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BUILDING DAMAGE AND HUMAN CASUALTIES DURING THE BAM-IRAN EARTHQUAKE

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ABSTRACT

On December 26th, 2003 a devastating earthquake occurred in the southeastern Iran, causing a large number of collapsed buildings and human casualties. This study addresses the earthquake damage to buildings and its human casualties. Firstly, we analyze overall tendency of damage on basis of damage statistics comparing preceding surveys on building vulnerability and the relation between human casualties and building damage, and also on the basis of a questionnaire survey conducted in the stricken area. Finally, seismic response of an adobe masonry structure is analyzed by using Discrete Element Method, which can demonstrate the simulation of collapse of the structure.

Keywords: Bam earthquake, adobe masonry structure, human casualties, DEM

1. INTRODUCTION

At 5:26 AM (local time) on December 26th, 2003 a devastating earthquake occurred in the southeastern Iran, causing a catastrophic damage to Bam, in Kerman province. This earthquake was firstly estimated to be caused by a right-lateral strike-slip movement of Bam fault, but some researchers report another hidden fault running in the center of Bam based on the hypocenteral determination of aftershocks [1]. The epicenter and depth of the earthquake were estimated at 29.10N, 58.26E, and 10 km, respectively by the IIEES (International Institute of Earthquake Engineering and Seismology), Ref. [2]. The Moment Magnitude of the earthquake was estimated as Mw=6.6 by the USGS (United States Geological Survey) [3]. In the EMS98 seismic intensity scale, it is estimated with a maximum of IX near the vicinity of the fault [2], corresponding to the range between 5+ and 6 in the seismic intensity scale of Japan Meteorological Agency.

Main stricken area by this earthquake is shown in Figure 1. The Bam fault runs in the center of Figure 1, dividing into Bam in the west and Baravat in the east. There are some scattered villages near them. The other areas except for those seen as a green belt are deserts.

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Before the earthquake approximately 120,000 people (90,000 people in two cities) lived in the area shown in this figure. In a bulletin released immediately after the earthquake, the death toll was estimated to 41,000 people, but several months later after the Iranian government conducted detailed statistics of the earthquake damage, the number of deaths was finally corrected to 27,200 and the number of injured people to 14,300. In the other words, it means that approximately 30 percent of the Bam's population died during the earthquake. In the world, a large number of unseismic-engineered houses still exist, and even small-scale earthquakes have come out with building damage and casualties in the order of several tens of thousands. The Bam earthquake clearly shows its evidence, and also indicates that it is the most urgent task to make quake-proof of residential houses in those areas.

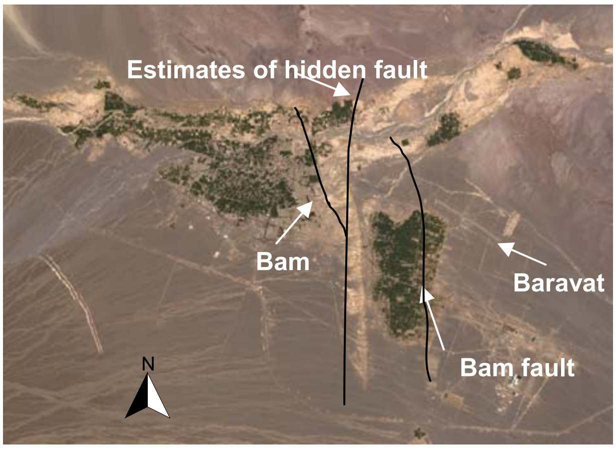


Figure 1. Stricken area

Something remarkable about this earthquake is that epicenter was directly under the city and the ratio of deaths was very high in the cities. Besides, on casualties by the earthquake, more death toll was reported than those injured. Generally speaking, the injured people outnumber the deaths, though statistics on the damage of injured people have somewhat difference from one earthquake to the other because it is difficult to define the injured compared to the dead. By the way, this earthquake shows an opposite tendency, presenting a new case. From these facts, this paper aims to analyze the relationship between building collapse and human casualties due to the Bam earthquake, and also to show the damage factors quantitatively in order to mitigate human casualties in the future earthquake.

This study is composed as follows. Firstly, Section 2 shows the overall tendency of damage on the basis of damage statistics conducted by the Iranian government [4] and also a comparative study based on preceding surveys of building vulnerability in order to examine the relation between human casualties with building damage. In Section 3, the relation between building damage and human casualties is further analyzed on the basis of a questionnaire survey conducted in the stricken area. In Section 4, the seismic response of an adobe masonry structure is analyzed by using the Discrete Element Method, which can demonstrate the collapse process of an adobe masonry structure.

2. BUILDING DAMAGE AND HUMAN CASUALTIES BASED ON STATISTICS

Damage statistics [4] were prepared by the Iranian government following the earthquake. Analysis herein is based on damage statistics of the 57 districts in which Bam and Baravat are classified, excluding 5 districts of Bam. Table 1 shows the building and human casualties of Bam and Baravat. Among 25,700 buildings in Bam and 7,200 buildings in Baravat (residential houses and commerce use houses are included), 92% of them collapsed in Bam and 61% in Baravat. Concerning the deaths and injured, while in Bam the deaths accounts for 28% of total population and the injured people for 10%, in Baravat the deaths accounts for the 7% and the injured people for the 4%. At whichever of these areas the number of injured people was half of the number of the deaths.

Table 1. Earthquake damage in Bam and Baravat

City	Jurisdiction province	Complete collapse		Damaged		No damage		Deaths	Injured people	Missing	Survived
		Houses*	Others	Houses*	Others	Houses*	Others				
Bam	Fars	1,633	1,369	44	267	0	9	2,132	433	18	5,692
	Gilan	1,487	643	1	0	0	0	1,127	692	39	6,376
	Hormozgan	1,684	1,289	48	61	1	3	1,566	758	9	7,078
	Isfahan	896	317	16	40	0	0	956	864	5	2,879
	Khorasan	1,324	791	198	73	19	48	2,180	726	25	6,439
	Markazi	1,254	1,536	8	25	3	1	3,403	749	16	2,005
	Mazardaran	1,296	563	49	557	4	14	659	188	14	5,876
	Tehran	2,931	1,164	15	54	1	0	6,059	2,694	211	7,104
	Yazd	1,873	999	78	313	1	8	3,842	684	74	5,236
	Subtotal**	14,378	8,671	457	1,390	29	83	21,924	7,788	411	48,685
Baravat	Sistan & Baluochest	2,804	1,838	33	2,536	1	5	1,112	578	36	13,598

Note: *) Houses include those partially used for commerce at the first floor as well as residential house.
**) Among 10 jurisdiction provinces of Bam, 5 districts of 1 jurisdiction province are excluded.

The distributions of ratios of building damage, deaths and injured people in the 52 districts of Bam and Baravat are shown from Figure 2 to Figure 5. As a whole, the building damage is concentrated in the west of Bam, which is near the hidden fault line [1]. The buildings that collapsed completely in Baravat are fewer if compared with those in Bam, in which more than half of the total buildings were completely collapsed (Figure 2). However, assessing the damage ratio of completely collapsed residential houses, more than 95% of the assessed houses turned out to be completely collapsed (Figure 3). It can be said that in Baravat the ratio of completely collapsed buildings is low because there are many non-residential houses. Considering the fact that earthquake occurred early in the morning when many residents were sleeping, more than 90% people were in the houses that collapsed completely. However, while the ratio of completely collapsed residential houses was almost the same among the districts, the impact to human differed. As shown in Figure 4, about half of residents died in the northern Bam, near the Arg-e Bam (Bam castle in Persian) and also in the southeastern area, while in the other areas had lower ratio by about 10%. Considering that neighborhood of Arg-e Bam is an old town and the south part of Bam is a new town, the high density of damage in the north can be attributed to the old buildings there. On the other hand, comparing the ratios of death and injures, northern and southeastern areas that had high death toll ratio also had high injured ratio, which represents about 20%, equal to half of the death ratio. In addition, the area where human casualties are low appears in the region between the northern and southeastern Bam. During the field survey, the authors had an occasion to inspect the damaged area by helicopter. Few buildings seemed to be collapsed from the sky, and buildings in these areas had flat roofs; few of the adobe masonry structures had a particular arch form. The difference between the complete collapse of adobe masonry structure and other masonry structures may have influenced in the death toll and the injured people.

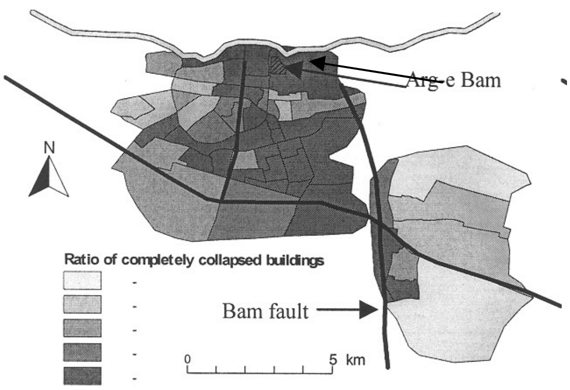


Figure 2. Completely collapsed buildings

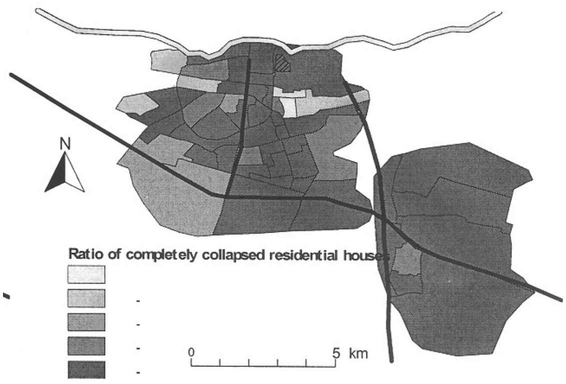


Figure 3. Completely collapsed residential houses

Figure 4. Ratio of deaths

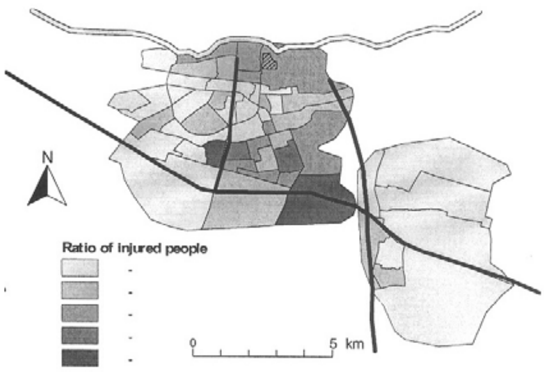


Figure 5. Ratio of injured people

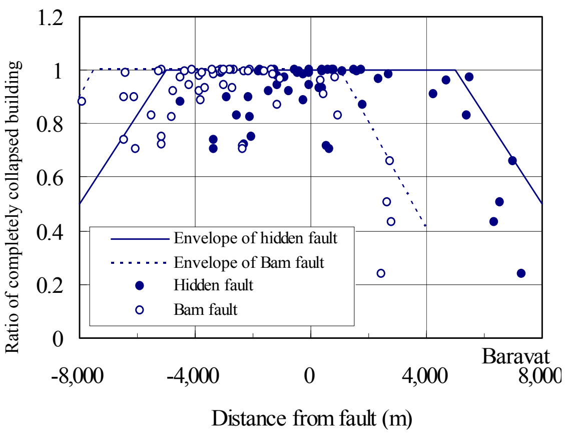


Figure 6. Completely collapsed buildings

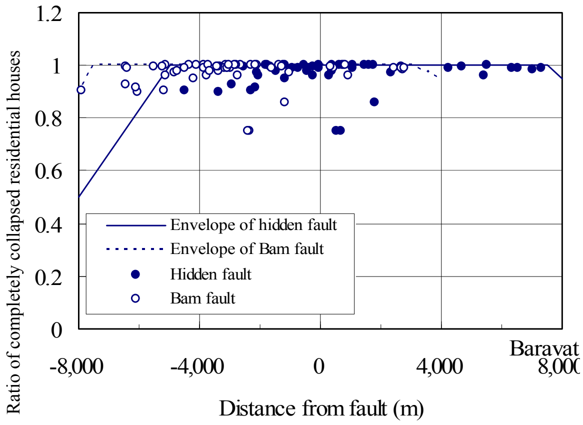


Figure 7. Completely collapsed residential houses

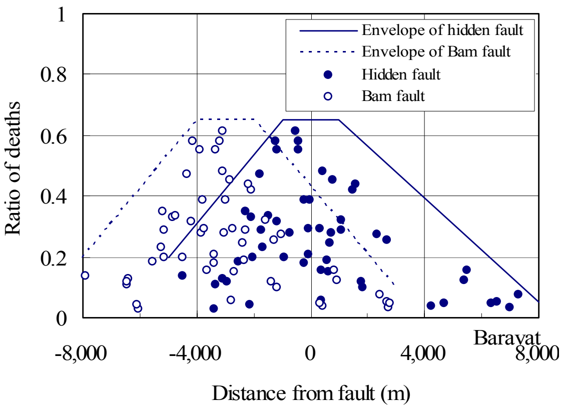


Figure 8. Ratio of deaths

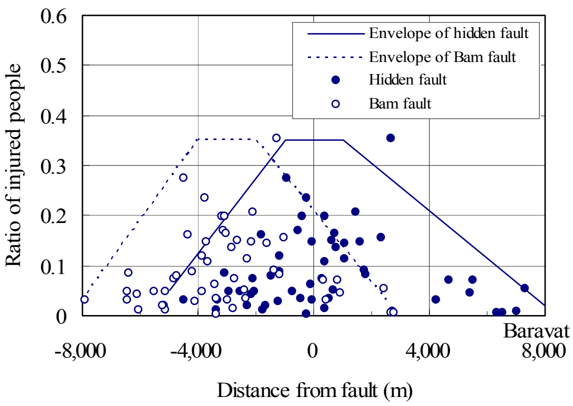


Figure 9. Ratio of injured people

Figure 6 to Figure 9 show the distribution of damage ratios in each district related to the distance from fault lines. The plus direction of distance axis means the distance on the east side, Baravat, and the minus one on the west side. Here we used two fault lines; Bam fault and the hidden fault based on aftershock records [1] as shown in Figure 1. The hidden fault is considered as a straight line from south to north, omitting the short branch. With respect to the building damage, the ratios of most districts are so high as to be close to 1.0, especially for completely collapsed residential houses. When a line enveloping dots of ratio is drawn in the same Figure, the ratio distribution of completely collapsed building shows that the flat top of ratio exist in 10 km distance close to fault line and the ratio decreases as distance from the fault line increases. The hidden fault line lays in the middle of the bell-shaped distribution. In case of Bam fault, the middle of bell-shaped distribution shifts toward to the Bam. The ratios of human casualties show the distribution more clearly in Figures 8 and 9. The ratios of deaths and injured people distribute with peaks at the hidden fault, and at 3 km west of Bam fault. From these Figures, if the damage were related to strong ground motion propagated from a fault, the hidden fault would be identified to cause the Bam earthquake. Not only from hypocenter determination of the aftershocks but also from the damage distribution, the hidden fault line is thought to reasonably exist.

With respect to the seismic resistance of buildings, there is an Iranian code of practice for seismic resistant design of buildings [5], but it is targeted for tied-framing masonry structure and rigid-frame structures such as steel frame and RC. So, there are no legal regulations for sun-dried brick (called abode) masonry structure that prevailed in the stricken area. Furthermore, seismic resistance of adobe masonry structures is not considered sufficiently. At the time of the Manjil earthquake of Iran in 1990, the relation between peak ground acceleration and the building damage ratio was investigated based on damage data [6]. Based on that, fragility curves for a variety of building structures in Tehran was developed regarding to the research on seismic hazard in Tehran, in a framework of an overseas JICA research project [7]. In Figure 10, the fragility curve for ‘brick and steel’ (steel frame filled with brick walls) was empirically obtained on basis of the Manjil earthquake when over 80% of the existing buildings were those masonry structures. This curve represents the fragility for brick and steel buildings; the fragility curves for other buildings were constructed by shifting the mean value of ‘brick and steel’. The peak ground accelerations observed in Bam during the earthquake were 0.7g and 0.8g horizontally and a maximum of 1.0g vertically [8]. According to the Zeraati’s report [9], 100% of adobe masonry structures, 100% of brick masonry structures without concrete frame, 90% of brick masonry structures with concrete frame, 90% of brick and steel structure were collapsed. Almost any buildings composed of masonry structures collapsed completely during the earthquake as indicated in the ratio of completely collapsed buildings shown in Figure 10, which has a value close to 100%. It can be said that the fragility curve shows a good relation with actual damage.

Two reasons can be thought about why Baravat had fewer damage. One is that the non-residential houses had ductile structures against building collapse compared with the buildings shown in Figure 10. The other is that Baravat is located at the east side of both the Bam fault and hidden fault where the ground motions were smaller. According to the acceleration records of BHRC [8], acceleration was not recorded in the area of the east side of the fault despite of being equipped with seismometers.

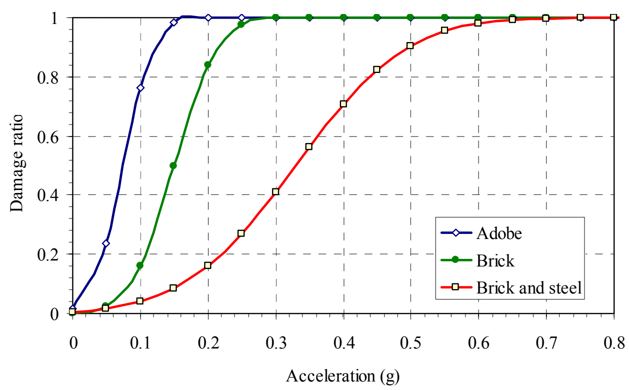


Figure 10. Fragility curves for structures

Next, in this paper the relationship between buildings type and human casualties is examined. According to statistics by the Iranian government, nearly 50% of the deaths were caused by the collapse of adobe masonry structures following the brick masonry structures as indicated in Table 2. On the other hand, the number of injured people caused by brick masonry structures was larger than those caused by adobe masonry structures. From the absolute number of the overall casualties shown in Table 1, the ratio of deaths to injuries in adobe masonry structures was 3.5 to 1, while in brick masonry structures 2.3 to 1 respectively. Here, the relation between the number of building damage and the number of casualties is presented. Figure 11 shows the number of buildings that collapsed completely and the number of deaths by jurisdiction provinces listed in Table 1. Although only the distribution for Baravat has a large deviation value, districts in Bam show upward proportional relation with rather large scattered values. Besides, districts on the east side of

Table 2. Human casualties' inhabited structures [4]

	Deaths	Injured people
Adobe masonry structure	500	39%
Brick masonry structure	440	52%
Reinforced concrete structure	10	1%
Steel structure	5%	8%

Bam are indicated with black dots; while districts on the west side are indicated with white dots, it is possible to find a steeper relationship for the eastern area districts closer to the hidden fault which resulted in more deaths even with the same completely collapsed buildings. A regression function for the deaths D obtained by districts only in Bam is expressed with collapsed buildings H as follows.

$$D = 0.988H \qquad (1)$$

Where, the number of buildings include all the buildings (residential houses account for 60.9%). The regression obtained herein means that one building brings about one death. The other relation between building and deaths in past Japanese earthquakes is indicated in the same Figure. Da is the deaths obtained by Ohta et al's regression [10] by substituting parameters related to the condition of the Great Kanto earthquake in 1923. Db is the deaths obtained by Miyano's regression [11] from inland earthquakes such as Kitatajima, Kitatango, Kitaizu, Mikawa, Fukui and Izuo Oshima earthquakes. Dc is the deaths obtained by regression from Kobe earthquake in 1995, Ref. [11]. These regressions are expressed as follows:

$$Da = 1.45H^{0.93}C_1C_2C_3 \quad (2)$$

$$Db = 0.145H^{0.99} \quad (3)$$

$$Dc = 0.05H^{0.886} \quad (4)$$

Equation (2) shows the relation in the year of 1923, equation (3) between years of 1925 and 1978, and equation (4) in the 1995 Kobe earthquake. As the building design has been improved in Japan, coefficients of above equations decrease as the year of earthquake increases. The death toll of Bam outnumbered that of the Great Kanto earthquake, and was six times that of the six inland earthquakes, and 50 times more than the Kobe earthquake. Here, the toll of the Great Kanto earthquake is assumed as the severest case such as large-scale fire due to earthquakes, in which all the conditional coefficients C_i (i=1,3) of equation (2) become 1.0, and it is special case including the burned tolls. However, for the death toll only due to collapsed houses, the number in the Bam earthquake was still more than the estimated by the regression equations for earthquake damage in Japan, even by doubling the results of this estimation. The enormous death toll of Bam earthquake appears to be influenced fundamentally by structural type of masonry structures, which is completely different from Japanese wooden houses.

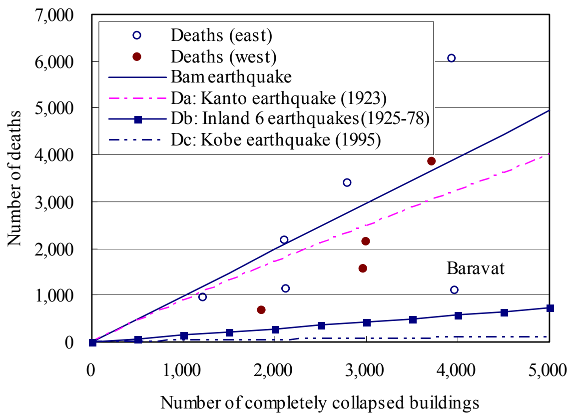


Figure 11. Relation between the number of completely collapsed number of completely buildings with number of deaths

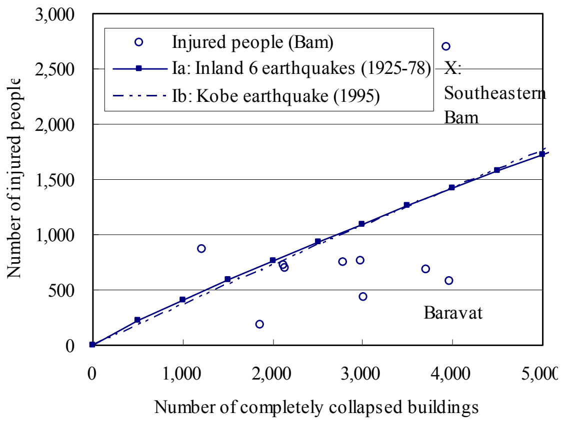


Figure 12. Relation between the collapsed buildings with the number of injured people

Although there is dispersion of half or twice in the number of injured persons in Bam regarding to the regression line, there is a tendency that the number of injured people in Bam distributes near the regression line similarly to the cases of Japan's earthquakes such as Kobe or previous ones. In the other word, damage statistics have showed that residences in Bam were overwhelmingly vulnerable to the ground motions of this earthquake. Comparing with building damage, the deaths are more than 6 times of those in the six inland earthquakes in Japan and 50 times more than in Kobe earthquake, this appears to be fundamentally due to the differences of structural types of Iranian masonry structures and Japanese wooden houses. However, results concerning to injured people during previous earthquake are similar. This pattern of casualty occurrence can be seen in the collapse of adobe masonry structures that not exist in Japan.

3. CASUALTIES DUE TO BUILDING TYPES BY QUESTIONNAIRE SURVEY

Since the damage statistics shown in Section 2 do not include the statistical report on the structural types of buildings in which people were killed or injured in the district basis, the authors conducted questionnaire surveys on damage conditions to residents of the area stricken by the Bam earthquake of January 2004, one month after the earthquake. The influence of collapsed building on residents was analyzed. Among research topics in this survey, the damage situation of housings as well as the present living situation of the affected people are included. The questionnaire was translated into Persian language in advance, and three Japanese-Iranian teams were composed by three researchers from Kobe University and three Iranian researchers who accompanied the authors in this investigation; questionnaire surveys were conducted by interviewing the affected people. It was conducted in 5 districts of Bam and Baravat obtaining a total of 31 questionnaires replied with 6 to 7 in each district. Figure 13 shows the districts we conducted a questionnaire survey. Targeted people were victims evacuated to shelters along roads in the neighborhood of several places of each district. The district in Bam were from districts B to E except Baravat district. Figures 14 and 15 show the surroundings in questionnaire-surveyed districts. The detail results of its survey are report in our report [12], but in this paper some results are shown.

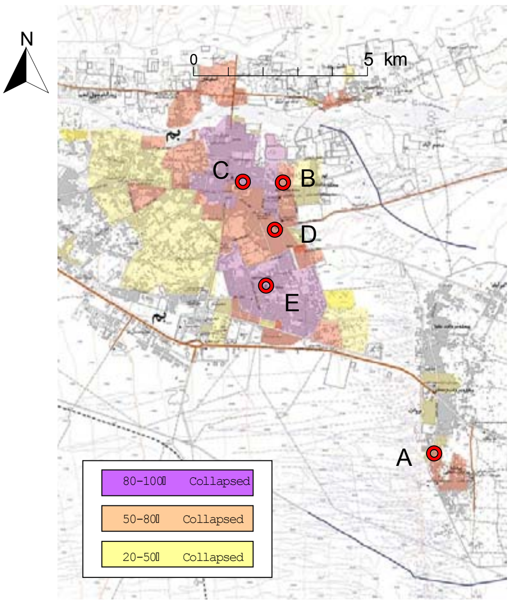


Figure 13. Questionnaire surveyed districts

Figure 14. Surroundings of district B

Figure 15. Surroundings of district D

Results of 31 cases in 5 districts concerning the building type indicate that adobe masonry structure and brick masonry structure with and without concrete frame were the most occupied in any district, as shown in Figure 16. Especially, houses of adobe masonry structure accounted for more than 50 % in all districts except for district D. There is a couple way to constructive brick masonry structures. One is just to pile up brick forming wall and the other is to pile-up bricks to form a brick wall, which is confined afterwards with concrete columns and beams. Though there are some houses built as masonry structures with concrete columns, the distinction of either masonry structure with concrete columns or not is not clear because the answers depended on the surveyed-residents judgment and we did not investigate the answers of each surveyed person. Furthermore, the damage level of houses is not viewed from the structural yield strength evaluation, but from the answers of the surveyed-residents. More than 90% of them answered their house had collapsed and were uninhabitable. As people evacuated to shelters answered the questionnaire, some of their answers could be considered a little exaggerated. By the way, the damage level compared with damage statistics shows similar results, thus more than 90 % of the answers can be regarded as appropriate. About collapse situations, in district D depicted in Figure 16, houses were damaged but roof-ceilings remained in many cases, while in other districts houses remained without ceilings or collapsed adobe bricks were piled around the houses. Thus, collapse situations differ even in the same answer of completely damaged houses.

Figure 17 shows the damage situation about all the surveyed families. 70 out of 175 people died among the members of the surveyed families with 30 people injured and the rest 66 surviving without injuries. In district D, the death ratio is small while in other districts the earthquake killed 40-50 % of family members.

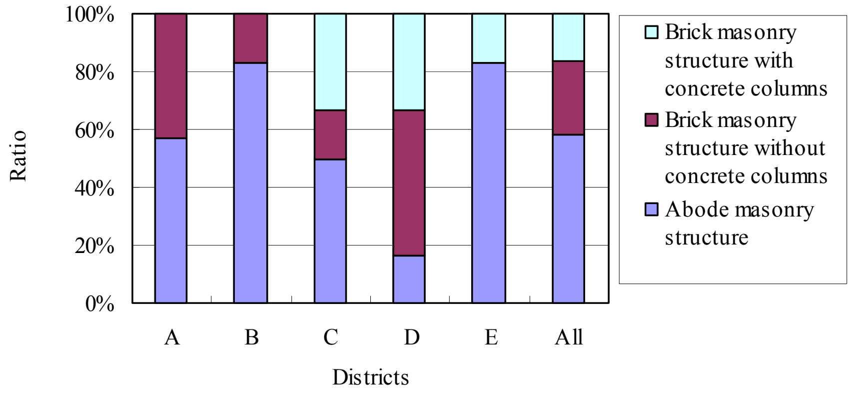


Figure 16. Building structures in questionnaire-surveyed

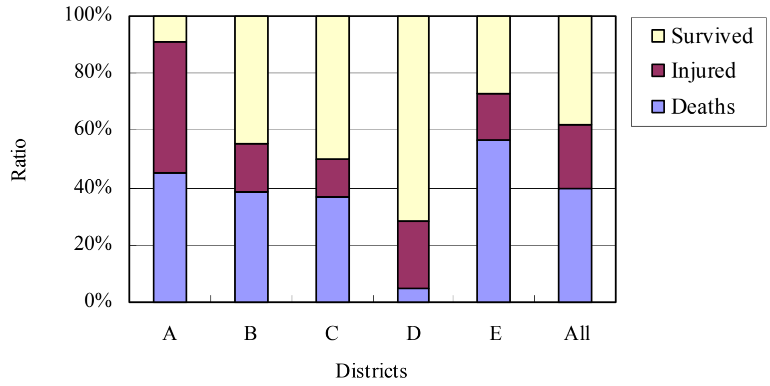


Figure 17. Damage to surveyed families

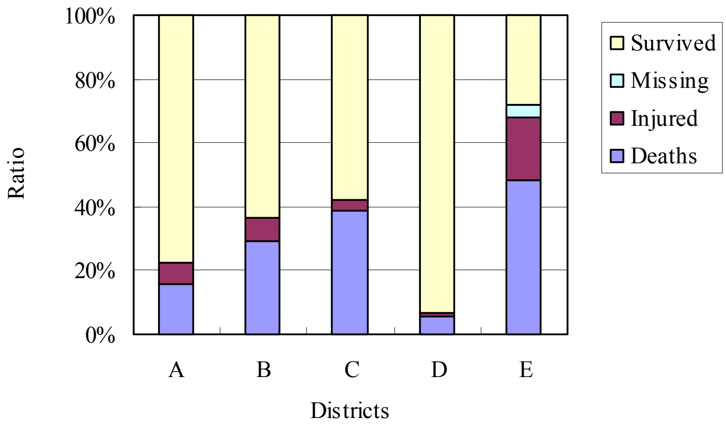


Figure 18. Statistics of damage to surveyed families

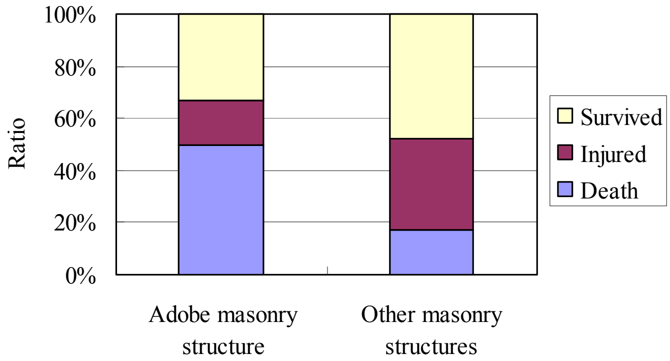


Figure 19. Damage rate for building structures

According to the answers of surveyed people, all the deaths were caused by fallen debris of houses that collapsed during the earthquake. In the survey of this investigation, the injured were fewer than the deaths, 40% were deaths and 20% were injured according to the average of all the answers. Results of the questionnaire survey in surveyed districts are compared with those in the same districts in damage statistics as shown in Figure 18. In district A of Baravat, the death ratio exceeded that of actual statistics while in other districts the death ratios are almost similar to the statistics results. Thus, our survey reflects the damage situation well though 6-7 questionnaires were applied in each district. On the other hand, our questionnaire survey had several times more injured people than the statistics. Therefore, we are now investigating what kind of standards of statistics are the most suitable to use. However, we can suggest that our results include minor injuries and thus more injuries were reported than the governmental statistics. Because, our questionnaire did not define several conditions for injuries such as whether conditions, treatment received from medical institutions, period of hospitalization or the levels of injuries, but just asked "Is there any family member who was injured?". Moreover, districts A and D had higher or similar ratio of injures than the death ratio. These two districts have characteristically more masonry structures without concrete columns than other districts. We can say that the collapse of adobe masonry structures caused more deaths and the brick masonry structures caused many injures as well as the deaths.

In addition, when death ratios according to the type of building structure were calculated for all the answers, it turned out that 50 % (61 out of 123) of deaths occurred in adobe masonry structures, and 17% (9 out of 52) of deaths in brick masonry structures (see as Figure 19). Among masonry structures, the collapse of adobe masonry structures had great influence on the occurrence of deaths, whereas fewer injures occurred in adobe masonry structures. In brick masonry structures, the pattern indicates that the number of injured people is more than deaths. According estimations from damage statistics, the northern and southeastern Bam where more deaths were claimed had many houses built as adobe masonry structures, while the places were the more injured people occur had many masonry structures other than adobe masonry structures.

4. COLLAPSE SIMULATION OF ADOBE MASONRY STRUCTURES

In order to evaluate the vulnerability of an adobe masonry structure and its impact on human casualties, a collapse simulation was conducted herein by using a DEM (Discrete Element Method) computer program developed by the authors [13]. For this purpose, an adobe masonry structure was modeled in two-dimensions with its roof arch-shaped as shown in Figure20. The size of the model was determined on basis of site surveys in the stricken areas (Figure21). The elements are circular with radius of 5 cm and arranged to form a regular triangle between elements (disregarding the arch part). Putting axial force spring and shearing force spring between elements toward the axis and the tangent respectively, we calculate the axial force, the shearing force and the bending moment at each time step from relative displacement that occurs between elements, and update the position of the elements. When a spring moves 1.1 times away from the initial length between elements, the spring between elements is cut down and do not transmit force [14]. The model was designed to account for a new contact spring when other elements approach the length limit of 1.1 times longer than the elements themselves. As for spring coefficients, spring coefficient toward axial force and spring coefficient toward shearing force can be designed as elastic objects when the element's Young moduls is given.

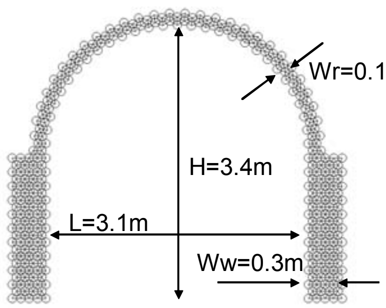


Figure 20. Analytical model

Figure 21. Survey of adobe masonry structure

Table 3. Mechanical properties of adobe masonry structure

Unit weight (kN/m^3)	12.74
Young's modulus (kPa)	42,857
Poisson's ratio	0.25
Cohesion (kPa)	49
Angle of internal friction (deg)	20
Damping coefficient	0.02
Compressive strength(kPa)	29,400

Now unit weight of the elements and material characteristics for spring are listed in Table 3. The Mohr Coulomb failure model is used for the spring failure by shearing force. In the model, predominant period obtained by free vibration, was 0.13 seconds. This result corresponds nearly to the natural period of 0.1 seconds for adobe masonry structures obtained by microtremor [12] as shown in Figure 22. Therefore, this analytical model is appropriate.

The ground motion used in the analysis consists of two components, horizontal and vertical, recorded by accelerometers of Bam earthquake [8]. Two waves of Bam and Abaragh are used in this study, as shown in Figure 23. About the analysis cases, we considered four cases adjusting the amplitude of wave lines; case 1, no adjustment of the amplitude in Bam wave, case 2, 1/2 adjustment of the amplitude in Bam wave, case 3, 1/4 adjustment of the amplitude in Bam wave, and case 4, no adjustment of the amplitude in Abaragh wave.

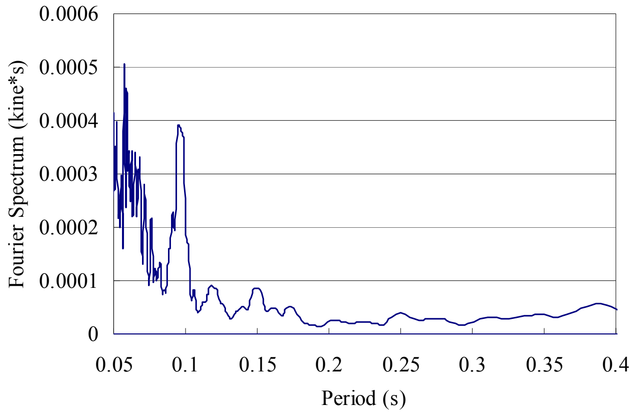
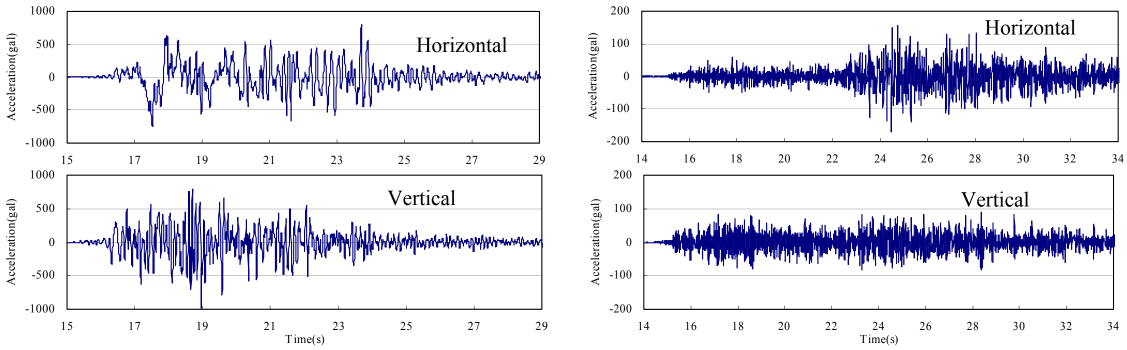


Figure 22. Survey of adobe masonry structure

The results of simulation show the only Bam wave's cases caused to collapse, while the Abaragh wave did not. Figures 24, 25 and 26 are examples of collapse situations of adobe masonry structures by the ground motion of Bam (cases 1 and 3). As the ground motion registered in Bam had a characteristic period ranging in the range of 0.1-0.2 seconds, it is possible to say to collapse easily by resonance effect. The collapse mechanism is as follows; at first, shear failure of the arch occurs upwards from the joints of the columns. It is followed by cracking at the top of columns, then the top of the arch falls down. When the amplitude of the ground motion is large, cracks may occur in the walls. Once failure pattern is generated when cracking starts to occur in the arch, the blocks forming the arch and columns collapse and turn into granular elements. The time for arch roof to reach on the ground differs by the case. For the cases of small amplitude of ground motion, difference between cases 3 and 4 is the amplitude of vertical component. It is thought that the high vertical ground motion makes more chance to collapse.



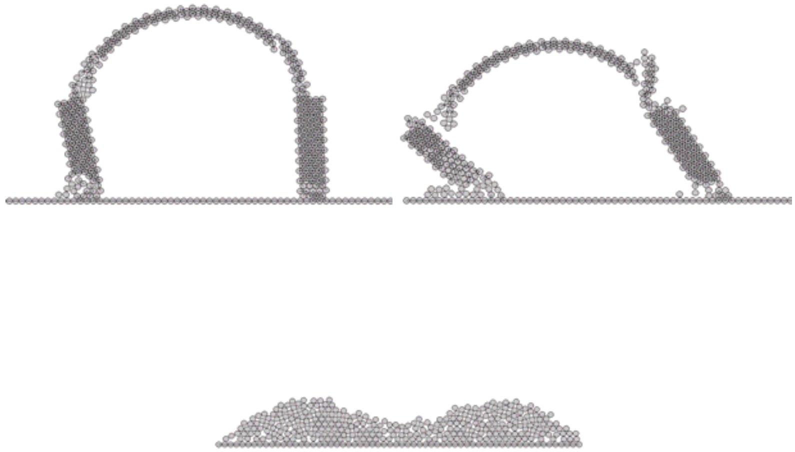
(a) Bam (b) Abaragh

Figure 23. Ground motion

Figure 27 is a photo of Arg-e Bam taken from the helicopter. What can be seen from a post-earthquake inspection of the adobe masonry structures built inside the rampart of this castle are only several walls and piles of adobe bricks or sand mound. Failure mode in the analysis reproduces similar collapse condition with columns of small adobe bricks in the stricken area. The analysis of this example shows that collapse situation may differ if input parameters, the model and the ground motion change. By the way, in any case, it is obvious that adobe masonry structures turns fragile once it is cracked somewhere and turns strong when is monolithic.

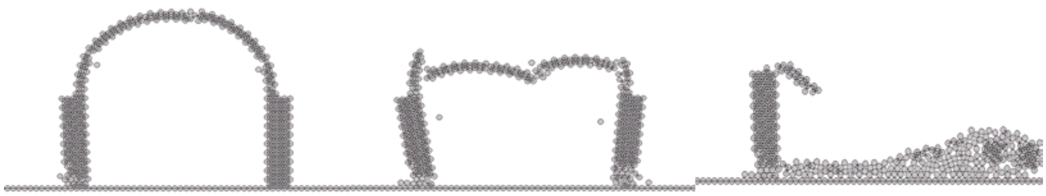
Figure 28 shows the vertical force that affects elements at top of the arch when collapse occurs, such as the collapse of case 1 in which no adjustment of the amplitude is considered. As soon as cracks occur in the arch, the element of the arch has as strong shock as maximum 45g at the floor. Another report [14] says that human breast becomes a few chance of severe injure by more than 45g acceleration, and more chance by more than 60g. As shown in certain models, failure depends on the thickness of the arch section, and acceleration more than 60g may cause serious impact to human lives. These shocks attacking human body are very dangerous.

As seen from the collapse results, it is clear that once the arch fails, in several seconds the room is covered with collapsed bricks and when it happens, people get confined by the debris and cannot have space for survival. Wooden houses and RC buildings may not have the ceilings fallen all at once because the main structure is composed by beams and columns that resist the ground motion even if the secondary structure members are damaged. There are cases in wooden houses that even if the ceiling falls, as there is much furniture, people may result protected by the furniture. However, when adobe masonry structures collapse, they chunks into pieces, smaller than furniture. This type of structures that had great impacts on the human lives in Bam where there are many adobe masonry structures.



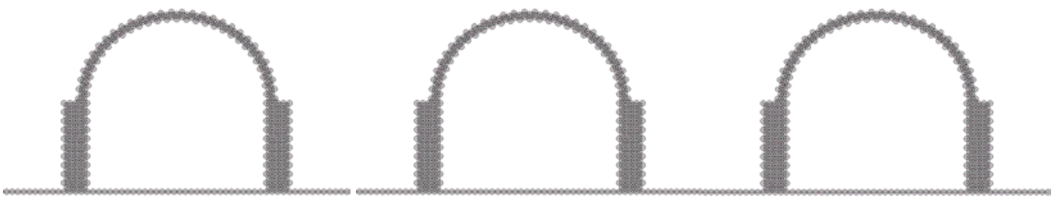
18.4 sec 19.3 sec 27.1sec

Figure 24. Collapse situation (Bam ground motion, no adjustment of the amplitude)



18.4sec 20.6sec 24.9sec

Figure 25. Collapse situation (Bam ground motion: 1/4 adjustment of the amplitude)



14.0sec 24.0sec 34.0sec

Figure 26. Collapse situation (Abaragh ground motion: no adjustment of the amplitude)

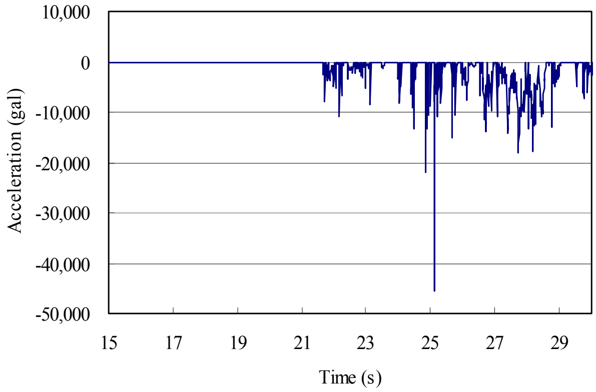


Figure 27. Collapse situation in Arg-e Bam collapse

Figure 28. The acceleration affected the indoors causing brick

5. CONCLUSIONS

This paper analyzed human casualties and building vulnerability during the Bam, Iran earthquake. The conclusions are the following.

1. In Bam earthquake, more than 90 % of buildings collapsed. The fragility estimated for buildings by observed ground motion showed almost the same as the actual state.
2. Distributions of building damage and human casualties during the Bam earthquake could verify the hidden fault that was obtained by the hypocentral determination of aftershocks.
3. Comparing the relation between building damage and the casualties in Japan's past earthquakes, this earthquake claimed deaths six times more than in Japan, while the injured exhibited the similar tendency.
4. From the survey questionnaires, the survival rate was only 50% due to the collapse of adobe masonry structures. Also, it became clear that brick masonry structures brought about twice more injured people as deaths due to building collapse.
5. The DEM simulation of adobe masonry structures makes clear that once it started to collapse, blocks turned into pieces and the arch part fell in several seconds. The impact on things inside building turned out to be very dangerous to human lives.

We did the collapse simulation of adobe masonry structures with an analytical model and show a good tool to would like to express their collapse process of structures. By the use of the DEM analysis, reinforcement measures of adobe masonry structure are considered in the future work.

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