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Building Damage around Bam Seismological Observatory Following the Bam, Iran Earthquake of Dec. 26, 2003

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Abstract

The post-earthquake investigations of the Bam, Iran earthquake of Dec. 26, 2003 were conducted by the Joint Reconnaissance Team of the Ministry of Education, Culture, Sports, Science and Technology (MEXT), the Japan Association for Earthquake Engineering (JAEE), the Architectural Institute of Japan (AIJ) and the Japan Society for Civil Engineers (JSCE) in collaboration with the International Institute of Earthquake Engineering and Seismology (IIEES) from Feb. 23 2004 to Mar. 4 2004. This paper reports the results of a damage evaluation of buildings around the Bam Seismological Observatory operated by the Building and Housing Research Center (BHRC). The results show that many residential houses in the investigated area were seismically vulnerable structures such as adobe and simple masonry structures. Poor construction quality was also found in some of the investigated buildings designed according to the current Iranian seismic code. Moreover, a good correlation between wall area ratio and damage levels was observed. Therefore, wall area ratio may be applicable for evaluating seismic capacity and screening retrofit candidates.

Key words: 2003 Bam Iran earthquake, building damage survey, masonry structure, seismic design code, European Macroseismic Scale 1998 (EMS-98)

1. Introduction

The Bam, Iran earthquake struck Bam city on Dec. 26, 2003, destroying many buildings and houses, and killing more than 26,000 persons, almost 20% of the population in Bam city. To investigate the stricken area, the Ministry of Education, Culture, Sports, Science and Technology (MEXT), the Japan Association for Earthquake Engineering (JAEE), the Architectural Institute of Japan (AIJ) and the Japan Society for Civil Engineers (JSCE) established the Joint Reconnaissance Team in collaboration with the International Institute of Earthquake Engineering and Seismology (IIEES). This paper presents a brief summary of the Iranian building seismic code, results of the investigation on building damage around the Bam Seismological Observatory by the Building and Housing Research Center (BHRC), and approximate evaluation of the seismic capacity of the damaged masonry buildings.

2. Building Seismic Code of Iran

The history of preparing the seismic code in Iran dates back to the 1963 Bouein-zahra earthquake with a magnitude of 7.2. In 1967, the Iran ministry of Housing and Development published "the building safety code during earthquake." In this code buildings higher than 11 m were restricted to steel-frame or reinforced concrete frame structures. The code had two chapters: 1- masonry buildings 2- analysis of buildings against earthquake. The code became the

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legal basis of construction activities in the country in 1969, and was published by Iran Planning and Budget Organization. Later, a second chapter of the code was added to the Iran National Standard code No. 519 (Minimum loads applied to buildings). Since then the code has been the basis for the seismic resistant design of buildings (ISIRI).

In 1987, the National standard code No. 2800 "Iranian Code of Practice for Seismic Resistant Design of Buildings" replaced chapter 8 of code No. 519. Subsequently, a second revision of the code was put into practice in 1999 (BHRC, 1999). The code is applicable to the design and the construction of reinforced concrete, steel, wood and masonry buildings to determine the minimum criteria and regulations for seismic building designs. The criteria for designing general buildings to withstand earthquake forces are described in chapter 2. The seismic base shear coefficient C is defined as follows:

$$C=\frac{ABI}{R} \tag{1}$$

where:

- A: design base acceleration (ratio to gravity acceleration), which varies from 0.35, 0.30, 0.25, to 0.20 according to the region.
- B: building response factor obtained from design response spectrum is as follows:

$$B=2.5\left(\frac{T_0}{T}\right)^{2/3}\leq 2.5 \tag{2}$$

- T: the building natural period (sec.), T_0: a scalar quantity determined according to soil specifications and may be 0.4, 0.5, 0.7, or 1.0.
- I : building importance factor (0.8, 1.0 or 1.2).
- R: building behavior factor (4 to 11), which is a reduction factor related to the structural system and its ductility, as well as uncertainty of strength.

However, the B/R ratio must in no case be less than 0.09.

Bam city is located in region 2 of the seismic microzonation map of Iran with a high relative seismic hazard ($A=0.3\,g$). Based on the types of the building investigated in the area and assuming $B=2.5$, $I=1.0$, and $R=4$, the base shear coefficient in the area may be roughly estimated as $C=0.19$.

Chapter 3 of the code describes the criteria for unreinforced masonry (masonry with tie confining) buildings. These buildings are limited to 2 floors with minimum 6% and 4% of relative wall sectional area in each direction for the first and second floor, respectively.

3. Typical Structural Systems in the Stricken Area

The common structural system in the stricken area, considering the load-bearing system, is roughly described below:

1- Adobe: adobe bricks with mud or lime mortar in the form of cylindrical dome or wood beam roof.

2- Simple masonry: brick or sometimes stone and concrete block with cement mortar and jack arch roof system.

3- Unreinforced masonry: brick walls with tie confining and jack arch roof.

4- Reinforced concrete moment resisting frame with cast in place or precast slab and masonry infill walls.

5- Steel moment resisting or brace frame with jack arch or cast in place slab and masonry infill walls. (Some steel frames had no lateral resisting components)

The common slab in the buildings was of the brick jack arch type (Fig. 1). The system consists of parallel I-shape steel beams at intervals of about 90 cm. These beams support the brick arches, which are covered and leveled off with gypsum plaster at the bottom and mortar and tiling at the top.

These slabs are heavy and behave like a flexible diaphragm unless detailing is considered. Slabs constructed in this way are usually not tied together or to supporting walls or girders. Therefore, these kinds of slabs have caused many building failures and an unusually high death toll in many recent earthquakes in Iran.

4. Damage Statistics of Buildings around the Bam Seismological Observatory

4.1 Outline of the Survey

An inventory survey of the buildings around the Bam seismological observatory (Governor's Building) operated by the BHRC was carried out to investigate building characteristics and damage levels. This investigation was conducted within one block along the main street in N-S, E-W, and NW-SE directions from the center point of the Governor's Building (Fig. 2).

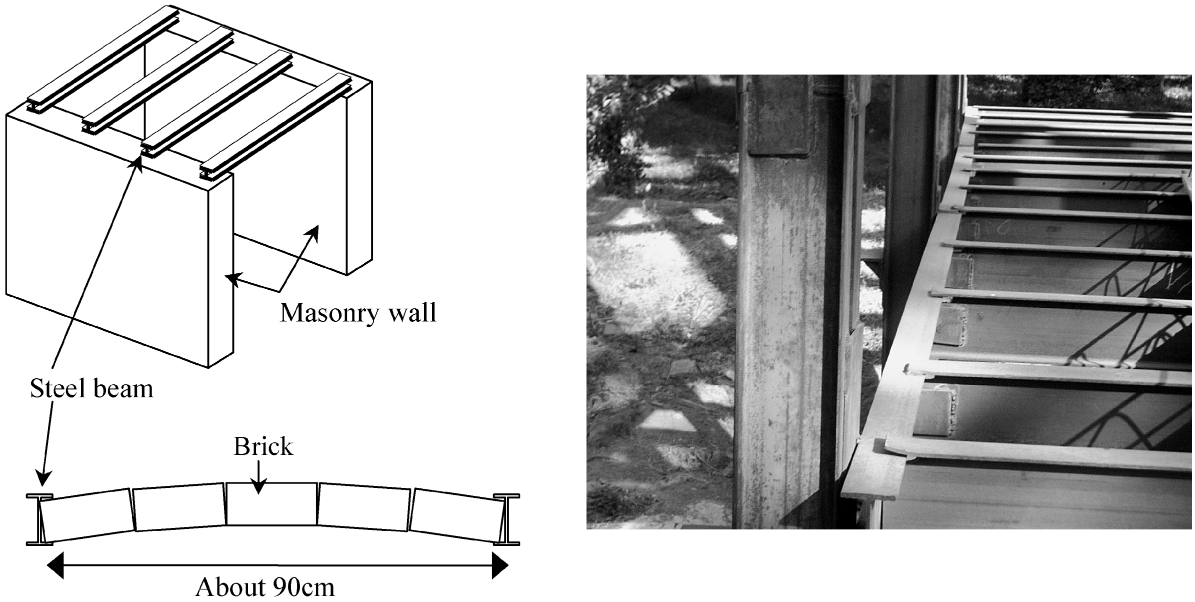


Fig. 1. Commonly used jack arch slab (left: wall supporting; right: girder supporting).

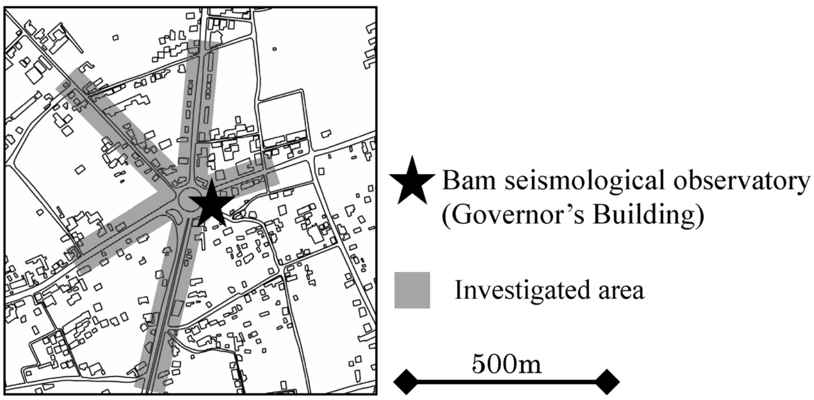


Fig. 2. Investigated area.

Data regarding I: building name, II: structural system, III: age, IV: number of stories, V: usage, and VI: damage level of 94 buildings in the investigated area were collected. The types of building are categorized as follows:

Adobe	: adobe masonry.
SM	: simple masonry.
S-frame+SM	: steel moment resisting frame with simple masonry wall.
S-brace+SM	: steel braced frame with simple masonry wall.
RC-tie+SM	: simple masonry wall confined with reinforced concrete tie.
RC-frame+SM	: reinforced concrete resisting frame with simple masonry wall.
S	: steel moment resisting frame.

Figure 3 shows the distribution of structural systems in the investigated area. The distributions of usages of Adobe, SM, S-frame+SM, and S-brace+SM buildings, which occupy 90% of all 94 buildings in this area, are shown in Fig. 4. The ratios of S-frame+SM and S-brace+SM buildings, which were mainly used for residence and store buildings, are as large as those of Adobe and SM buildings, which were mainly used for residential buildings, because the area investigated is located in the center of the city.

To have a framework for evaluating the damage grade of buildings, the European Macroseismic Scale 98 (EMS-98) classification of masonry buildings shown

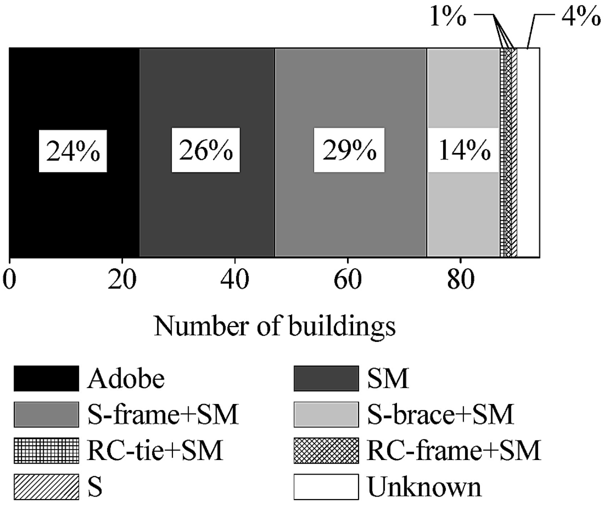


Fig. 3. Distribution of structural systems.

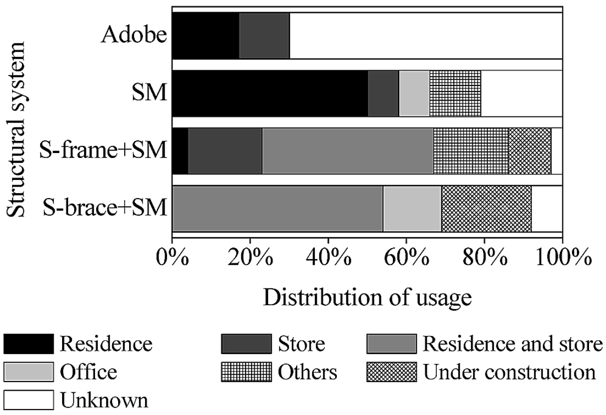
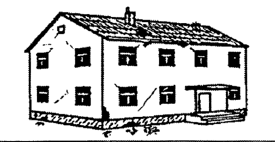
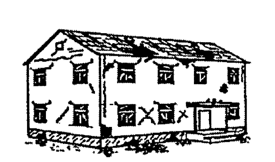
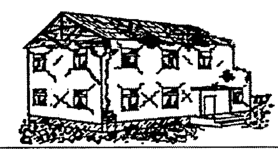
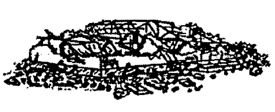


Fig. 4. Distributions of usage of major structural systems.

Table 1. Damage grade according to EMS-98 (Grünthal, 1998).

Classification of damage to masonry buildings	
	**Grade 1: Negligible to slight damage (no structural damage, slight non-structural damage)** Hair-line cracks in very few walls. Fall of small pieces of plaster only. Fall of loose stones from upper parts of buildings in very few cases.
	**Grade 2: Moderate damage (slight structural damage, moderate non-structural damage)** Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimneys.
	**Grade 3: Substantial to heavy damage (moderate structural damage, heavy non-structural damage)** Large and extensive cracks in most walls. Roof tiles detach. Chimneys fracture at the roof line; failure of individual non-structural elements (partitions, gable walls).
	**Grade 4: Very heavy damage (heavy structural damage, very heavy non-structural damage)** Serious failure of walls; partial structural failure of roofs and floors.
	**Grade 5: Destruction (very heavy structural damage)** Total or near total collapse.

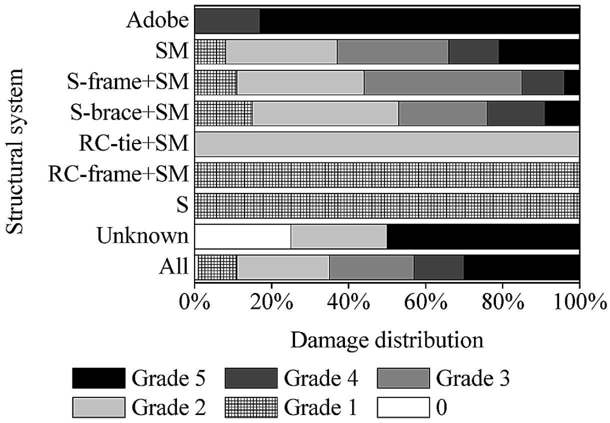


Fig. 5. Damage Distribution of each structural system.

in Table 1 (Grünthal, 1998) was selected for the investigation. In this classification, building damage is categorized into 5 grades.

4. 2 Damage Distributions around the Bam Seismological Observatory

Figure 5 shows the damage distribution of each structural system. All Adobe buildings were classified into Grade 4 and Grade 5. The sum of the ratio of Grade 4 and Grade 5 in SM buildings exceeded 30%, which was much smaller than that of the Adobe buildings. The damage ratios of S-frame+SM and S-brace+SM buildings were expected to be much less than that of the SM buildings, however, there were no major differences among them. This was caused by brittle fractures of poorly welded connections in a few S-frame+SM and S-brace+SM buildings. On the other hand, the damage to RC-tie+SM and RC-frame+SM buildings was quite slight because the connections in these buildings were constructed monolithically with other elements. These results, however, were derived from only one case in each system. The damage level of the only S building, which was a gymnasium structure, was Grade 1.

Subsequently, the relationships among damage level and number of stories, construction age, and location were investigated. Adobe buildings, however, were excluded from the statistical data, because Fig. 5 obviously showed the low seismic performance of these buildings, which were usually single-story residences constructed before 1987. The effect of the number of stories on damage distribution is investigated in Fig. 6. The ratios of Grade 5 and Grade 4 were larger in the case of higher buildings except the only 4-story building. Fig. 7 shows the damage distribution before the establishment of National Standard code No. 2800 in 1987, from 1987 until the revision in 1999, and after 1999. No major differences were observed among these distributions; however, these results were derived from about half of the buildings. This was caused by the technical and social background in Iran. These results reveal that the seismic performance of Iranian buildings were strongly affected by partial weak points, especially jack arch slab and poorly welded connections, and that the seismic code might have not been diffused to local areas. To investigate the effects of input directivity (EW components＞NS components in the records) on building damage, the damage distributions of buildings along the N-S and E-W streets are shown in Fig. 8. The building damage along E-W street is estimated to be larger than that along N-S street, considering the horizontal irregularity due to the arrangement of openings in buildings along the streets, whereas the statistics do not show significant directivity of building damage.

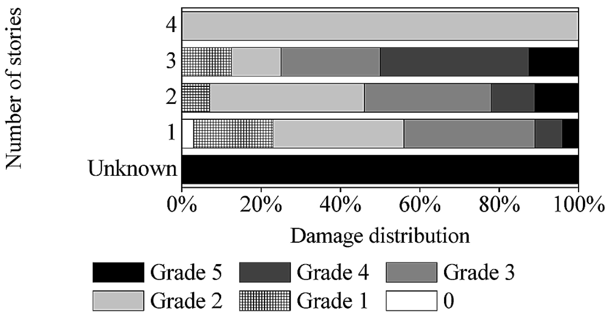


Fig. 6. Effect of number of stories on damage distributions.

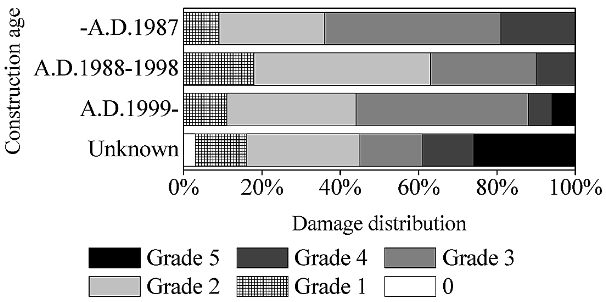


Fig. 7. Effect of construction age on damage distributions.

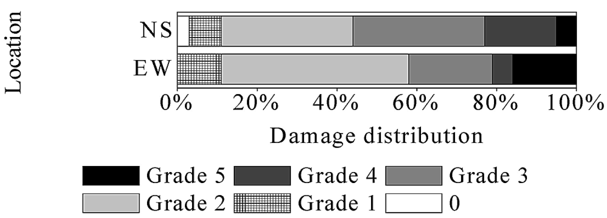


Fig. 8. Damage Distributions along the N-S and E-W streets.

5. Damages and Seismic Capacity Estimation of Individual Buildings

4 buildings are investigated in detail to clarify the building collapse mechanism, the relations between damage level and wall ratio, and seismic capacity. The selected buildings are Governor's Building, Bam Tourist Inn, which is the building neighboring the Governor's Building, 17 Shariwar High-School and a residence and store building under construction which are a few hundred meters from the Governor's Building.

5. 1 Governor's Building

The Governor's Building is a 2-story SM building with reinforced concrete horizontal ties, as shown in Photo 1. This building has an irregular plan. The wall arrangement is illustrated in Fig. 9. The damage level, classified by EMS-98, was Grade 4 due to the partially collapses of NW- and SW-sections as shown in Photo 2. The location of the seismograph is

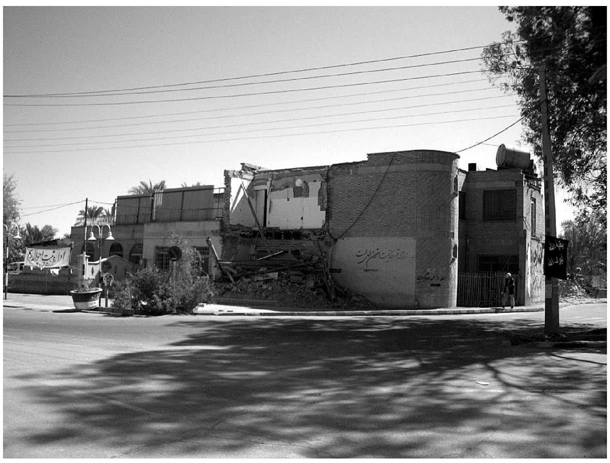


Photo 1. North view of Governor's Building.

Photo 2. Collapse at the south west section.

also illustrated in Fig. 9, which shows that the seismograph was placed far from both collapsed areas. The wall ratios (=the sum of the first floor wall sectional area/the first floor area) were 6.4% to 6.8% in the NS direction and 5.8% to 6.7% in the EW direction, considering those with and without the collapsed area.

Moreover, the damage levels and the maximum crack widths of all masonry walls in the first story, except an inaccessible one, were measured in the Governor's Building according to the criteria shown in Table 2. The damage levels of walls are also shown in Fig. 9 and the distribution of wall damage level in each direction is shown in Fig. 10. The

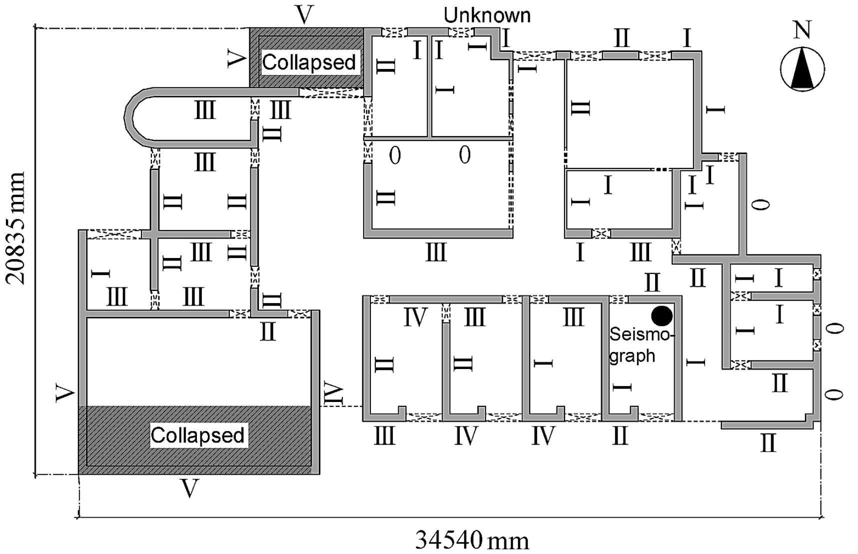


Fig. 9. First floor plan and damage levels of masonry walls of Governor's Building.

Table 2. Definition of damage level of masonry wall.

Damage level	Definition
I	Hair crack in finishing materials
II	Hair crack, which does not cross the wall section, in masonry walls
III	Moderate crack, which crosses the wall section, in masonry walls
IV	Partial collapse and Serious damage of masonry walls
V	Collapse of masonry walls

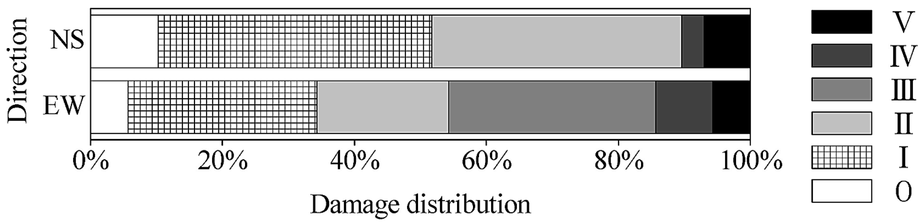


Fig. 10. Distributions of the wall damage level in Governor's Building.

average damage level of all walls in the EW direction of 2.3 is larger than that in the NS direction of 1.7, which means the directivity of the input motions, estimated by the wall ratios (NS≈EW) and damage levels (NS<EW), corresponds to that of actually recorded data (NS<EW).

5. 2 Bam Tourist Inn

Bam Tourist Inn, used as hotel and restaurant, is a 2-story SM building as shown in Photo 3. The plan of this building is relatively regular (Fig. 11). The damage level, classified by EMS-98, was as low as Grade 2 as estimated from Photo 3, however, the roof of the penthouse collapsed as shown in Photo 4. The wall ratio in the NS direction was 9.4%, which was much larger than that of the Governor's Building, and that in the EW direction was 5.5%. The damage levels of walls except inaccessible ones, which were evaluated from the definition in Table 2, are illustrated in Fig. 11. Fig. 12 shows the distribution of wall damage level in each direction. The average damage level of walls in the NS direction of 1.3 was a little smaller than that in the EW direction of 2.3,

Photo 3. South west view of Bam Tourist Inn.

Photo 4. Falling down of the roof of penthouse.

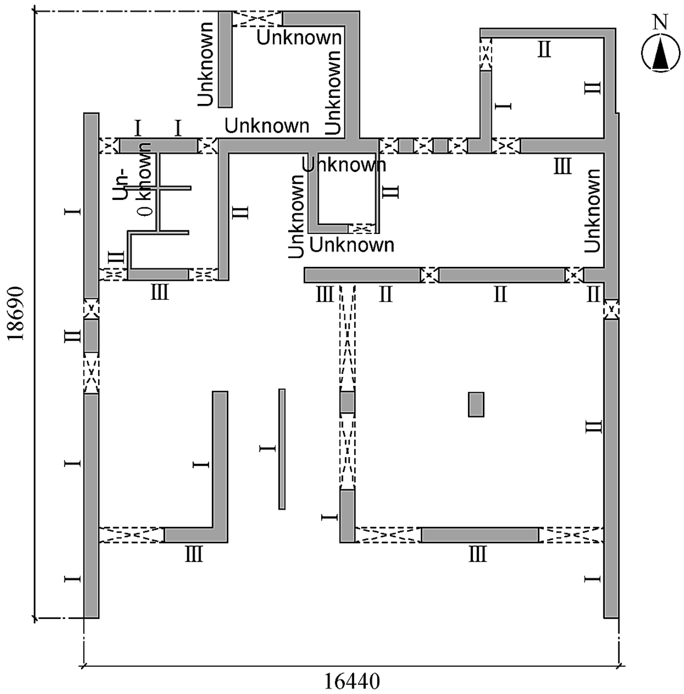


Fig. 11. First floor plan and damage levels of masonry walls of Bam Tourist Inn.

which roughly corresponds to the damage level of Governor's Building except the collapsed area.

Figure 13 shows the relationships between wall ratio and average damage level, and correlation between the wall ratio and the maximum crack width, respectively. It can be concluded from Fig. 13 (a) that the average damage levels were larger in the case of a smaller wall ratio. The maximum crack widths were also larger in the case of a smaller wall ratio among the NS direction of Governor's Building and both directions of Bam Tourist Inn, as shown in Fig. 13 (b). However, the maximum crack width in the EW direction of the Governor's Building was much higher than those in the other cases. This may be caused by torsional responses due to the horizontal irregularity of Governor's Building, because larger crack widths were observed in the outside walls. The building damage cannot be clarified in detail based only on the wall ratio as mentioned here, however, it can be concluded that the wall ratio is considered to be one of the reliable indexes for evaluating the seismic performance of unreinforced masonry buildings.

The base shear coefficient, *C,* of this kind of building can be estimated using the wall ratio in the first floor A_w/A_f and the floor weight per area w as follow:

$$C=\frac{\tau A_w}{wNA_f} \tag{3}$$

where, N: Number of stories (=2).

In general, designs of simple masonry buildings assume a floor weight per area of 800 kgf/m^2, according to some Iranian engineers. It is generally difficult to estimate the average shear strength per area of masonry walls τ, however, it is assumed to be 1 kgf/cm^2=10000 kgf/m^2 herein. As a result of these assumptions, base shear coefficients, *C,* are obtained as 0.63 in case of A_w/A_f=10% and 0.31 in case of A_w/A_f=5%.

5. 3 17 Shariwar High-School

17 Shariwar High-School is located a few hundred meters west of the Governor's Building and consists of 3 SM buildings. The 2 single-story buildings escaped severe damage, as shown in Photo 5, although minor cracks were found in brick walls. On the other hand, the 2-story building had partially collapsed (Photo 6). This building consists of intermediate steel frame and exterior brick walls. The floor slab system is a jack arch type, mentioned earlier. The floor plan of the collapsed part is shown

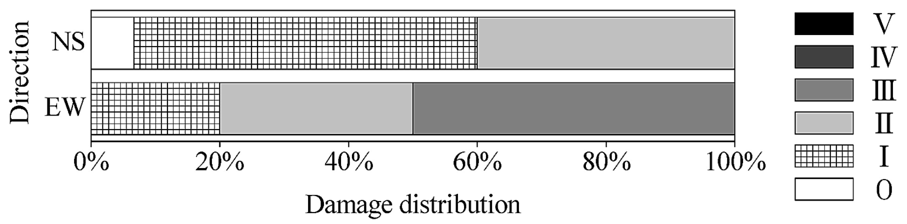


Fig. 12. Distributions of the wall damage level in Bam Tourist Inn.

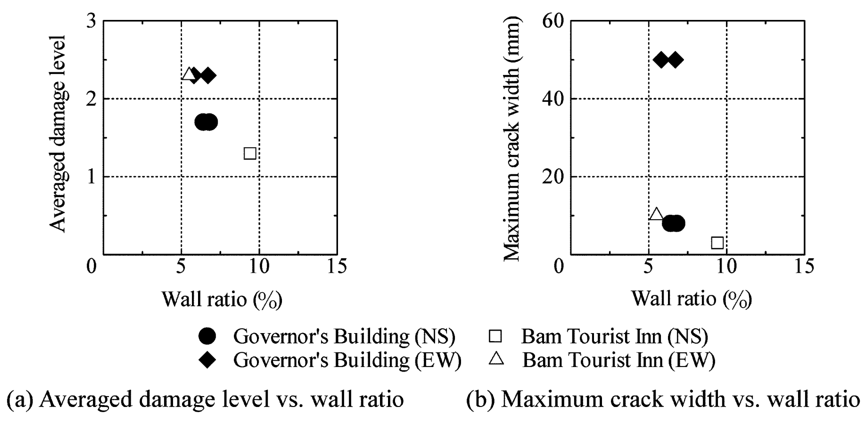


Fig. 13. Relationships between the wall ratio and the wall damage level.

Photo 5. Single-story school building (slight damage).

Photo 6. Collapsed two-story school building.

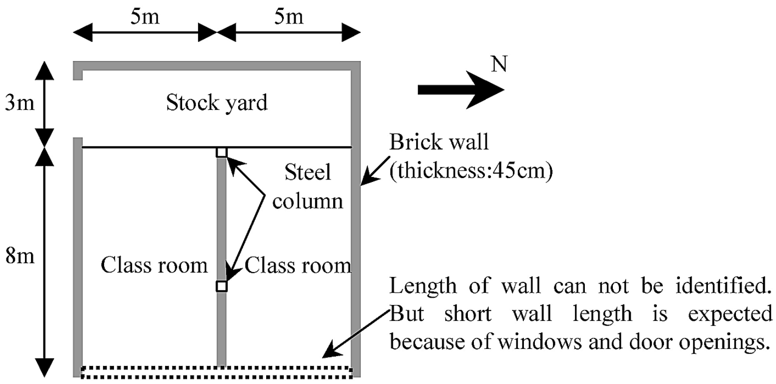


Fig. 14. Floor plan of collapsed part of two-story school building.

in Fig. 14. The roof and floor slab fell off due to the collapse of an east exterior brick wall.

The wall area ratio of the first story obtained is 4.1% in the NS direction and 11.0% in the EW direction. Note that the value in NS was calculated assuming that the area of collapsed east exterior wall is 0, not only because thickness and length of the collapsed wall could not be identified, but also besause a very short wall length may be expected due to the existence of windows and doors. The wall area ratio in the NS direction of 4.1%, in which severe damage occurred, is less than values of the 2 buildings mentioned before.

5.4 Residence and Store Building under Construction

The building under construction (Photo 7) is located a few hundred meters south of the Governor's Building. The structural system of this building is quite typical of the buildings along the main streets in the downtown area. The 3-story steel structure consists of 4 bays in the NS direction along the street and 1 bay in the transverse direction (EW), as shown in Fig. 15. Columns are erected using coupled I-

Photo 7. Residence and store building under construction.

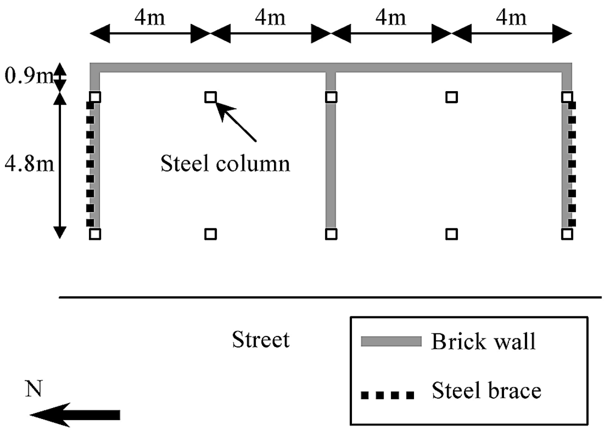


Fig. 15. First floor plan.

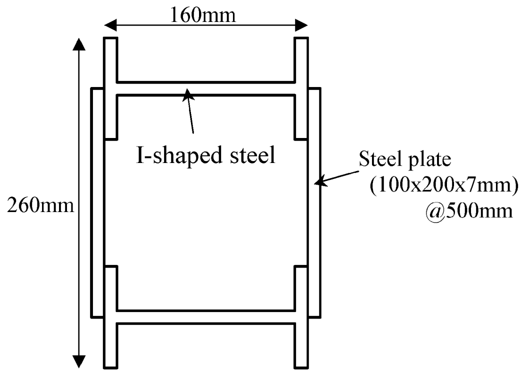


Fig. 16. Section of coupled I-shaped steel column.

shaped steel columns (Fig. 16). Steel braces (I-shape, 70 mm × 140 mm, 7 mm in thickness) are installed in both exterior frames in the EW direction. Brick walls, which are post-installed in the frame without being confined by the surrounding steel frame, are not expected to contribute to carrying the lateral load. I-shaped steel profiles are also used for girders and beams (Photo 7).

In the first story, fractures of welding joints and buckling of steel braces were observed (Photo 8 and 9). As a result, the brick walls had collapsed. Damage to the brick wall on the second story (Photo 10) was also observed. No remarkable structural damage to the steel columns in NS direction was found, although bricks had fellen off the facade of the building.

Lateral load carrying capacity of the first story in EW, in the direction in which the most severe damage occurred, was estimated from the following assumptions: (1) yielding strength of steel is 2.4 tf/

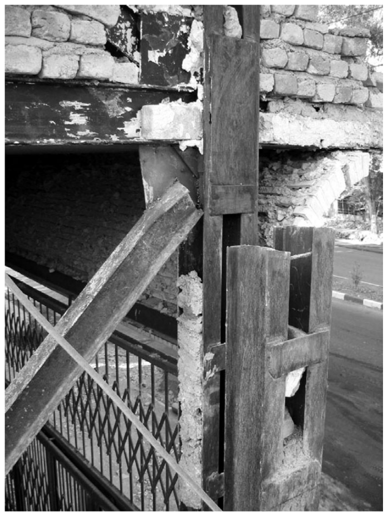


Photo 8. Fracture of welded joint of a steel brace.

Photo 9. Close-up of Photo 8.

Photo 10. Buckling of steel brace and damage to brick wall.

cm^2, (2) angle of steel brace is 45 degrees, (3) unit weight of the building for each floor is 800 kgf/m^2, and (4) floor area is $5.7\,m \times 16\,m = 91.2\,m^2$. These assumptions give a base shear coefficient, *C,* of 0.33. This base shear coefficient is lower than the approximated values for both the Governor's building and Bam Tourist Inn, in spite a higher than minimum requirement of 0.19. This may be one reason why this building suffered severe damage. Other reasons may be poor quality of welding (Fig. 8 and 9) and unconfined brick walls.

6. Concluding Remarks

This paper presents the study results of a damage assessment following the Bam, Iran earthquake of Dec. 26, 2003. Many residential houses in the stricken area were seismically vulnerable structures such as adobe and simple masonry structures. Poor construction quality was found in some of the investigated buildings, which were designed according to the current Iranian seismic code. These might be some of the reasons for the damage to buildings and trasic loss of human lives in spite of the moderate magnitude (Mw = 6.6) of the earthquake.

A good correlation between wall area ratio and damage levels was observed. Therefore, the wall area ratio might be applicable for evaluating seismic capacity and screening retrofit candidates.

Improving the seismic capacity for adobe and masonry structures is an urgent matter to mitigate further seismic damage to such buildings, because these structural systems are the most popular not only in Iran but also in many Asian countries.

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