Analytical Study on Out-of-plane Vibration Characteristics of Reinforced Masonry Walls

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ABSTRACT:
This paper reports the results of eigenvalue analysis to understand change in vibration characteristics of masonry wall before and after reinforcement. Two-storied model of masonry walls are constructed by beam elements and the inspection of retrospective measurement results are studied by eigenvalue analysis. And parametric analysis is conducted under moment of second order of steel, thickness of RC shear walls and so on, and the relationship between reinforcement and frequencies are quantitated. Major findings from the research are as follows: (1) By the eigenvalue analysis based on microtremor measurement, it is found out that frequencies can be reproduced. (2) In reinforced buildings by steel frames, increasing moment of second order of steel, 1st natural frequency is increased. But the rate of increase depends on quantity of reinforcement. (3) In reinforced buildings by RC shear walls, increasing thickness of RC walls, 1st natural frequency is increased and is asymptotic constant value.

Keywords: Reinforced masonry wall, Eigenvalue analysis, Natural frequency

1. INTRODUCTION

Recently, many self-governing bodies and groups tried to preserve or restore historic masonry constructions as symbol of local history and culture in Japan. But, these masonry walls don’t generally reinforce. In Japan which many earthquakes occur in, it is important problem to promote seismic retrofit of these constructions. There are some cases of seismic retrofit, but seismic performance is not clear. Also, the structural characteristics of masonry walls needed to retrofit are unknown well. On the other hands, concerning historic masonry constructions such as national treasures or important cultural properties, there are the demands to try as less change appearances as possible, because the preservation of cultural worth is the top priority.

Under seismic retrofit, it is important not only to raise strength of masonry walls but also to grasp how high natural frequency is when earthquakes occur. In the past earthquakes, there are many cases that they collapsed toward out-of-plane. So, it is needs to study about behavior toward out-of-plane.

In past paper, we conducted microtremor measurement for unreinforced and reinforced walls of real historic masonry constructions. Compared vibration characteristics of unreinforced and reinforced walls, reinforced effects were confirmed: the walls are reinforced by steel frame or RC shear walls. And out-of-plane vibration characteristics of masonry walls were investigated such as natural frequency, vibration mode or damping factor.

In this paper, to understand change in vibration characteristics of masonry wall before and after reinforcement, two-storied model of masonry walls are constructed by beam elements and the inspection of retrospective measurement results are studied by eigenvalue analysis. The buildings which are focused on in this paper are reinforced by steel frames or RC shear walls. And parametric analysis is conducted under moment of second order of steel, thickness of RC shear walls and so on, and the relationship between reinforcement and frequencies are quantitated.
2. OBJECTS AND REINFORCEMENT

In this chapter, the details of objected masonry buildings and the reinforced methods used on each building are explained.

2.1. Objected Buildings

The details of objected buildings are shown in Table 2.1. Both buildings are important cultural assets built in 1902 yrs. They have 2 stories and rectangle plan. The long side of a rectangle is 72.2 [m], the short side of one is 10.3 [m]. The story’s height and thickness of masonry wall are nearly equal. 2nd floor and roof truss are constructed by wood. Here, the length of wall is defined the length between the axis of orthogonal masonry walls as.

Table 2.1. Details of objected Buildings

<table>
<thead>
<tr>
<th>Bldg.</th>
<th>Built Year</th>
<th>Stories</th>
<th>Length [m]</th>
<th>Story’s height [m]</th>
<th>Thickness [m]</th>
<th>Structure of 2nd FL &amp; roof reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1902</td>
<td>2</td>
<td>72.2</td>
<td>4.6</td>
<td>0.57</td>
<td>wood</td>
</tr>
<tr>
<td>II</td>
<td>4.6</td>
<td>2</td>
<td>10.3</td>
<td>2.7</td>
<td>0.47</td>
<td>RC wall, Steel</td>
</tr>
</tbody>
</table>

2.2. Reinforced Methods

The reinforced methods used on each building are shown in Fig.2.1. Masonry wall is indicated by gray thick line. Steel columns are by black squares. And horizontal steel trusses and circumferential girders are each by black thin and thick line. RC shear wall is indicated by double line painted inner gray. And the specifications of steel member and RC walls used for reinforcement are shown in Table 2.2.

Table 2.2. Specifications of steel members and RC walls used for reinforcement

<table>
<thead>
<tr>
<th>Bldg.</th>
<th>Moment of second order of steel [x 10^5 m^4]</th>
<th>Steel flame</th>
<th>RC wall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>column</td>
<td>beam</td>
<td>girder</td>
</tr>
<tr>
<td></td>
<td>1st FL</td>
<td>2nd FL</td>
<td>1st FL</td>
</tr>
<tr>
<td>I</td>
<td>71.00</td>
<td>5.00</td>
<td>71.00</td>
</tr>
<tr>
<td>II</td>
<td>0.55</td>
<td>-</td>
<td>4.00</td>
</tr>
</tbody>
</table>

Bldg.I is reinforced by steel flame as drawn in Fig.2.1(a). Main reinforced members are steel columns of wide flange shapes on straight side frame crossed at right angles to masonry walls, steel circumferential girder arranged horizontally and horizontal steel truss. Steel circumferential girder and horizontal steel truss are found at the height of 2nd floor and roof truss. They are jointed to masonry walls by anchor bolts.

Bldg II is reinforced by RC wall and steel flame as drawn in Fig.2.1(b). Main reinforced members are wide-flange beam steel columns of straight side frame crossed at right angles to masonry walls, floor...
3. GRASP OF OUT-OF-PLANE VIBRATION CHARACTERISTICS BASED ON MICROTREMOR MEASUREMENT BASED ON RETROSPECTIVE STUDY

In this chapter, we explain about retrospective field survey of vibration characteristics. Microtremor measurement on masonry walls was conducted at Bldgs.I and II before and after reinforcement.

First, method of microtremor measurement is explained. Next, the measurement results before and after reinforcement are shown such as natural frequency, vibration mode and damping factor. Finally, the results before and after reinforcement are compared.

3.1. Method of Microtremor Measurement

We measured microtremor of masonry walls. The measuring points were at the 1st floor and on the 2nd story’s floor. When vibration mode was investigated, some accelerometers were arranged to horizontal and vertical directions along the walls and measurements were concomitantly conducted.

The accelerometers which we used can measure two horizontal components and one vertical component. The frequency of sampled data was 100 [Hz], one measurement was for 7 minutes. The measurement data was translated Fourier transform and ensemble average. It was smoothed using Parzen Window which band width was 0.1Hz

3.2. Results of Microtremor Measurement

The microtremor measurement on masonry walls was conducted at Bldg.I before reinforcement, Bldg.I and II after reinforcement. Here, we didn’t conduct it at Bldg.II before reinforcement, but it assume that Bldg.II has same vibration characteristics because built date, structure, shape and several dimension of building are nearly equal to ones of Bldg.I. In following analysis, the results of reinforced Bldgs.I and II are compared with the result of unreinforced Bldg.I. The results are shown in Figs.3.1 to 3.3 and Table 3.1.

![Figure 3.1. Comparison of Fourier spectral ratio of long side of wall by reinforcement](image)

3.2.1. Natural frequency

Figure 3.1 shows comparison of Fourier spectral ratio of the long sides of masonry walls before and after reinforcement at Bldgs.I and II. Fourier spectral ratio is the data of 2nd floor divided by data of 1st floor. There are some natural frequencies, and 1st natural frequency is written $f_1$. 

As to Bldg.I, before reinforcement, 1st natural frequency is 2.2 [Hz]. After reinforcement, 1st natural frequency is 3.5 [Hz] and be increased approximately 1.6 times. All natural frequencies tend to increase like parallel translation.

As to Bldg.II, after reinforcement, 1st natural frequency is 4.0 [Hz] and be increased approximately 1.8 times. Some peaks which are found before reinforcement are disappeared and the number of natural frequencies is decreased.

The comparison of natural frequency before and after reinforcement is shown in Fig.3.2. Natural frequencies after reinforcement are nearly 1 to 2 (Hz) larger than before reinforcement whatever natural frequency it is. Rate of increase is nearly 1.1 to 1.9 times by reinforcement. As the degree of natural frequency is higher, rate of increase is smaller.

**Table 3.1.** Comparison of 1st natural frequency and damping factor

<table>
<thead>
<tr>
<th>Bldg.</th>
<th>reinforcement</th>
<th>1st natural frequency $f_1$ [Hz]</th>
<th>Damping factor $h_1$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Before reinforcement after</td>
<td>Before reinforcement</td>
</tr>
<tr>
<td>I</td>
<td>Steel flame</td>
<td>2.2</td>
<td>3.5</td>
</tr>
<tr>
<td>II</td>
<td>RC walls, steel flame</td>
<td>-</td>
<td>4.0</td>
</tr>
</tbody>
</table>

**Figure 3.2.** Natural frequencies before and after reinforcement

### 3.2.2. Vibration mode

Fig.3.3 shows reinforced method and comparison of vibration modes of the long sides of masonry walls on 2nd story’s floor level before and after reinforcement in case of 1st natural frequency. Vibration mode is shape swelling toward out-of-plane before reinforcement.

As to Bldg.I, it is found that vibration modes of horizontal direction don’t change remarkable before and after reinforcement. But amplitude after reinforcement is smaller than one before reinforcement.

As to Bldg.II, out-of-plane deformation of masonry wall is restrained predominantly at area which RC shear walls are arranged in comparison with at area which steel frame only are done.

### 3.2.2. Damping factor

1st damping factor $h_1$ against 1st natural frequency $f_1$ of the long sides of masonry walls is identified by RD method as shown in Table.3.1. Even though 1st natural frequency is changed before and after reinforcement, 1st damping factors don’t change remarkable in both buildings.
4. EIGENVALUE ANALYSIS

In this chapter, eigenvalue analysis is conducted. And we study about relation between added bending stiffness of masonry walls and changed natural frequencies.

4.1. Two Dimensions Plane Framework Model

Two dimensions plane framework model is constructed as shown in Fig.4.1. First, an effective length of wall is defined as length of wall per one steel column as shown in Fig.4.1(a). Next, masonry wall, steel frame and RC shear wall are picked out in this section. And analytical model is constructed; members are permuted beam element and one member is signified by one element.

The method by which analytical model is constructed is shown in Fig. 4.1(b). The half of short side of building is modelled. Masonry wall has 2 members and 3 nodes. In Bldg.I, analytical model is combined masonry wall with steel frame. It has 4 steel members and 5 nodes. In Bldg.II, analytical model is combined masonry wall with steel frame of 1st floor and RC shear wall.

The size of members and material characteristics such as moment of second order of steel frame or thickness of RC shear wall are indicated in Tables.2.1 and 2.2. Young’s modulus of masonry wall is $0.41 \times 10^4$[kN/cm²], one of steel is $2.05 \times 10^4$[kN/cm²] and one of RC is $2.05 \times 10^3$[kN/cm²]. In the past paper, it does not depend whether the weight of roof is considered or not, natural frequencies are within the calculate error range. So in this study, the weight of roof is ignored. $H=1.3\%$
4.2. Transfer Function in Bldgs.I and II

Table 4.1 indicates the values and the rate of increase of 1st natural frequency, and rate of increase of stiffness estimated from change of 1st natural frequency.

In Bldg.I, 1st natural frequency after reinforcement \( f_1^* \) is estimated higher than surveyed \( f_1 (=3.5\text{Hz}) \) because the weight of roof is taken no account. But rate of increase of 1st natural frequency \( f_1^*/f_1 \) is 1.60 times and is generally equal to surveyed value. Furthermore, rate of increase of bending stiffness calculated by rate of increase of 1st natural frequency is 256%.

In Bldg.II, 1st natural frequency after reinforcement \( f_1^* \) is estimated smaller than surveyed \( f_1 (=4.0\text{Hz}) \) because it is thought that there are some crossed RC wall in this building. Furthermore, rate of increase of bending stiffness calculated by rate of increase of 1st natural frequency is 243%.

<table>
<thead>
<tr>
<th>Bldg.</th>
<th>Reinforcement</th>
<th>1st natural frequency ( f_1 ) [Hz]</th>
<th>Rate of increase ( f_1^*/f_1 ) [times]</th>
<th>Estimated rate of increase of stiffness [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Steel flame</td>
<td>2.5</td>
<td>1.60</td>
<td>256</td>
</tr>
<tr>
<td>II</td>
<td>RC walls, steel flame</td>
<td>3.9</td>
<td>1.56</td>
<td>243</td>
</tr>
</tbody>
</table>

4.3. Reinforced Quantity and Changed natural frequencies

We study about influence of 1st natural frequency by reinforced quantity such as moment of second order of steel frame and thickness of RC shear wall.

4.3.1. Second moment of area of steel frame in Bldg.I

Figure 4.2 shows rate of increase of natural frequency \( f_1^*/f_1 \) by moment of second order of steel members \( I \times 10^4 \text{cm}^4 \) which is valuable. The steel columns of 1st floor and 2nd floor are given each moment of second order \( I_1 \) and \( I_2 \times 10^4 \text{cm}^4 \). And \( I_1 \) and \( I_2 \) are given \( I \) and/or \( I/10 \).

As moment of second order of steel members on 1st floor increased, 1st natural frequency got higher. The increasing depends on reinforcement quantity on 2nd floor.
4.3.2. Thickness of RC shear wall in Bldg.II

Figure 4.3 shows rate of increase of natural frequency $f_1'/f_1$ by thickness of RC shear wall $t_c$ [cm] which is valuable.

As thickness of RC shear wall increased, 1st natural frequency got higher. And it gradually approaches a fixed value.

5. CONCLUSIONS

This paper reports the results of evaluation on out-of-plane vibration characteristics for reinforcement masonry walls based on framework analysis. The two-storied model of masonry walls are constructed by beam elements and the inspection of retrospective measurement results are studied by eigenvalue analysis. Parametric analysis is conducted under moment of second order of steel, thickness of RC walls and so on, and the relationship between reinforcement and frequencies are quantitated.

Major findings from the research are as follows:
In the eigenvalue analysis based on microtremor measurement, it is found out that frequencies can be reproduced.

In reinforced buildings by steel frames, increasing moment of second order of steel, 1st natural frequency is increased. But the rate of increase depends on quantity of reinforcement.

In reinforced buildings by RC walls, increasing thickness of RC walls, 1st natural frequency is increased and is asymptotic constant value.

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