1. ABSTRACT

Based on the provisions of a new AIJ (Architectural Institute of Japan) standard which will be published in 1997, a structural design method for medium-rise reinforced concrete (R/C) grouted masonry buildings is introduced. Special emphasis is placed on the seismic design method adopted in the proposed new design standard.

2. INTRODUCTION

In accordance with the current AIJ Standards for Structural Design of Masonry Structures, the maximum stories or height of the masonry buildings which can be designed and constructed are limited up to three-stories or eleven meters in height, respectively. Based on the recent extensive development in research and construction technique in the field of the R/C grouted masonry structures (Figure 1), establishment of a new design standard for structural design of medium-rise R/C grouted masonry buildings with less than five stories or sixteen meters in height is now being discussed in the AIJ Masonry Committee, and a new Structural Design Guideline will be published by the end of 1997. Herein, a structural system adopted in the ordinary R/C grouted masonry buildings in Japan is introduced first, and then the structural design methods including seismic design, which are provided in the new AIJ Standards, are briefly presented. Since there were almost no severe structural damage to this kind of R/C grouted masonry buildings even during the 1995 Hyogoken-Nanbu earthquake [1], the masonry buildings with this type of boxed-wall structural system are expected to become more popular in Japan.

Keywords: Grouted masonry building structure; Seismic design; New AIJ Standard.
3. GROUTED MASONRY BUILDING SYSTEM IN JAPAN

One of the typical R/C grouted masonry structural systems adopted in the ordinary residential buildings in Japan is schematically illustrated in Figure 2, where grouted masonry bearing walls, R/C wall girders and cast-in-place R/C floor slabs are shown respectively [2]. As shown in the figure, each of the masonry bearing walls is composed of concrete hollow masonry unit with or without mortar joints, reinforcing bars (Re-bars) and grout materials, and all of the cells of the hollow masonry units are completely and continuously filled with grouts such as concrete or a mixture of cementitious materials and aggregate, and so on.

Figure 2. A typical grouted masonry
The first structural design standard for this type of masonry building system was established and published in 1952 as one of the AIJ Standards for Structural Design of Masonry Structures [2], where maximum stories or height of the masonry buildings are limited up to three-stories or eleven meters in height, respectively. Such a maximum story- and height-limitations of the masonry buildings including R/C grouted masonry buildings are still in use and are specified in the current AIJ Structural Standards for Masonry Building Structures [2].

In order to develop more seismic R/C grouted masonry building structures, however, a large number of theoretical and experimental studies were conducted during the period from 1984 through 1988 as a part of the US-Japan Coordinated Earthquake Research Program on Reinforced Masonry (RM) Buildings [3]. During this five-years’ project, a five-story full-scale grouted masonry or reinforced masonry (RM) building was tested on a laboratory test floor of the BRI (Building Research Institute) of the Ministry of Construction of Japanese Government, and since then the seismic safety of the medium-rise grouted masonry buildings has been verified [4]. Based on the results of these research projects, guidelines and their commentaries for structural design and construction of the medium-rise grouted reinforced masonry (RM) buildings were published in 1991 [5 and 6].

Based on the fact that there were almost no severe structural damage to this type of R/C grouted masonry buildings even during the 1995 Hyogoken-Nanbu earthquake (see Figure 3), and also based on the recent extensive development in research and construction techniques in the field of the grouted masonry building structures, establishment of a new design standard for structural design of medium-rise R/C grouted masonry buildings with less than five stories or less than sixteen meters in height is now being discussed in the AIJ Masonry Committee (the Chairman of this Committee is the first author of this paper), and a new guideline for structural design will be published by the end of 1997. Herein, the structural design methods including seismic design method of the medium-rise R/C grouted masonry buildings, which are provided in the draft of a new AIJ Structural Design Guideline, are briefly introduced, and a design example of a five-story grouted masonry residential building is also presented.

![Figure 3. Survived grouted masonry buildings in Kobe City](image-url)
4. STRUCTURAL DESIGN FOR MEDIUM-RISE GROUTED MASONRY BUILDINGS

Followings are the brief description of the structural design methods provided in the new AIJ Guideline for Structural Design of Medium-rise Grouted Masonry Buildings, which will be published in 1997. All of the design provisions including minimum requirements for low-rise masonry buildings which are specified in the current AIJ Standards for Structural Design of Masonry Buildings [2] are not described in the present paper.

4.1 Scope

Objective of this proposed Guideline is to present the design standards for structural design of the medium-rise R/C grouted masonry building structures as well as the seismic design for both medium and strong motion earthquakes specified in the present Building Standard Law (BSL) of Japan [7]. Herein, the definition of the medium-rise buildings is the four- and five-story masonry buildings whose height is less than sixteen meters in height. The maximum story height in each story is also limited up to 3.0 meters, except for less than 3.5 meters in the first story. It is noted that the dead plus live loads for determining the design earthquake forces are assumed to be 0.013 MPa (1,300 kg/m²) in this Guideline.

Structural design methods for one-, two- and three-story masonry buildings lower than eleven meters in height are unchanged, and are given in the current AIJ Design Standards [2].

4.2 Fundamental Seismic Design Concept

For all of the four- and five-story reinforced grouted masonry buildings which are designed in accordance with the design provisions of this Guideline, seismic safety of the designed building must be investigated for both medium and severe earthquakes specified in the current BSL [7]; that is:

For medium design earthquake forces with standard base shear coefficient, $C_o=0.2$ or more, allowable stress design based on the elastic structural analysis shall be performed for determining the design forces and required reinforcement for all the structural members. In addition to such an ordinary elastic design for all the structural members, story-drifts less than $1/2,000$ rad. And eccentricity caused by the same medium design earthquake forces must be investigated, as well as the lateral stiffness distribution along the height of the designed building.

In addition to the first-stage of structural design based on the elastic design technique as shown above, seismic safety of the designed building must be investigated against severe earthquake forces ($Q_{ud}$) having a standard base shear coefficient of $C_o=1.0$ or more, which are necessary for determining the required ultimate lateral strength ($Q_{un}$) in each story of the designed building. In accordance with the design provisions of the current BSL, the required ultimate lateral strength ($Q_{un}$) can be calculated by the following equation;

$$Q_{un} = D_s F_e s Q_{ud}$$  \hspace{1cm} (1)

where $(D_s)$ is a required strength reduction factor depending on the deformability or deformation capacity, and is given by the function of ductility factor ($\mu$) of each story. In equation form;

$$D_s = 1/(2 \mu -1)^{1/2}$$  \hspace{1cm} (2)

In case of the ordinary R/C building structures, the values of $(D_s)$ are specified between 0.30 to 0.55 according to the requirements of the current BSL. In the second-stage of the
structural design of medium-rise R/C grouted masonry buildings, however, it is recommended in the new AIJ Guideline that the value of \( D_s \) shall be more than 0.55; in other words, the ultimate lateral strengths of all the stories \( (Q_u) \) shall be designed so as to be larger than the required strengths \( (Q_{un}) \) calculated by using the values of \( D_s = 0.55 \) or more. \((F_{es})\) in the above equation is an increasing factor for required ultimate lateral strengths which depend on the eccentricity and irregularity in lateral stiffness along the height of the designed building [7].

In addition, it is recommended in the new AIJ Design Guideline that the R/C grouted masonry building shall be designed to fail in an acceptable failure mode such as the beam-mechanism in its ultimate state when a very big earthquake attacks the designed building. One of the recommended failure modes is shown in the design example (Figure 8) of the present paper.

4.3 Quality of Masonry Units, Re-bars, Mortar and Concrete

Minimum requirements for quality of concrete masonry units and Re-bars are specified in the Japanese Industrial Standard, JIS A5406, JIS G3112 and JIS G3117, respectively. Among them, the minimum compressive strength of the masonry units shall be more than 40 MPa (408 kg/cm\(^2\)). The compressive strengths of mortar and grouts including cast-in-place concrete shall be more than 34 MPa (350 kg/cm\(^2\)) and 24 MPa (240 kg/cm\(^2\)), respectively.

4.4 Allowable Stresses and Material Strengths of Masonry

The compressive strength of masonry \((F_m)\) shall be determined by a set of three masonry prisms based on tests at 28 days, and shall be more than 24 MPa (240 kg/cm\(^2\)). If the compressive strengths of the masonry determined by the prism tests are larger than 26 MPa (270 kg/cm\(^2\)), the compressive strength of 26 MPa (270 kg/cm\(^2\)) shall be adopted. Allowable stresses of the masonry used for the first-stage of the structural design of medium-rise R/C grouted masonry buildings are given by the function of the compressive or material strength of the masonry \((F_m)\). In accordance with the provisions of the new AIJ Design Guideline, the allowable compressive strengths of the masonry in long- and short-term loading are \( F_m / 6 \) and \( F_m / 3 \), respectively, which are determined based on the analysis results obtained from a large number of calculations conducted against the typical medium-rise R/C grouted masonry buildings having various size and shape of the bearing wall arrangement. The allowable shear stresses of the masonry are \( 4(F_m/180)^{1/2}/1.5 \) and \( 4(F_m/180)^{1/2} \) for long- and short-term loading, respectively, which are from the conservative values specified in the Guideline for Structural Design of Medium-rise Reinforced Masonry (RM) Buildings [5]. Allowable stresses and material strengths of all other materials used for the structural design of medium-rise R/C grouted masonry buildings are the same with the corresponding design standards.

4.5 Arrangement of Bearing Walls

All the bearing walls shall be arranged in good balance on the horizontal floor diaphragms within the eccentricity limitations of \((Re)\) is less than 0.15 and each of the floor area surrounded by the bearing walls shall be less than 45 m\(^2\), where "bearing walls" are defined as the walls designed to resist in-plane lateral shear forces and moments as well as axial forces including vertical gravity loads. In addition, all the upper-story bearing walls are recommended to be placed just above the adjacent lower-story bearing walls so as that the
irregularity in lateral stiffness along the height of the building is within the limitation of lateral stiffness ratio \( (R_s \approx 0.6) \).

In both of the longitudinal and transverse directions of each story of the building, the values of “Wall Rate” shall be more than the values given in Table 1, where wall rate is defined as the total horizontal length (cm) of all the bearing walls located in one direction is divided by the floor area (m\(^2\)).

<table>
<thead>
<tr>
<th>Location</th>
<th>Four-story building</th>
<th>Five-story building</th>
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<tbody>
<tr>
<td>5th story</td>
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<td>15</td>
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<tr>
<td>4th story</td>
<td>15</td>
<td>18</td>
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<td>3rd story</td>
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<td>20</td>
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<td>2nd story</td>
<td>20</td>
<td>20</td>
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<tr>
<td>1st story</td>
<td>20</td>
<td>20</td>
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</tbody>
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4.6 Structural Details of Bearing Walls

The minimum requirements given in all the bearing walls are in the followings:

1. Horizontal length shall be more than 100 cm.
2. Total thickness of the bearing wall shall be more than 20 cm. By considering the minimum requirements for this wall thickness and horizontal wall-length per unit floor area given in Table 1, the maximum value of the average (or mean) shear stresses induced in the bearing walls can be easily determined. The result is \( \bar{c}\) = \(0.2 \times 12700 \times 5/(20 \times 20)\) = 0.3 MPa (3.25 kg/cm\(^2\)) in case when a five-story grouted masonry building without any eccentricity in plan is subjected to the design medium earthquake forces with the standard base shear coefficient of \( C_o = 0.2 \). It is worthy of note that the maximum value of the average shear stresses induced in the grout sections within the masonry bearing wall sections becomes as \( \bar{c} = 0.2 \times 12700 \times 5/(20 \times 14)\) = 0.4 MPa (4.64 kg/cm\(^2\)). It can be understood that these values of \( \bar{c}\) are very conservative by taking into account of the allowable shear stresses specified herein and corresponding other AIJ Design Standards.

3. Thickness of each shell of the concrete masonry unit shall be less than 3 cm.
4. By considering the above Requirements 2 and 3, thickness of the grout concrete inside the masonry bearing walls shall be more than 14 cm.
5. Shear reinforcement ratios \((p_{sh} \text{ and } p_{sv})\) provided in the bearing walls in lower two (or three) stories of the four-story (or five-story) buildings shall be more than 0.20 %, and shall be more than 0.15 % in the upper two stories, where definition of the shear reinforcement ratios \((p_{sh} \text{ and } p_{sv})\) are the total cross-sectional areas of the shear Re-bars provided in horizontal or vertical directions which are divided by the vertical or horizontal cross-sectional areas of the bearing wall section, respectively. The values of \((p_{sh} \text{ and } p_{sv})\) in the third-story bearing walls shall be more than 0.20 % in five-story building and 0.15 % in four-story building, respectively. The minimum requirements for these shear reinforcement were determined based on the designed shear forces carried by the unreinforced masonry bearing walls against the medium design earthquake forces with the standard base shear coefficient of \( C_o = 0.2 \).
6. The minimum requirements for flexural reinforcement provided along the wall edges
are also given in the new AIJ Guideline, which were determined based on the member forces against the medium design earthquake forces with the standard base shear coefficient of $C_o = 0.2$.

Validity of the determined wall reinforcement required in all the bearing walls for both lateral shear and flexural design forces shall be investigated in the second-stage of the seismic structural design against severe earthquakes, where most of the structural members shall be designed so as to avoid the brittle shear failure mode before developing their flexural moment capacity.

4.7 Structural Design of Wall Girders

Structural design of the wall girders (or collar beams) which are required to be provided along the top of all the bearing walls are very important, because excessive bending and/or shear forces are expected to be induced especially in the ultimate state of the building. Following are the minimum requirements specified in the new AIJ Guideline for structural design of medium-rise R/C grouted masonry buildings.

1. Width ($b$) and depth ($D$) of the wall girders shall be more than the thickness of the adjacent bearing walls (or 20 cm) and 60 cm, respectively.

2. Clear span to depth ratio ($l_o/D$) shall be more than 1.5.

3. Flexural (or longitudinal) reinforcement shall be provided in top and bottom of all the beam sections. The minimum flexural reinforcement ratio ($p_f$) shall be 0.2%, or more, and at least two deformed flexural Re-bars with bar size of D13 (or #4 bars) or more, but less than D19 (#6), shall be provided. Definition of the flexural reinforcement ratio is $p_f = a_t / bd$, where ($a_t$) is the cross-sectional area of the flexural Re-bars provided in top or bottom of the beam section and ($d$) is the distance between extreme compression fiber and centroid of the tensile flexural Re-bars.

4. Required shear reinforcement ratio ($p_{sv}$) shall be more than 0.30, and all the Re-bars of D10 (#3) or D13 shall be used as the shear reinforcement in the wall girders. In case of the second and third-floor wall girders whose clear span to depth ratio ($l_o/D$) is less than 2.0, shear Re-bars of D13 shall be placed at least 10 cm spacing or less along the beams.

5. Design Example

Figures 4 and 5 are the typical floor plan and one of the elevations of a five-story R/C grouted masonry residential building which is selected as an example for a structural and seismic design presented in the new AIJ Guideline for Structural Design of Medium-rise Grouted Masonry Building Structures.

In this design example, R/C grouted masonry bearing walls with 20 cm thickness are provided along through the height of the building. Amount of wall rate in longitudinal and transverse directions are 22.1 and 25.3 (cm/m²), respectively, which are more than the required minimum wall rates shown in Table 1 of this paper. In accordance with the provisions and recommendations provided in the new AIJ Guideline and its Commentary, the structural design including seismic design of this selected model-building was conducted, and all of the adopted structural design techniques, design calculation processes and obtained results are presented in detail in the latter part of the new AIJ Guideline.

In the first-stage of the structural design of this building, four different structural analyses based on the conventional simplified method and direct stiffness method using electronic computers are performed against medium design earthquake forces with $C_o = 0.2$, and analysis results are compared each other. In these structural analyses, mechanical modeling for all the bearing walls and wall girders are conducted by adopting the column and beam
line models with rigid zones around their connections, respectively. Based on the precise analysis results by a computer, maximum values of the calculated story-drift (R) and eccentricity ratio (Re) are 0.11 ($\times 10^{-3}$ rad) and 0.01, respectively, and minimum lateral stiffness ratio (Rs) obtained is 0.79, all of which are within the limitation of the specified requirements.

Figure 4. Typical floor plan of a five-story R/C grouted masonry residential building

Figure 5. Elevation of a five-story R/C grouted masonry residential building for design example

After finishing the first-stage structural design for medium earthquake loading which is based on the allowable stress design method, the second-stage structural design based on the ultimate strength design method was performed for investigating the seismic safety of the designed building against severe earthquakes. Figure 6 shows a failure mode observed in one of the R/C grouted masonry frames, in which reinforcement details of all the structural member sections were determined based on the precise computer analysis during the first-stage structural design. In this figure, there are three bearing walls shown by the symbol of ( × ) which are expected to fail in brittle shear failure mode before developing their ultimate flexural moment capacity. The location of the flexural or plastic hinges are shown in Figure 6 by using the symbols (●). Other structural members including all the wall girders in this
frame do not fail in such a shear failure mode but are expected to fail in ductile manner. Since the similar failure mechanisms were obtained in other frames of this model building, additional amount of shear reinforcement were provided in all the members which are expected to fail in brittle shear failure modes. By providing such an additional shear reinforcement, all the brittle structural members have completely disappeared as being observed in Figure 7.

Figure 6. Failure mechanism based on member reinforcement details by allowable stress design

Figure 7. Failure mechanism after providing additional shear reinforcement in brittle members

Up to this stage of the present structural calculations, all the bottom of the first-story bearing walls (or columns) have been assumed to be fixed supports. After this stage, however, various types of final failure modes can be selected depending on the reinforcement details adopted in the R/C foundation beams. Figure 8 shows one of the solutions of the expected failure mechanism in Frame (Y1) of this model building. The ultimate lateral strengths \( (Q_u) \) determined in each story of this building are approximately 1.22 to 1.98
larger than the required lateral strengths ($Q_{un}$), which are specified in this new AIJ Structural Design Guideline.

![Figure 8. One of the selected final failure mechanisms in Frame (Y1)](image)

6. CONCLUDING REMARKS

By emphasizing the seismic design method especially, the structural design procedures adopted in the new AIJ Guideline for Structural Design of Medium-rise Grouted Masonry Building Structures are introduced, as well as a structural design example of a five-story R/C grouted masonry building.

7. REFERENCES