NOTE

Damage to masonry buildings caused by the 1995 Hyogo-ken Nanbu (Kobe, Japan) earthquake

Michel Bruneau and Koji Yoshimura

Abstract: The seismic performance of the few masonry structures present in the Kobe area and subjected to the severe Hyogo-ken Nanbu earthquake is a minor concern when compared to the overwhelming damage suffered by other types of structures. However, in order to dispel the myth that masonry structures are nonexistent in Japan as well as a few other misconceptions, and for the sake of completeness within the concerted multipaper reporting effort on the Hyogo-ken Nanbu (Kobe) earthquake by the Canadian reconnaissance team which visited the epicentral area of this earthquake, a brief description of the past and present state of masonry construction in Japan is first presented, followed by a short description of the damage to unreinforced masonry buildings, masonry garden-walls, and nonstructural masonry elements, as observed by the authors during their visits to the Kobe area.

Key words: earthquake, seismic, masonry, buildings, bearing walls, unreinforced masonry, reinforced masonry, failures, design codes.

Résumé : La performance séismique des quelques structures en maçonnerie présentes dans la région de Kobé et soumises au sévère tremblement de terre Hyogo-ken Nanbu est un problème mineur comparativement à l'endommagement majeur subi par d'autres types de structures. Cependant, afin de dissiper le mythe que les structures en maçonnerie sont inexistantes au Japon, ainsi que quelques autres fausses conceptions, et dans le but de compléter l'effort concerté d'un rapport à plusieurs articles sur le tremblement de terre Hyogo-ken Nanbu (Kobe) par l'équipe Canadienne de reconnaissance qui a visité la zone épicentre de ce séisme, une brève description de l'état passé et présent des constructions de maçonnerie au Japon est premièrement présentée, suivie par une courte description de l'endommagement des bâtiments en maçonnerie non renforcée, des murs de jardin en maçonnerie et des éléments de maçonnerie non structuraux, tel qu'observé par les auteurs lors de leur visite à la région de Kobe.

Mots clés : tremblement de terre, séismique, maçonnerie, bâtiments, murs portants, maçonnerie non renforcée, ruptures, codes de design.
[Traduit par la rédaction]

1. Introduction

Unarguably, the seismic performance of the few masonry structures present in the Kobe area and subjected to the severe Hyogo-ken Nanbu earthquake is a minor concern when compared to the overwhelming damage suffered by other types of structures. However, silence on the issue would be misleading and perpetuate the myth that masonry structures are nonexistent in Japan. This may be true in relative terms, as the volume of structural masonry construction is small and certainly overshadowed by that of reinforced concrete, steel, and wood, but not accurate in absolute terms. First, for few decades at the turn of the century, and somewhat surprisingly for those not familiar with Japanese history, unreinforced masonry buildings of western style have been constructed in many parts of Japan such as Kobe. Second, beyond this historical legacy, Japanese researchers have also actively conducted research on the seismic behaviour of reinforced masonry buildings; seismic design requirements for reinforced masonry structures have appeared as an offspring of this effort, and some have been constructed.

Hence, for the sake of completeness, this technical note has been prepared for inclusion in the concerted multipaper reporting effort by the reconnaissance team of the Canadian Association for Earthquake Engineering which visited the epicentral area of this earthquake. A brief description of the past and present state of masonry construction in Japan is first presented, followed by a short description of the damage to unreinforced masonry buildings, masonry garden-walls, and nonstructural masonry elements, observed by the authors

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during their earthquake reconnaissance visits to the Kobe area. Satisfactory performance of reinforced masonry buildings is reported within limits, for reasons explained later.

The two authors visited the disaster areas separately, within days of the main shock. The first author conducted these visits sometimes on his own initiative, at other times joining the efforts of either the Kyoto University Disaster Prevention Research Institute team, the Architectural Institute of Japan (AIJ) investigation task force, or the official Canadian reconnaissance team. The second author's visits were conducted under the auspices of his home university as well as the official earthquake damage reconnaissance team sent by the Steering Committee for Concrete and Masonry Wall Structures of the AIJ.

2. Historical overview

2.1. General

In 1853, following centuries of self-imposed isolation from external and international influences, Japan embarked on an era of large-scale international trade. Under the rule of Emperor Meiji (1868 – 1912), the Japanese political, educational, medical, and military institutions (to name a few) were modified to resemble the European and American models, and numerous aspects of architectural and engineering technology were enthusiastically imported. For example, the first "western style" structure in Japan, the British No. 1 House, was apparently constructed in Tokyo in 1860 (by the carpenter Iwakichi Kajima, whose small business then eventually grew to become the well-known Kajima Corporation), and the demand for this new architecture grew exponentially. The first clay bricks were imported to Japan in 1858, and production of clay bricks and cement in Japan started a decade later. In the 1870s, numerous public buildings were constructed throughout Japan using unreinforced clay brick masonry bearing walls according to "western" design and construction practices.

In this early period of international trade, Kobe rapidly developed to become the most important fully accessible deep water port of eastern Japan. Hence, western influence was pro-eminent in Kobe, and not surprisingly, many prestigious buildings were constructed using the same unreinforced masonry material and architectural and engineering details found in the North American practice. Likewise, their seismic performance during the Hyogo-ken Nanbu earthquake of January 17, 1995 (the first significant earthquake to hit Kobe since 1956), also resembled that observed following past North American earthquakes.

2.2. Evolution of masonry construction in Japan

When the 1891 Nobi earthquake struck, a large number of unreinforced brick masonry buildings located in Nagoya suffered severe damage. The extent of damage to modern structures as a result of that earthquake led to the establishment of the Earthquake Disaster Prevention Research Committee by the Japanese Ministry of Education, and the beginning of a sustained Japanese research activity in earthquake engineering and seismology. However, masonry construction was not banned. Instead, concrete masonry block units were imported to Japan (starting in the early 1900s) and widely used in the construction of unreinforced nonbearing building walls, replacing clay brick units for this purpose. In 1923, the Great Kanto (Tokyo) earthquake extensively damaged (among many structures) most of the brick masonry buildings and unreinforced concrete masonry nonbearing walls. Masonry construction effectively stopped in Japan following this most devastating earthquake.

A renewed interest in masonry construction appeared after 1945. Because most of the wood houses in Japan were burned by the bombing raids conducted by the American Air Force during World War II, research was initiated to develop more fire-resistant residential buildings. Most of that research was conducted at the Building Research Institute of the Ministry of Construction of Japan. As a result of these activities, Japan started to produce concrete masonry blocks, and the first edition of the AIJ *Standard for Structural Design of Reinforced Hollow Concrete Block Masonry Structures* was published (in 1952). On the basis of this standard, and particularly the requirements for fully grouted reinforced concrete masonry buildings, masonry residential buildings of less than three stories have been designed and constructed all over Japan. The scope of the AIJ standard was expanded to also address the design of small masonry property walls (called garden walls in Japan) after the 1978 Miyagiken-oki earthquake in which two thirds of all casualties were caused by collapsing garden walls (approximately 15 000 walls overturned during this earthquake).

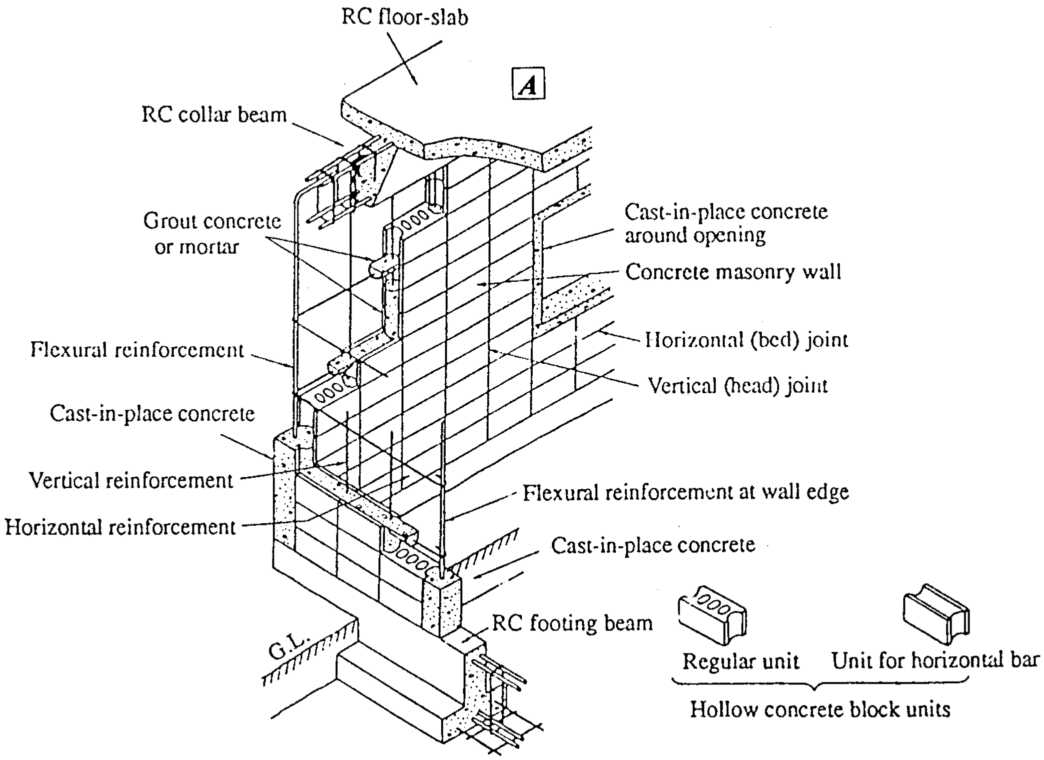
From 1984 to 1989, a U.S. – Japan joint research project was conducted to investigate the seismic resistance of reinforced masonry buildings and, in the case of Japan, to extend the AIJ provisions to include buildings up to five stories. To this purpose, a full-scale five-story three-dimensional reinforced masonry building was tested at the Building Research Institute of the Ministry of Construction. Based on the research results from this project, the Japanese Society for the Promotion of RM Buildings ("RM" meaning "reinforced fully grouted concrete block masonry") was founded and published a complete set of design and construction standards independently of the AIJ. Currently, the AIJ is updating the technical requirements of its standard to also address RM buildings of four and five stories.

It is noteworthy that severe structural damage has not been observed in reinforced masonry buildings well designed and constructed in accordance with the AIJ Standard following Japanese earthquakes prior to 1995. However, it remains that reinforced masonry construction is still sparse in Japan and that most of the hollow concrete block masonry units produced in Japan are currently used for the construction of nonbearing walls in buildings and garden walls.

3. Japanese masonry design requirements

The sixth edition of the *Standards for Structural Design of Masonry Structures* published by the AIJ (1994) covers six types of masonry constructions: (*i*) reinforced hollow concrete block masonry structures; (*ii*) reinforced fully grouted concrete masonry structures; (*iii*) concrete masonry nonbearing walls; (*iv*) concrete masonry garden walls and fences; (*v*) unreinforced masonry structures; and (*vi*) precast reinforced concrete assembly floors. A schematic typical wall layout for the first two types of structures is shown in Fig. 1.

Fig. 1. Schematic illustrations of some masonry construction types covered in the Architectural Institute of Japan *Standards for Structural Design of Masonry Structures*: (*a*) typical reinforced hollow concrete block masonry structure; (*b*) typical fully grouted masonry structure (from AIJ 1994).



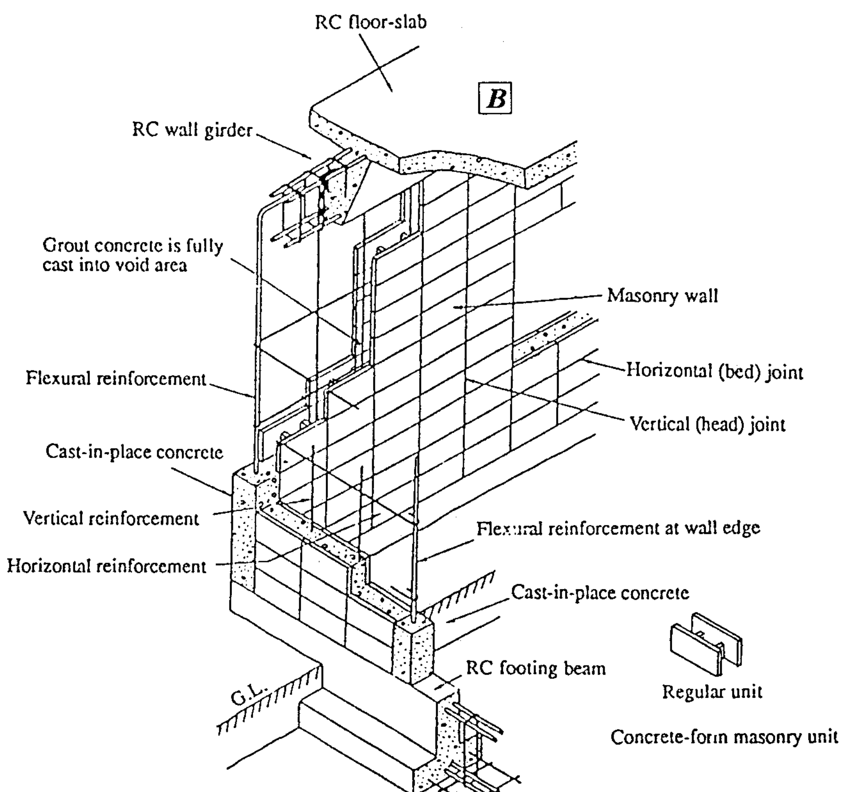
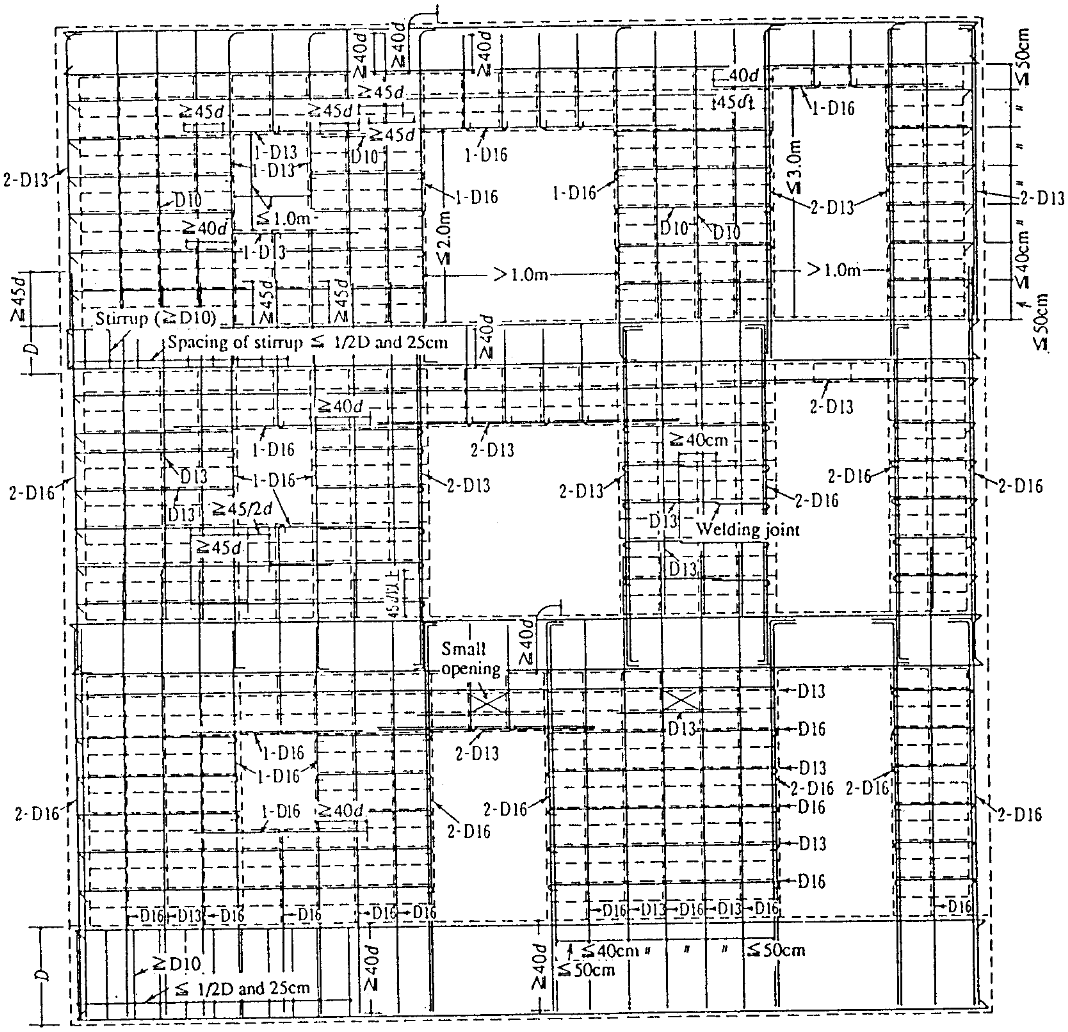


Fig. 2. Example of standard reinforcement specified by the Architectural Institute of Japan *Standards for Structural Design of Masonry Structures* for a typical fully grouted masonry structure (from AIJ 1994).



Both reinforced hollow and reinforced fully grouted concrete block masonry structures are designed using the concept of "wall rate" values, a simple ratio expressed by the length of walls (in centimetres) in a given story divided by the floor area of the story (in square metres). Required wall rates vary from 15 to 27, depending on masonry block quality and story height. These wall rates were developed by considering a maximum equivalent static seismic lateral force of 0.2W (and a progressively lesser value as structural period increases), allowable compressive strengths equal to 66% of the ultimate compressive strength of the masonry units, and allowable shear strengths equal to 10% of the allowable compressive strengths. Furthermore, walls must be regularly distributed over the entire floor plan according to a "divided floor area" formula, and maximum height is restricted to three stories. No explicit structural engineering calculations are necessary if these and some prescribed detailing requirements are respected. An example of standard reinforcement is shown in Fig. 2. Note that in the figure, the abbreviation D10, for example, refers to 10 mm diameter bars.

For reasons that will become obvious in Sect. 5, a detailed review of the Japanese reinforced masonry design requirements beyond what is presented above is unwarranted at this time.

Comparison of the seismic-resistant design practice in the two countries is also a major task beyond the present scope, and cannnot be justified in light of the observations made in Kobe; it would more suitably be the subject of a future paper. In the meantime, the reader who wishes to further explore this topic is referred to the English edition of the AIJ *Standards for Structural Design of Masonry Structures* (AIJ 1994). A recent summary of the Canadian masonry seismic-resistant design practice has already been presented elsewhere (Bruneau 1994*a*).

4. Damage to unreinforced masonry buildings

In past earthquakes worldwide, unreinforced masonry buildings have been identified to fail in a well-defined number of ways; the terminology for these failure modes, already presented elsewhere (Bruneau 1994*b*), will be used here.

Fig. 3. Collapsed unreinforced brick masonry buildings of a sake-distillery: (*a*) global view of rubble blocking a street, and showing type of masonry units; (*b*) walls partly collapsed in out-of-plane manner; (*c*) wall with visible in-plane cracking.

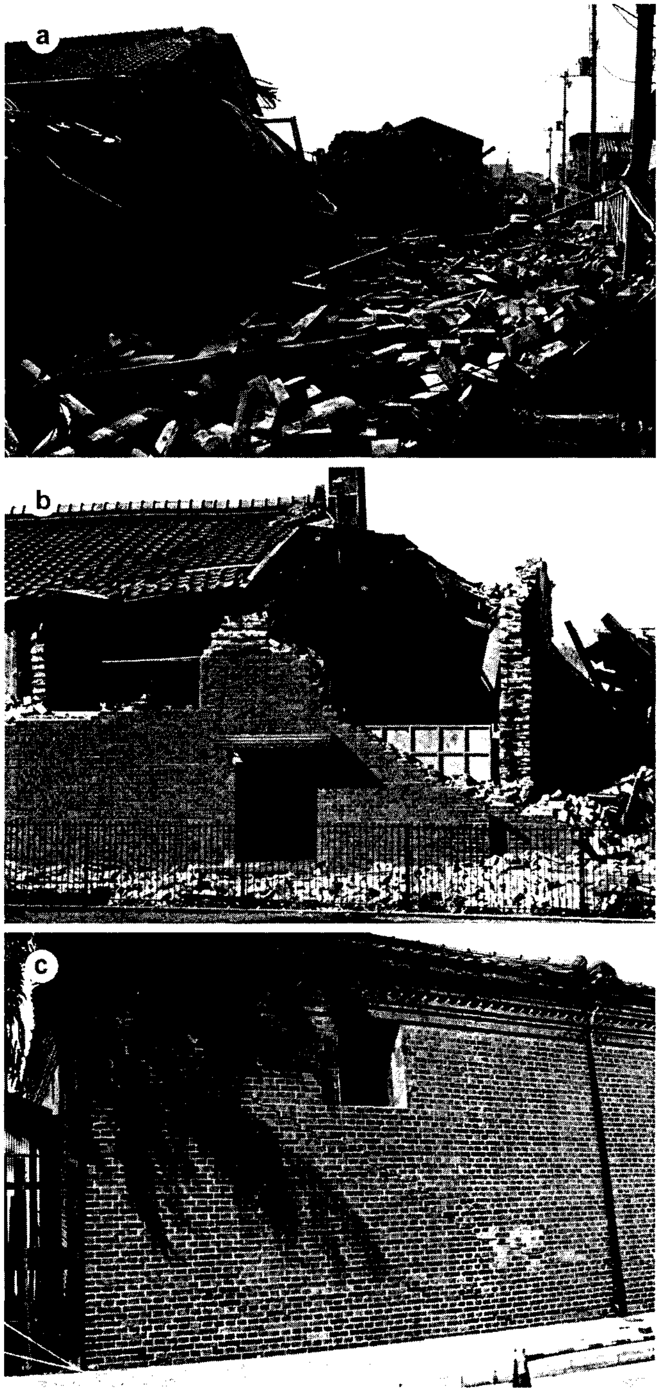


Fig. 4. Severely damaged unreinforced masonry building in downtown Kobe: (*a*) global view; (*b*) close-up view of a simply supported gravity structure.

4.1. Unreinforced masonry buildings

All unreinforced masonry buildings that could be found by the authors have suffered extensive damage, whether or not they were surrounded by damaged buildings constructed of other materials. For example, a sake-distillery near the shoreline east of Kobe suffered from the collapse of a large number of its buildings (Fig. 3), while none of the adjacent reinforced concrete and steel buildings showed signs of damage. Out-of-plane failures were dominant for that group of buildings (Fig. 3*b*), although some severe in-plane shear cracks could also be observed in the few uncollapsed single-story buildings (Fig. 3*c*). By contrast, another building that suffered significant out-of-plane failure of its walls at the higher stories, and the "caving-in" of its central portion (Fig. 4), was located in downtown Kobe and surrounded by numerous heavily damaged buildings of other construction types.

Interestingly, some buildings that appeared to have suffered no damage when seen from their main entrance side were actually found to have lost significant portions of their higher-story walls in an out-of-plane manner when inspected on the other sides. For example, this happened to the building shown in Fig. 5, located in downtown Kobe near one of the expressways that collapsed. Given the otherwise excellent in-plane behaviour of this building, this out-of-plane failure could have easily been prevented by adding vertical reinforcement braces or using other equally simple seismic retrofit techniques reported in the existing literature (Bruneau 1994*c*).

It is noteworthy that none of the unreinforced masonry buildings surveyed by the authors showed evidence of seismic

Fig. 5. Out-of-plane damage to unreinforced masonry building walls in downtown Kobe: (*a*) global view of a wall; (*b*) close-up view.

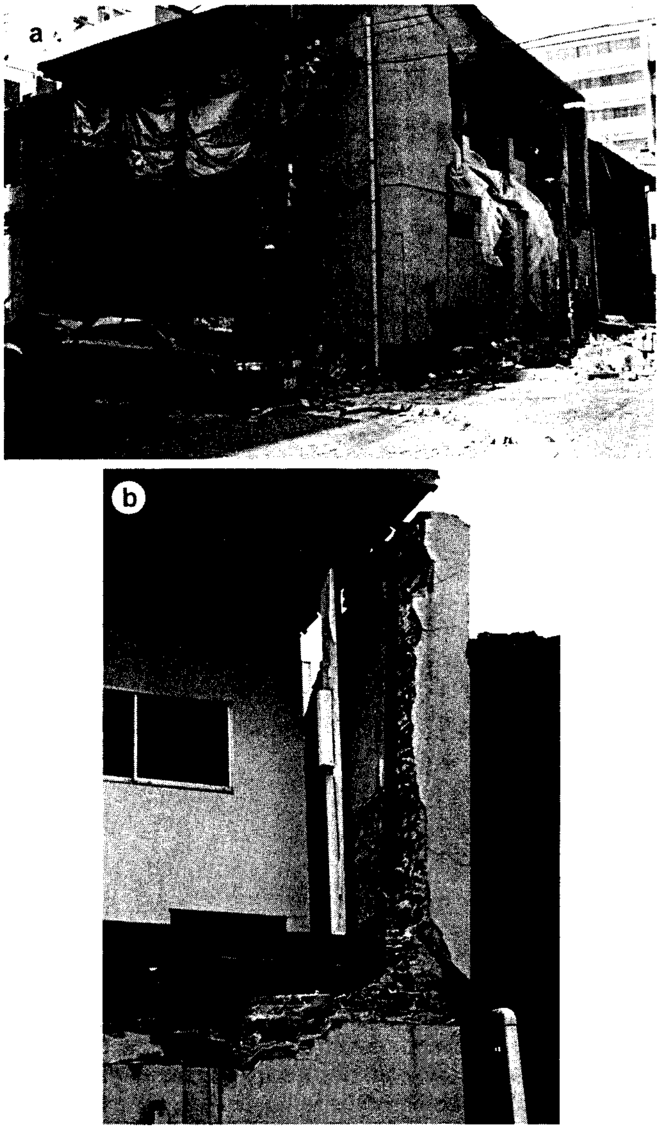
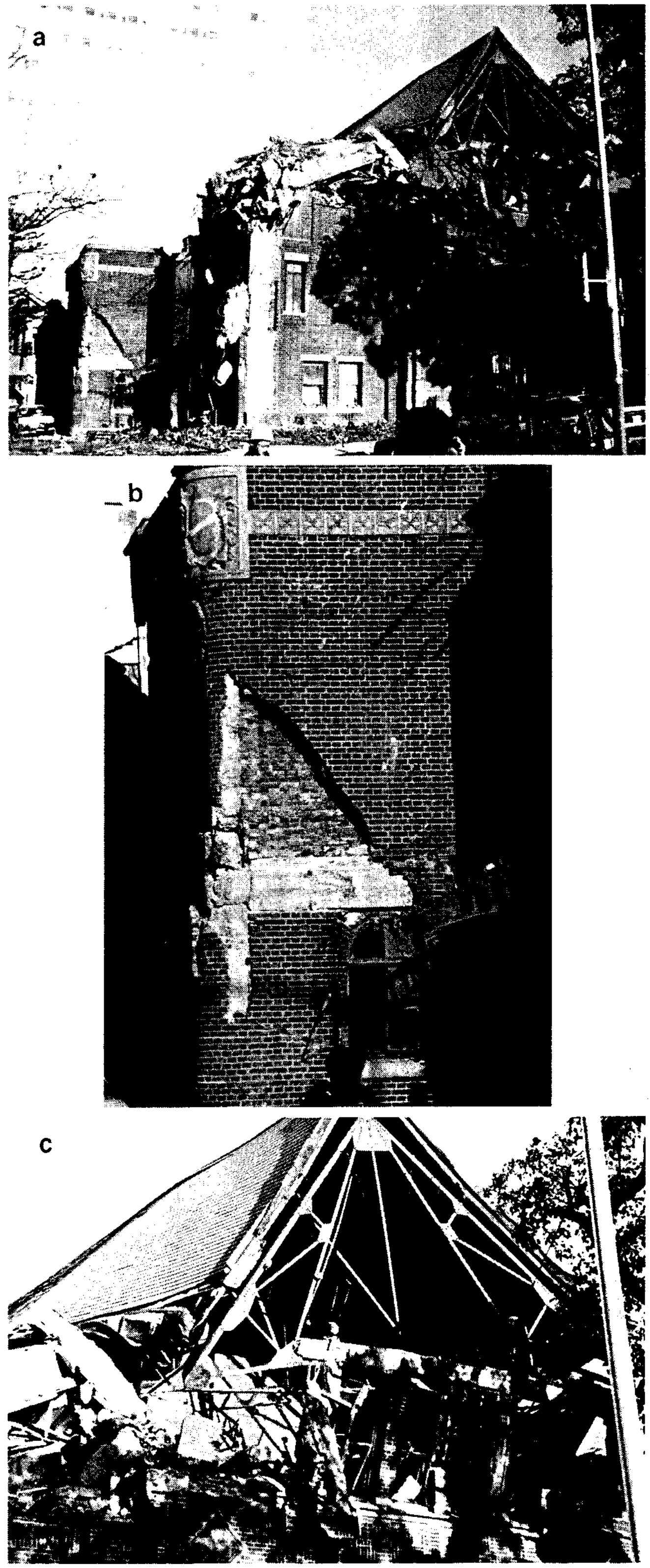


Fig. 6. Damaged church having reinforced concrete frames infilled with unreinforced masonry: (*a*) global view; (*b*) minor damage to masonry wythe covering the infilled frames at the church's lower level; (*c*) close-up view of the damaged level where more openings existed in the infilled reinforced concrete frame.



retrofitting. Although it is possible that some unreinforced masonry buildings may have been retrofitted in the past, these would be rare instances, as the seismic retrofit of buildings has not received much attention in Japan in recent years. The Japanese engineers and researchers nearly exclusively focused their structural engineering energies on the development of better seismic-resistant *new* constructions

4.2. Unreinforced masonry infills

In a few instances, damage was observed to reinforced concrete frames for which unreinforced masonry had been used as infills. For example, one church suffered a tremendous amount of damage to its lightly reinforced concrete frame and infills at the level where numerous window openings were present (Fig. 6). Damage to the lower part of the church was actually slight, as the infills and smaller amount of openings provided a considerable amount of overstrength to the

Fig. 7. Damage to nonstructural masonry elements used as decorative infill masonry at the top of a church tower.

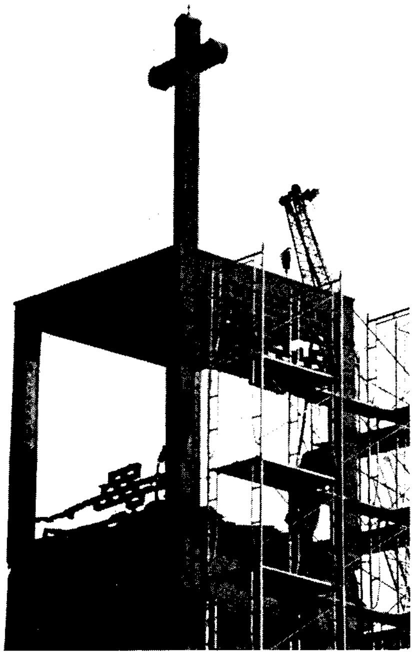


Fig. 8. Undamaged small reinforced masonry building located in Kobe (from Japanese Society for the Promotion of RM Buildings).

reinforced concrete frames. However, the gable of that church was a "pure" unreinforced masonry gable as opposed to an infilled gable. Being inadequately tied to the steel roof-frame, it partly collapsed in an out-of-plane manner. Some wall anchors, consisting of bent bars originally embedded in the masonry, were seen hanging from the steel frame (these can also be seen in Fig. 6, but somewhat difficultly).

Another interesting example of infill failure occurred at the top of a modern church tower. The tower consisted of a multilevel reinforced concrete frame, infilled by slightly recessed unreinforced masonry. Solid bricks were used at all levels, except at the top where units with large voids were utilized to provide a striking architectural finish (Fig. 7). The church and tower were both undamaged, except for the tower at its top level where the weaker masonry units were used. These were quickly crushed, providing no additional strength to the concrete frame that, in turn, suffered column damage at that level.

5. Seismic performance of reinforced masonry buildings

5.1. Direct observations by the authors

Although the authors have not found evidence of damage to reinforced masonry buildings, it must be remembered that these structures account for less than 0.01% of all buildings in the Kobe area (there are nearly 2 000 000 dwellings in the Hyogo prefecture, 1 100 000 in Kobe alone). The search for reinforced masonry buildings, trying to identify a rarely used construction type that frequently cannot be positively identified unless it suffered damage, is like searching for a needle in a hay stack, particularly knowing that the typical Japanese low-rise masonry construction blends itself harmoniously with the other residential constructions. Moreover, to enable a fair and worthwhile comparison, damaged reinforced masonry buildings would have to be located adjacent to undamaged modern engineered buildings of different construction materials, or vice versa (i.e., undamaged masonry next to damaged other buildings). Comparing undamaged buildings of different materials is inconclusive without knowledge of the felt ground motion at those buildings' actual site, an even rarer occurrence in the present context.

In that perspective, the authors have not been able to make conclusive observations on the seismic performance of reinforced masonry buildings during this earthquake, and second source reports were consulted instead.

5.2. Second source reports

The Architectural Institute of Japan conducted the most extensive reconnaissance inspection of buildings in all cities where damage was reported from this earthquake. Over 350 man days were invested in that field investigation (AIJ 1995), and damage to nearly 5000 concrete, steel, or steel-encased reinforced concrete structures was reported. Although severe damage to unreinforced brick and block masonry buildings was also observed, this task force did not report any examples of either satisfactory or unsatisfactory seismic performance of reinforced masonry buildings.

On a more moderate scale, the Japanese Society for the Promotion of RM Buildings also conducted a reconnaissance visit to the earthquake-stricken area. Even though this group obviously has a vested interest in the promotion of masonry construction in Japan, their findings are reported here, as no other second source material has been found reporting the performance of reinforced masonry during this earthquake. Interestingly, that reconnaissance team apparently could only identify six reinforced masonry buildings (of the RM type) in or near Kobe. Of those, only two were apparently surrounded by other damaged residential buildings (Figs. 8 and 9), the others being located in neighbourhoods where the intensity of shaking was not sufficient to damage any structures. As visible from these figures, the wall solidity ratio of the reinforced masonry buildings which survived strong

Fig. 9. Undamaged small reinforced masonry building located in Kobe (from Japanese Society for the Promotion of RM Buildings).

Fig. 10. Damage to unreinforced concrete block masonry garden walls.

Fig. 11. Collapsed thick unreinforced clay brick masonry property wall.

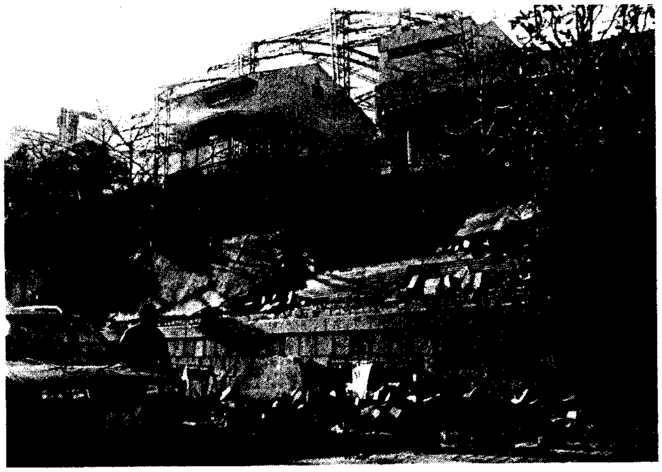
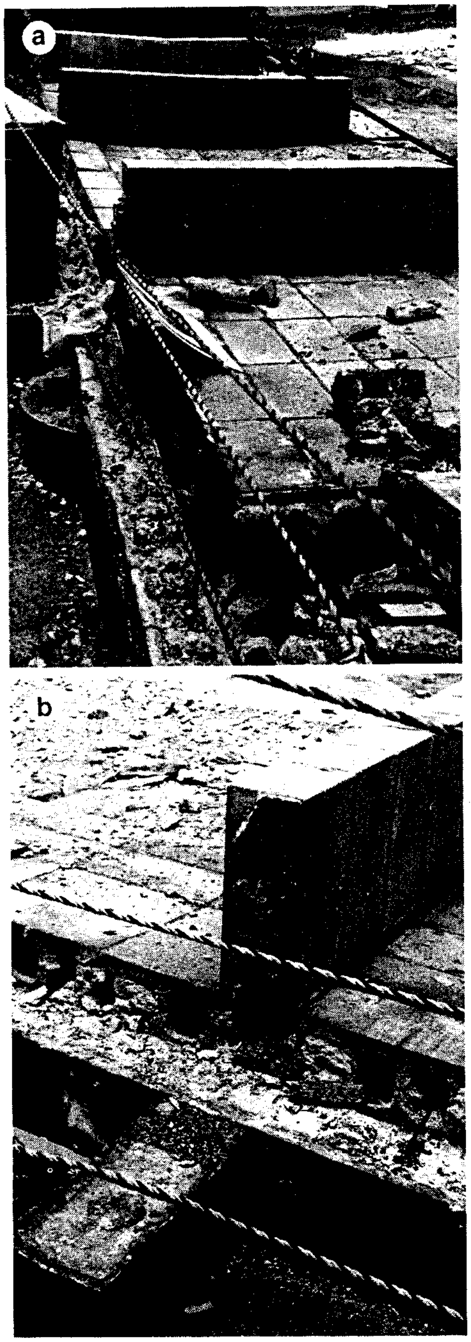


Fig. 12. Failed reinforced concrete block masonry garden wall: (*a*) global view; (*b*) close-up view.



shaking was quite significant (the walls have only a few small-size windows and door openings).

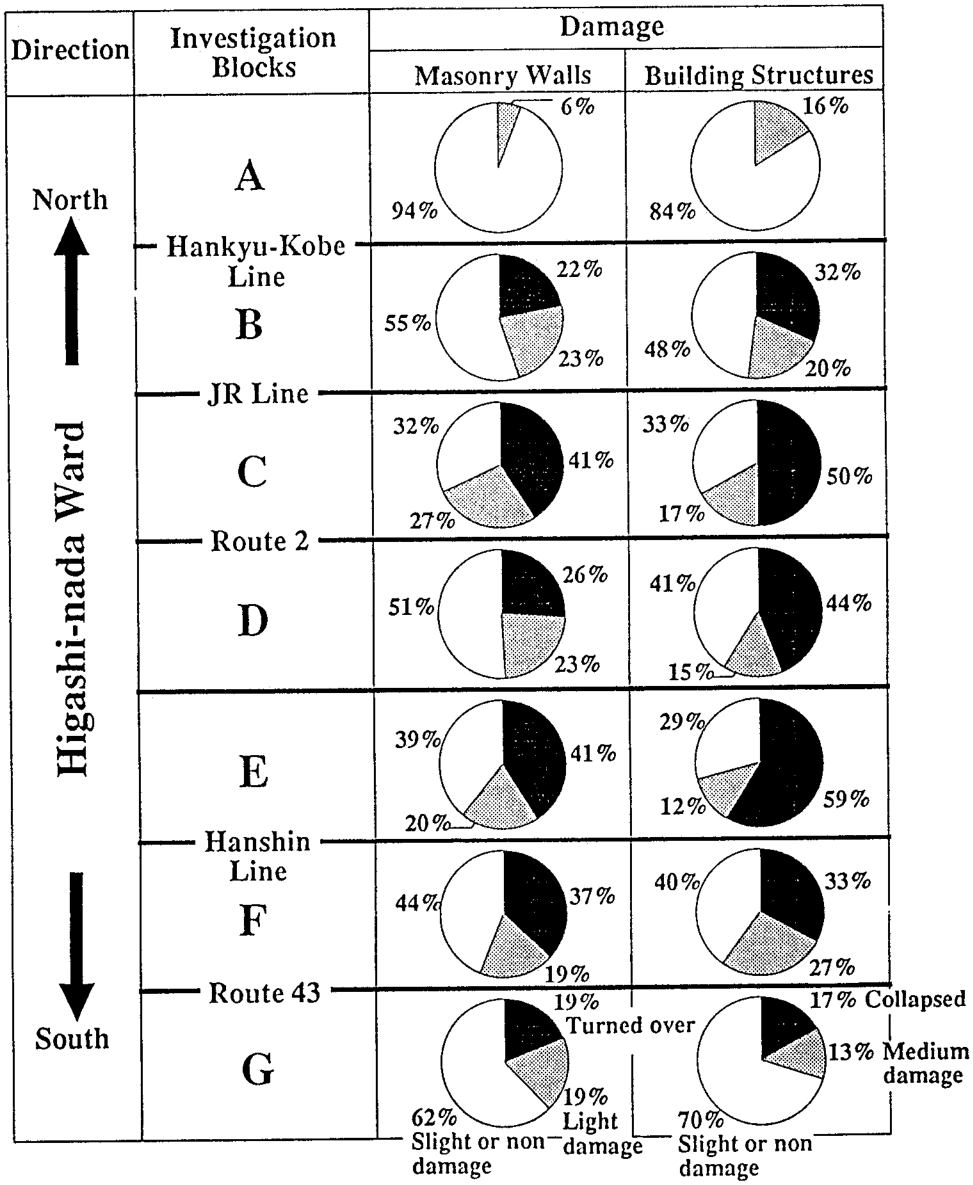
6. Damage to other masonry assemblies

6.1. Garden walls

Many small property-dividing walls (garden walls) also collapsed during this earthquake. These were frequently of unreinforced masonry. Reinforcement, when present, was light, and sometimes poorly anchored or even erroneously placed in ungrouted cells.

Slender unreinforced concrete block masonry walls typically failed by out-of-plane overturning due to rupture at

Fig. 13. Comparison of the severity of damage to masonry walls and buildings in the Higashi–Nada Ward of Kobe.



their base (Fig. 10), as did older thicker walls generally constructed of clay brick unreinforced masonry (Fig. 11, showing a wall located in a part of town where adjacent buildings did not suffer visible damage), and lightly reinforced slender reinforced masonry walls (Fig. 12). That latter and fairly representative wall was built using 150 mm wide blocks, 6 mm diameter bars in grouted cells at 400 mm spacing, and buttresses.

A comparison of the severity of damage to garden walls with that of buildings along six kilometres of parallel roads in the Higashi–Nada Ward of Kobe is presented in Fig. 13, for 236 walls and 603 buildings along those selected roads. Although in many areas, damage was frequently more extensive in buildings than in garden walls, damage to garden walls was widespread, particularly south of that Ward nearer to the shoreline.

Many types of walls damaged by this earthquake did not meet the current requirements of the Japanese Building Law and AIJ Design Standard (AIJ 1994), which call for horizontal and vertical wall reinforcing bars spaced at 800 mm or less in both directions, deep anchorage of the vertical bars in the reinforced concrete foundation, a maximum wall height of 2.2 m, and other requirements as illustrated in Fig. 14. The current AIJ standard specifically aims at preventing this type of out-of-plane flexural failure as well as foundation rotation failure, even for walls without buttresses.

6.2. Miscellaneous nonstructural masonry

The seismic performance of nonstructural masonry was not reviewed extensively by the authors. However, damage was sometimes observed to nonstructural masonry used in decorative architectural elements. For example, a circular reinforced glass-block wall that has been damaged is shown in Fig. 15. Also shown in the figure is an example of the excellent behaviour of thin adhesive masonry coverings, an architectural finish frequently used in Japan.

Fig. 14. Example of standard reinforcement specified by Japanese standards for concrete block masonry garden walls.

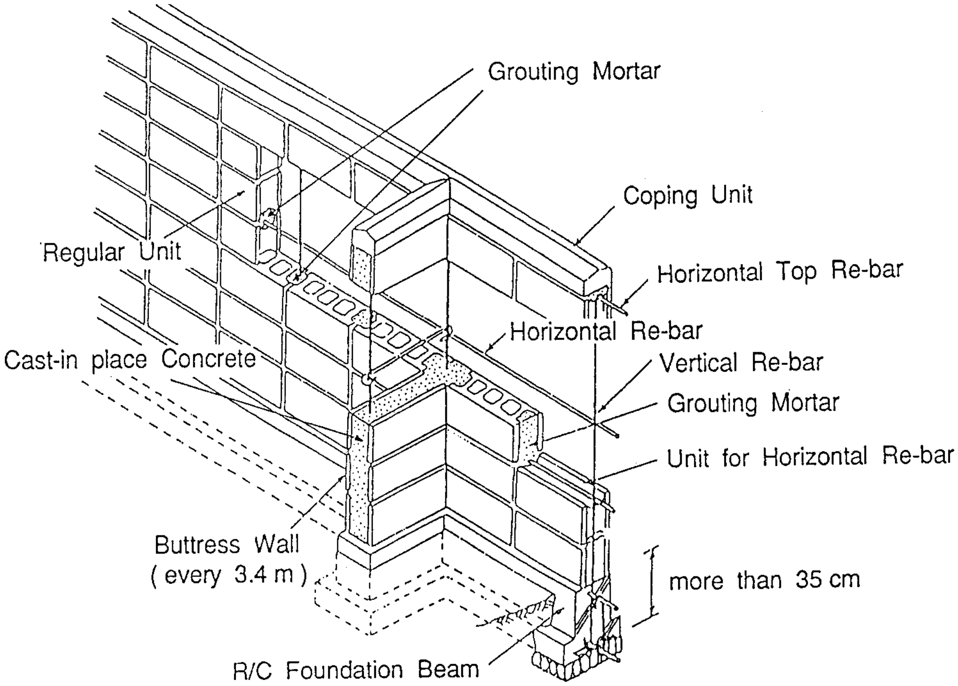
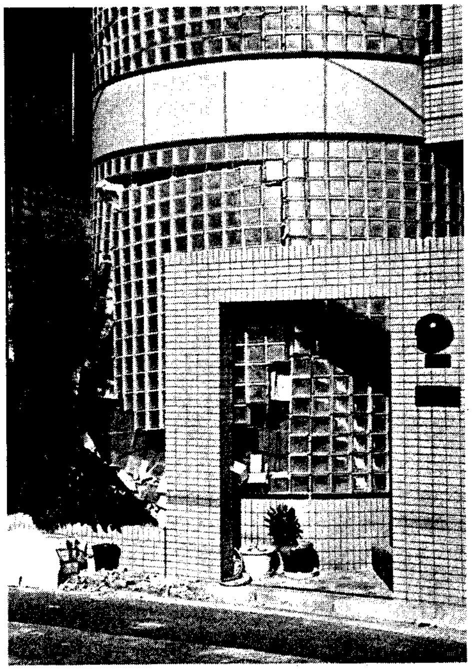


Fig. 15. Damaged circular reinforced glass-block masonry wall.



Also noteworthy was the failure of many small temple gateways. These portals, characteristically Japanese in their architecture, were sometimes constructed of piled stones. Small dowels were sometimes installed to connect these stones at their centre.

7. Conclusions

Contrary to what has often been thought about Japanese construction, some masonry buildings and structures were found to exist in the Kobe area hit by the January 17, 1995, earthquake. Typically, the existence of these buildings was revealed by their damage during this earthquake.

Prior to this earthquake, the seismic retrofitting of buildings was not a priority on the Japanese agenda, but as damage during the Hyogo-ken Nanbu earthquake was widespread among older buildings constructed with nonductile material detailing, the responsible Japanese agencies are now under pressure to urgently start addressing the seismic rehabilitation needs to avoid similar disasters in future Japanese earthquakes. In that perspective, the few unreinforced masonry buildings that still exist in Japan will undoubtedly need to be included in that rehabilitation effort. However, because of the small number of these buildings, the profile of their owners, past Japanese construction practice, and the Japanese philosophy regarding seismic-resistant design, it is quite possible that such retrofit will proceed using conservative procedures without much regards for the heritage value of these buildings.

As for reinforced masonry buildings, their scarcity in the earthquake-stricken region precludes conclusive observations, although a few cases of satisfactory seismic performance have been reported.

Acknowledgements

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References

AIJ. 1994. AIJ standard for structural design of masonry structures. English edition of the 1989 Japanese edition. Architectural Institute of Japan, Tokyo, Japan.

AIJ. 1995. Preliminary reconnaissance report of the 1995 Hyogoken-Nanbu earthquake. English edition. *Edited by* M. Nakashima and M. Bruneau. Architectural Institute of Japan, Tokyo, Japan.

Bruneau, M. 1994*a*. Assessing the seismic performance of existing masonry buildings in Canada. *In* Masonry in the Americas. ACI Special Publication SP-147, Detroit, Mich.

Bruneau, M. 1994*b*. State-of-the-art report on the seismic performance of unreinforced masonry buildings. Structural Journal of the American Society of Civil Engineers, **120**: 230–251.

Bruneau, M. 1994*c*. Seismic evaluation of unreinforced masonry buildings — a state-of-the-art report. Canadian Journal of Civil Engineering, **21**: 512–539.

SPRM. 1995. Investigation report on damage to masonry building structures caused by Great Hanshin earthquake. Society for the Promotion of RM Buildings, RM Buildings, **6**.