Reconnaissance Report on Building Damage Due to Bam Earthquake of 26 December 2003

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ABSTRACT: *The post earthquake investigations of the 26 December 2003 Bam-Iran earthquake were conducted by the Joint Reconnaissance Team of the Architectural Institute of Japan (AIJ), the Japan Society for Civil Engineers (JSCE), the Japan Association for Earthquake Engineering (JAEE) and the Ministry of Education, Culture, Sports, Science and Technology (MEXT) in collaboration with the International Institute of Earthquake Engineering and Seismology (IIEES). This paper reports the results of the AIJ team on damage evaluation of the buildings around the Bam strong motion station operated by the Building and Housing Research Center (BHRC). The seismic capacity of damaged buildings was approximately estimated. 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, good correlation between wall area ratio and damage levels was observed. Therefore, wall area ratio may be applicable for evaluating the seismic capacity and screening retrofit candidates.*

Keywords: Bam; Damage Statistics, Iranian seismic building code; Directional damage; Seismic capacity; Structural system

1. Introduction

This paper describes the outcomes of the reconnaissance team of the Architectural Institute of Japan (*AIJ*) on the damage survey due to the 2003 Bam-Iran earthquake.

The 2003 Bam-Iran earthquake struck Bam city on December 26, 2003, destroyed many buildings and houses and killed more than 25,600 people, almost 25% of the population in Bam city. The *AIJ* established a reconnaissance team chaired by Prof. M. Motosaka, Tohoku University, in order to investigate the stricken area. Damage investigation was carried out by the Joint Reconnaissance Team of the *AIJ*, the Japan Society for Civil Engineers (*JSCE*), the Japan Association for Earthquake Engineering (*JAEE*) and the Ministry of Education, Culture, Sports, Science and Technology (*MEXT*) in collaboration with the International Institute of Earthquake Engineering and Seismology in Iran (*IIEES*).

In this paper, a brief summary of Iranian building seismic code, results of the investigation by the *AIJ* team on building damages around the Bam Seismological Observatory, running by the Building and Housing Research Center (*BHRC*), and approximate evaluation of seismic capacity of the damaged masonry building are presented.

2. Building Seismic Code of Iran

The history of preparing the seismic code in Iran refers back to the 1963 Bouein-zahra earthquake with magnitude of 7.2. On 1967 the Iran ministry of Housing and Development published “the building safety code during earthquake”. In this code buildings higher than 11m were restricted to steel-frame or reinforced concrete frame structures. The code had two chapters: 1- masonry buildings 2- analysis of the buildings against the earthquake. The code became legally the instruction basis of construction activities in the country on 1969, published by Iran Planning and Budget Organization. Later the second chapter of the code was added to the Iran National Standard code No. 519 (Minimum loads applied to the buildings). Since then the code became the basis of the seismic resistant design of buildings [1, 2].

In 1987, the National standard code No. 2800 “Iranian Code of Practice for Seismic Resistant Design of Buildings” was replaced instead of chapter 8th of code No. 519. Subsequently, the second revision of the code has been put into practice since 1999 [3]. The code is applicable for the design and construction of reinforced concrete, steel, wood and masonry buildings, in order to determine the minimum criteria and regulations for seismic buildings design. The criteria to design general buildings against the earthquake forces are described in chapter 2 and the seismic base shear coefficient is obtained as follow:

$$C = \frac{ABI}{R} \quad (1)$$

where:

A: Design base acceleration (ratio to gravity acceleration), which differs from 0.35, 0.30, 0.25 or 0.20 according to the regions.

B: Building response factor obtained from design response spectrum as follow:

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

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).

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

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

Chapter 3 of the code describes the criteria for unreinforced masonry (confined masonry with reinforced concrete or steel elements as tie-beams or tie-columns) 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, can roughly describe as below:

1. Adobe: adobe bricks with mud or lime mortar in 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 confining elements 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 the brick jack arch type, see Figure (1). The system consists of parallel I-shape steel beams at about 90*cm* distance. These beams support the brick arches, which are covered and leveled off by gypsum plaster in the bottom and mortar and tiling at the top.

These slabs are heavy and behave as a flexible diaphragm unless detailing is considered. The slabs constructed in this way are usually not tied together and to the supporting walls or girders. Therefore these kinds of slabs have caused heavy 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 in order to investigate the building characteristics and the

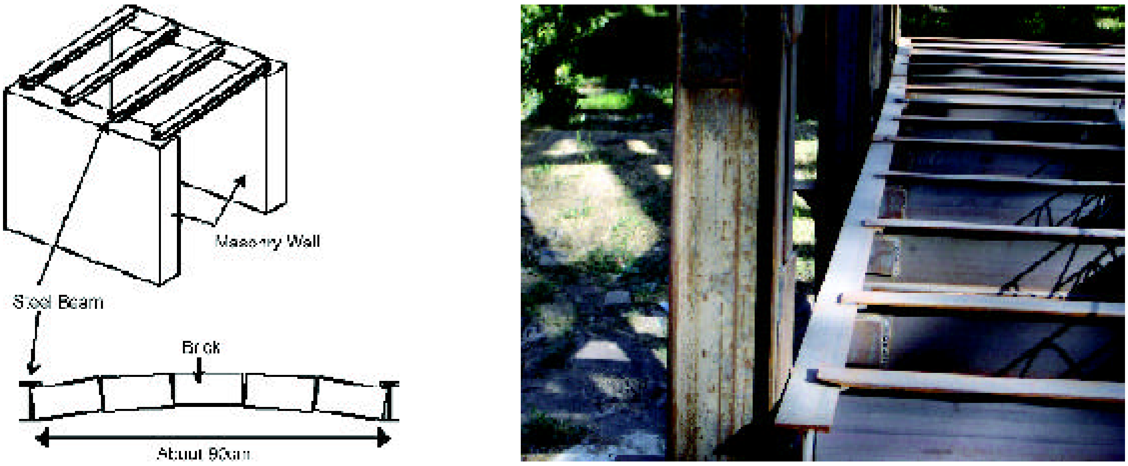


Figure 1. Commonly used jack arch slab (left: wall supporting, right: girder supporting).

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 Governor's Building, see Figure (2).

Data regarding to *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 type of buildings is 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 the structural systems in the investigated area. The distributions of usage of adobe, *SM*, *S-frame+SM*, and *S-brace+SM* buildings, which occupy 90% of all 94 buildings in this area, are shown in Figure (4). The ratios of

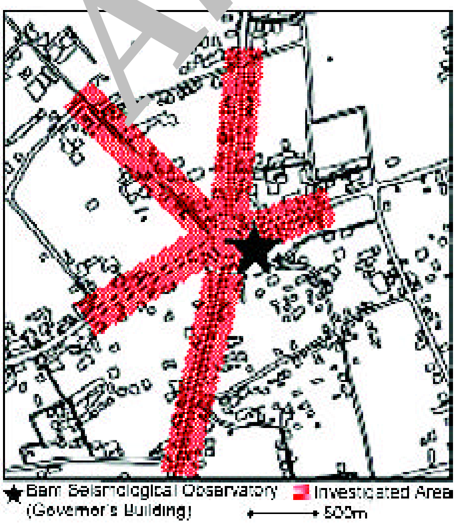


Figure 2. Investigated area.

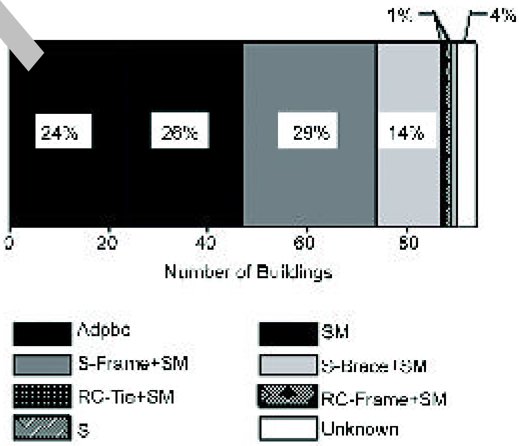


Figure 3. Distribution of structural systems.

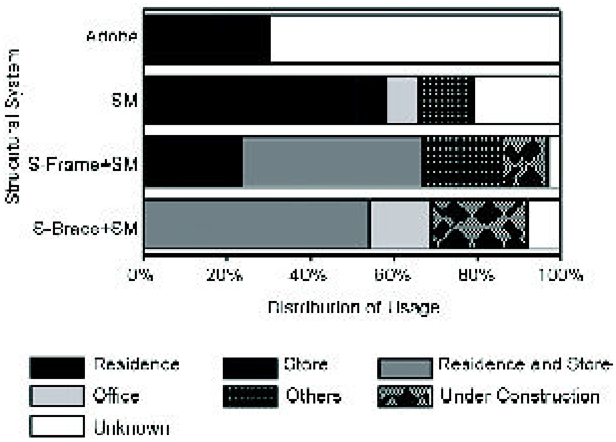


Figure 4. Distributions of usage of major structural systems.

S-frame+SM and *S-brace+SM* buildings, which were mainly used for residence and store buildings, are large as those of Adobe and *SM* buildings, which were mainly used for residential buildings, because the investigated area is located in the center part of the city.

In order to have a framework for evaluating the damage grade of the buildings, the European Macroseismic Scale 98 (*EMS*-98) classification of masonry buildings as shown in Table (1) [4] was selected for the investigation. In this classification, the building damages are categorized into 5 grades.

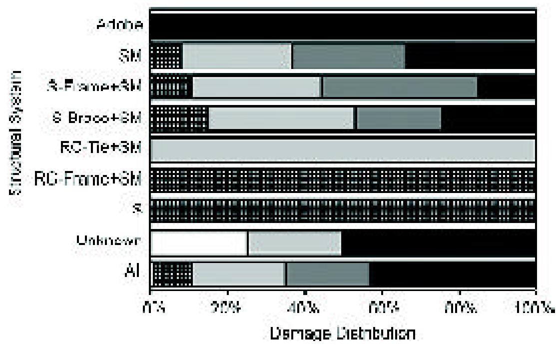


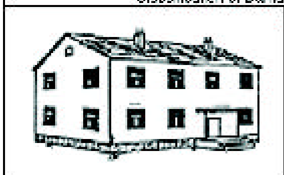
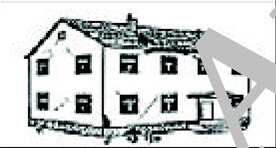
Figure 5. Damage distribution of each structural system.

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 the Adobe buildings. The damage ratios of *S-frame+SM* and *S-brace+SM* buildings were considered to be much less than that of the *SM* buildings, however, there were no big differences among them. This was caused by brittle fracture of poor welded connections in a few *S-frame+SM* and *S-brace+SM* buildings. On the other hand, the damages of *RC-tie+SM* and *RC-frame+SM* buildings were quite slight because the connections in these buildings were constructed monolithically with other elements. These results, however, were derived from the only case in each system. The damage grade of the only *S* building, which was the gymnasium structure, was Grade 1.

Subsequently, the relationships between the damage level and the number of stories, the construction age, and the location were investigated, however, adobe buildings were excluded from the data in order to prevent affecting the statistics. The effect of number of stories on damage distributions is investigated in Figure (6). The ratios of Grade 5 and Grade 4 were larger in case of higher buildings except the only four-story building case. Figure (7) shows the damage distributions before the establishment of National Standard code No. 2800 in 1987, from 1987 to the revision in 1999, and after 1999. No big differences were observed among these distributions; however, these results were derived from about half buildings except the unknown ones. This was caused by the technical and social backgrounds in Iran. These results revealed that the

Table 1. Damage grade according to EMS-98 [4].

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.

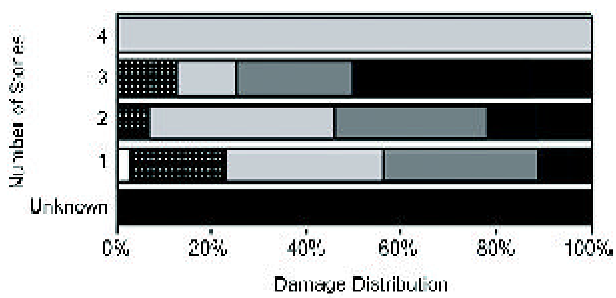


Figure 6. Effect of number of stories on damage distributions.

seismic performances of Iranian buildings were strongly affected by partial weak points, in especial the jack arch slab and poor welded connections, and that the seismic code might be not spread in the local areas. In order to investigate the effects of the input directivity (*EW* components>*NS* components in the records) on the building damages, the damage distributions of the buildings along the *N-S* and *E-W* streets are shown in Figure (8). The building damages along the *E-W* street are estimated to be lager than those along the *N-S* street considering the horizontal irregularity due to arrangements of openings in buildings along the streets, whereas the statistics result does not show significant directivity of the building damages.

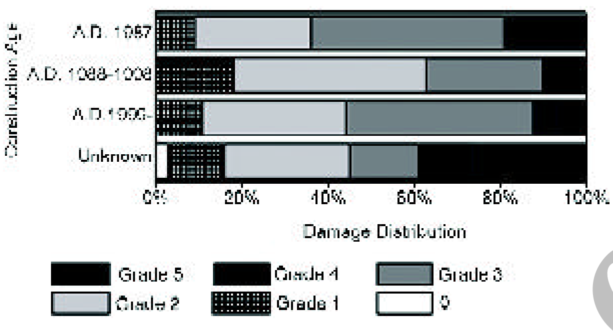


Figure 7. Effect of construction age on damage distributions.

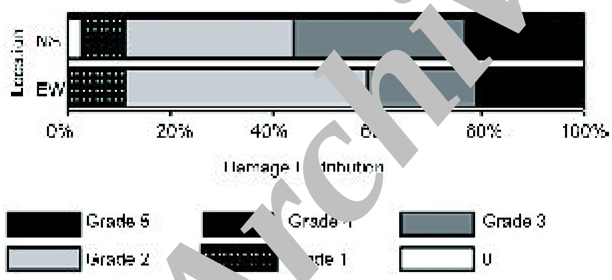


Figure 8. Damage distribution along the N-S and E-W streets.

5. Damages and Seismic Capacity Estimation of Individual Building

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

5.1. Governor's Building

Governor's Building is a two-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 Figure (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 also illustrated in Figure (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 the unknown collapsed area.

Moreover, the damage levels and the maximum crack widths of all masonry walls in the first story were measured in Governor's Building according to the criteria shown in Table (2). The damage levels of walls are also shown in Figure (9) and the

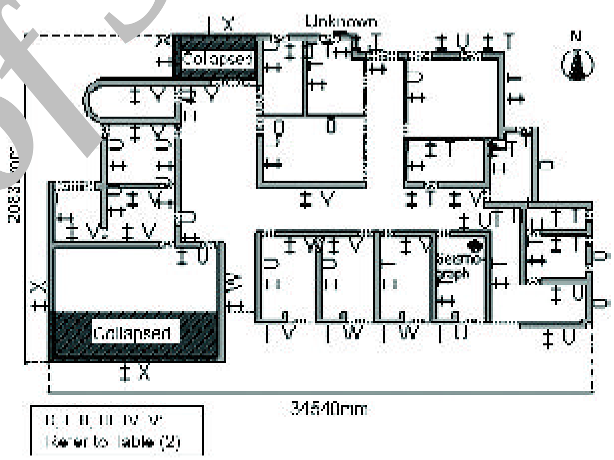


Figure 9. First floor plan and damage levels of masonry walls of Governor's building.

Photo 1. North view of Governor's building.

Photo 2. Collapse at the south west section.

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

distribution of the wall damage level in each direction was shown in Figure (10). The averaged damage level of all walls in the *EW* direction of 2.3, which is calculated as the mean value of damage levels of walls in Figure (10), 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 the actually recorded data (*NS*<*EW*).

5.2. Bam Tourist Inn

Bam Tourist Inn, used as hotel and restaurant, is a two-story SM building as shown in Photo (3). The plan of this building is relatively regular, see Figure (11). The damage level, classified by *EMS*-98, was as low as Grade 2 as estimated from Photo (3),

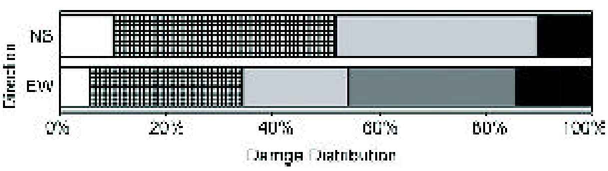


Figure 10. Distribution of the wall damage level in Governor's building.

however, the roof of the penthouse fell down as shown in Photo (4). The wall ratio in the *NS* direction was 9.4%, which was much larger than those of Governor's Building, and that in the *EW* direction was 5.5%. The damage levels of the walls, which were evaluated based on the definition in Table (2), were illustrated in Figure (11). Figure (12) shows the distribution of the wall damage level in each direction. The averaged damage level of walls in the *NS* direction of 1.3 was a little smaller than that in the *EW* direction of 2.3, which roughly corresponds to the damage level of Governor's Building except the collapsed area.

Figure (13) shows the relationships between the wall ratio and the averaged damage level and correlation between the wall ratio and the maximum crack width, respectively. It can be concluded from Figure (13a) that the averaged damage levels were larger in case of smaller wall ratio. The maximum crack widths were larger in case of smaller wall ratio

Photo 3. South west view of Bam Tourist Inn.

Photo 4. Falling down of the roof of penthouse.

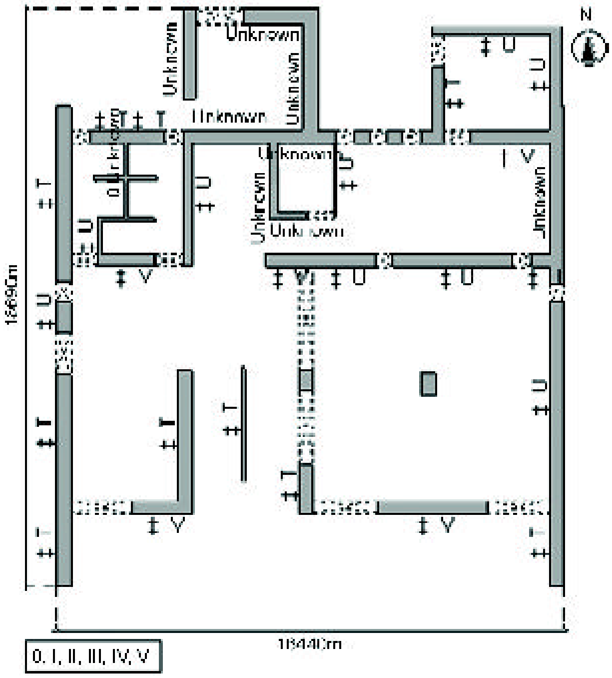


Figure 11. First floor plan and damage levels of masonry walls of Bam Tourist Inn.

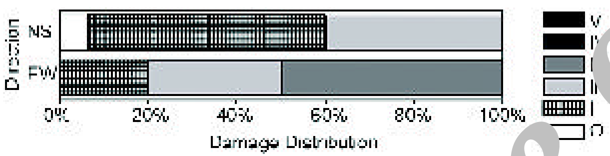


Figure 12. Distributions of the wall damage level in Bam Tourist Inn.

among the *NS* direction of Governor's Building and both directions of Bam Tourist Inn, as shown in Figure (13b). However, the maximum crack width in the EW direction of Governor's Building was much higher than those in the other cases. This may be caused by the torsional responses due to the horizontal irregularity of Governor's Building, because the larger crack widths were observed in the outside walls. The building damages can not be clarified in detail based on only 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 buildings can be estimated using the wall ratio in the first floor A_w/A_f and the floor weight per area w as follow:

$$C = \frac{\tau A_w}{w N A_f} \quad (3)$$

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

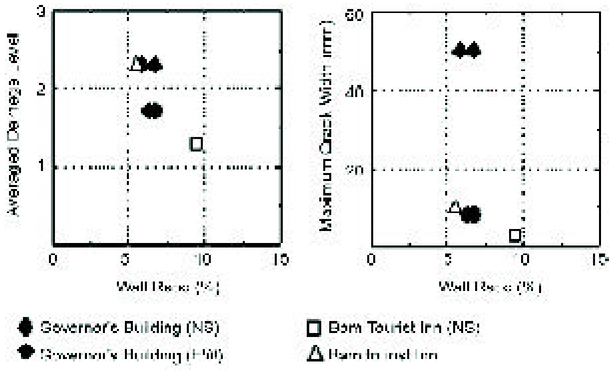


Figure 13. Relationships between the wall ratio and the wall damage level.

In general, simple masonry buildings are designed by assuming the floor weight per area of $800 kgf/m^2$, spoken by some Iranian engineers. It is generally difficult to estimate the averaged 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 hundreds meter west of Governor's Building and consists of three SM buildings. The two single-story buildings escaped severe damage, as shown in Photo (5), although minor cracks were found on brick walls. On the other hand, the two-story building was partially collapsed, see 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

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

Photo 6. Collapsed two-story school building.

Photo 7. Residence and store building under construction.

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

The wall area ratio in the first story is obtained as 4.1% in *NS* direction and 11.0% in *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 very short wall length may be expected due to existence of the windows and doors. The wall area ratio in *NS* direction of 4.1%, in which severer damage occurred, is less than values of the two buildings mentioned before.

5.3. Under Construction Residence and Store Building

The under construction building, see Photo (7) is located a few hundreds meter south of Governor's Building. The structural system of this building is quite typical of the buildings along the main streets in the downtown. The three-story steel structure consists of 4 bays in *NS* direction along the street and one bay in transverse direction (*EW*) as shown in Figure (15). Columns are erected using coupled I-shaped steel columns, see Figure (16). Steel braces (I-shape, $70mm \times 14mm$, $7mm$ in thickness) are installed in both exterior frames in *EW* direction. Brick walls, which are post-installed in the frame without confining by surrounding steel frame, are not expected to contribute for carrying lateral load. I-shaped steel profiles are also used for the girders and beams, see Photo (7).

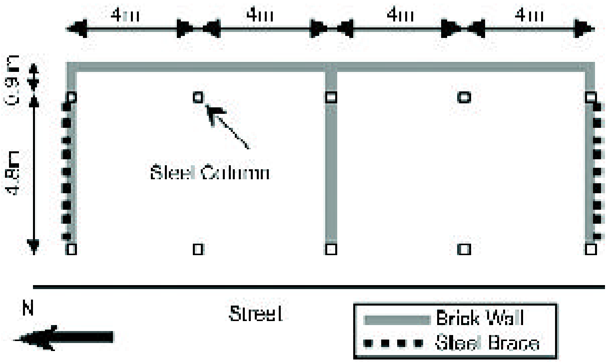


Figure 15. First floor plan.

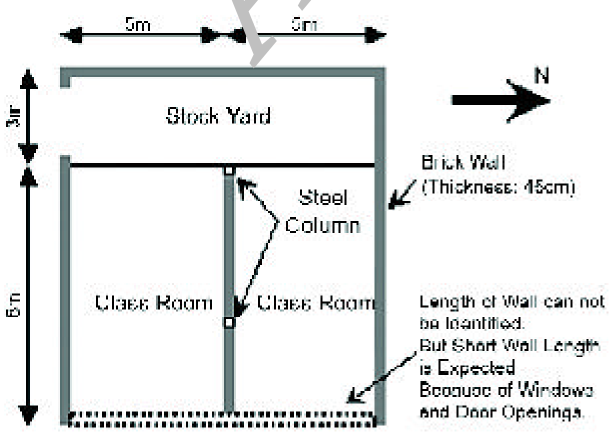


Figure 14. Floor plan of collapsed part of two-story school building.

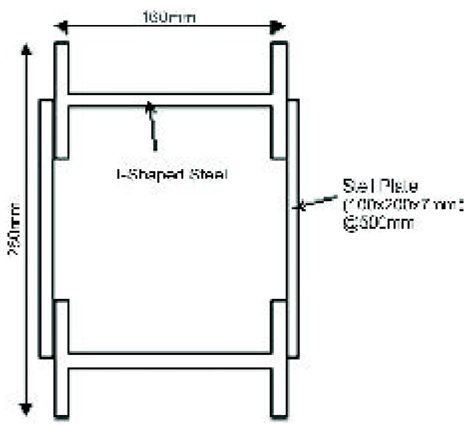


Figure 16. Section of coupled I-shaped steel column.

In the first story, fractures of welding joint and buckling of steel brace were observed, see Photos (8) and (9), and as a result, the brick walls were collapsed. Damage to the brick wall in the second story, see Photo (10) was also observed. No remarkable structural damage to the steel columns in *NS* direction was found, although bricks fell off the facade of the building.

Lateral load carrying capacity for the first story in *EW*, in the direction that the most severe damage occurred, was approximately estimated based on the following assumptions: (1) yielding strength of steel is $2.4 tf/cm^2$, (2) angle of steel brace is 45 degree, (3) unit weight of the building for each floor is $800 kgf/m^2$, and (4) floor area is $5.7m \times 16m = 91.2m^2$. These assumptions give a base shear coefficient, *C*, of 0.33. This base shear coefficient is relatively lower than the approximated values for both Governor's Building and Bam Tourist Inn. This may be one reason why this building suffered severe damage. Other reasons may be poor quality of welding, see Figures (8) and (9), and unconfined brick walls.

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

Photo 9. Close-up of Figure (8).

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

6. Concluding Remarks

Presented in this paper are the study results of the *AIJ* reconnaissance team on damage assessment due to the 2003 Bam-Iran earthquake. 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, designed according to the current Iranian seismic code. These might be some of the reasons for such a tragic damage to the buildings and human lives in spite of moderate magnitude ($Mw = 6.6$) earthquake.

Good correlation between wall area ratio and damage levels was observed. Although this result was derived from only two buildings (four cases), wall area ratio might be applicable for evaluating seismic capacity and screening retrofit candidates. Further studies are expected to apply it for practical design of masonry buildings.

The improvement of seismic capacity for adobe and masonry structures is a prior and urgent matter, in order to mitigate further seismic damages in such buildings, since these structural systems are most popular construction system not only in Iran but also in many Asian countries.

Acknowledgment

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