it was revealed that the seismic capacity of the Building No. 3 has deteriorated gradually.

The effective measures such as repair and retrofitting are urgently required in order to preserve those historically and culturally valuable buildings, including the Building No. 3.

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