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煉瓦壁体要素の非線形特性に関する実験的及び数値的研究 その2．面内振動台実験の研究

Experimental and Numerical Studies of Nonlinear Behavior of Masonry Wall Elements Part 2. In-plane Shaking Table Test

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This paper presents the results of in-plane shaking table tests carried out on small-scale conventional unreinforced brick masonry wall and SRB-DUP system masonry wall specimens to study fundamental response properties of the masonry specimens. The tests were conducted as a part of the study on nonlinear behavior of masonry structures. A total of 2 conventional and 7 SRB-DUP wall specimens were tested. The test program included free-vibration and harmonic shaking. The test results revealed significant degradations in fundamental dynamic properties, initiation and development of cracks by repeated shaking with stepwise increasing input acceleration level from 25 to 500 Gal. We found that SRB-DUP system masonry walls show very stable behavior even to large acceleration input.

Keywords: *brick masonry, SRB-DUP, masonry wall, shaking table test, dynamic properties*
煉瓦組積造, SRB-DUP, 煉瓦壁体, 振動台実験, 振動特性

1. Introduction

Unreinforced masonry structures are vulnerable to seismic actions, creating hazardous habitats in earthquake prone areas. To reinforce them properly, first of all, we need to evaluate their seismic resistance. Due to scarcity of structural behavior data during real earthquakes, usually this evaluation is performed by testing the masonry specimens to static and dynamic loading. Part 1 of this paper reported on static tests conducted. Here in Part 2 we will discuss dynamic testing on masonry specimens, namely shaking table test.

This time in addition to conventional unreinforced masonry system, we studied one kind of reinforced masonry system called SRB-DUP (Steel Reinforced Brick structure based on Distributed Unbond Prestress theory), developed by a group of researchers in Kyushu University under the leadership of Prof. Matsufuji [1]. In brief, the SRB-DUP system uses steel plates and bolts for bonding bricks by introducing prestress without any cementing mortar.

Observed seismic in-plane damage in conventional unreinforced brick masonry structures often includes shear failure of window piers [3,4]. Therefore mechanisms of in-plane lateral force resistance depend primarily on the pier geometry, on their boundary conditions and on the magnitude of vertical loads. For this reason, window pier can be the structural element to be studied. As for SRB-DUP masonry structures, there is no observation on their seismic damages, mostly due to its relatively recent invention. But it can be speculated to be similar to structures with reinforced concrete walls as primary resisting elements, in which case spandrel beam or pier can be studied.

Shaking table tests were conducted as a part of the study on nonlinear behavior of masonry structures. Dynamic loading test was planned to study the fundamental response properties of the specimens under one directional loading.

In this paper we describe outline of shaking table test program and summarize the test results.

2. Scope of Study

In this study in-plane seismic behavior of conventional unreinforced brick and SRB-DUP system masonry walls are studied through reduced-scale wall specimens, which were subjected to dynamic excitation using shaking table. It is always better to test the structure in real size, but capacity of the shaking table limits to testing of reduced-scale model or testing of a particular structural component.

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Response of the structure to ground motions during an earthquake depend on the structure's natural frequency and the magnitude of the damping present. Therefore, the dynamic characteristics such as natural frequency, damping will be sought.

Also microtremor measurements were conducted to find natural frequencies of the specimen before and after each test in order to compare it to the results of accelerometer measurements. Microtremor measurements are the most convenient method to acquire the natural frequency of existing buildings under very small strain condition. Microtremor measurements also were conducted on real masonry structures.

3. Outline of Test Program

3.1 Specimen and Test Setup

The first problem in experimental testing is to determine the components and subsystems which most closely represent realistic structural forms. There is no solitary answer to the question of what can be the minimum scale of the model or what should be the minimum size of substructure. In our study wall specimens of two different sizes/hights resembling window pier and fitting to 1x1 metre shaking table were planned.

In constructing conventional brick masonry wall specimen 210x100x60 mm size red clay brick and C:W:S=1:0.6:2.5 mortar tested in Part 1 were used, whereas for SRB-DUP perforated coal fly ash mix red clay brick with the size of 220x110x85 mm, steel plates of 1 mm thickness, and bolts of diameter 12 mm were used in building the specimens.

The specimens consisted of two parallel walls fixed at the bottom to the table via baseplates with bolts and connected at the top by a concrete slab, which also served as mass (Figure 1). The weight of the slab is 215 kg, with additional steel plates fixed to the slab making lumped mass to be 315 kg, and the gravity load in the walls - 0.04 N/mm2. In the case of conventional masonry specimen after two walls were fastened to the table prefabricated slab/roof was pasted on top of the walls through prefabricated beams with high-strength epoxy E250 of Konishi company.

A total of 2 conventional masonry walls of two different sizes 100x660x514h mm, 100x660x955h mm, and 7 SRB-DUP walls of two different sizes 110x660x516h mm, 110x660x946h mm were constructed for in-plane dynamic testing. Height/length (h/l) ratios are 0.78 and 1.45 respectively.

Material properties of the masonry constituent materials for conventional brick masonry are given in Part 1 of the paper [2], and those for SRB-DUP masonry, namely brick, D12 mm bolt and 1 mm thick steel plate, are summarized in Table 1.

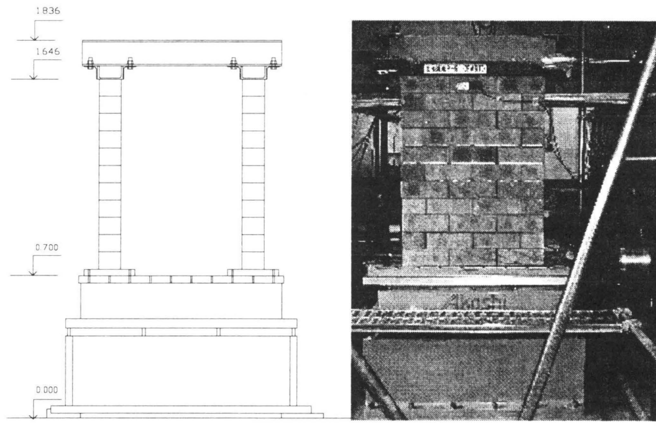

Fig.1 An eleven layers SRB-DUP masonry wall specimen

Table 1. Properties of SRB-DUP masonry materials [1]

Property	Brick	Steel plate	Bolt
Compression strength,Mpa	96.6	-	-
Yield stress, Mpa	-	273.7	435.7
Tensile strength, Mpa	6.21	369.6	521.4
Modulus of elasticity, Mpa	9e3	1.95e5	2.08e5
Yield strain, μ	-	-	0.0021
Poisson's ratio	0.14	-	-

The presstress for SRB-DUP walls was set to be 7 kN.

List of all specimens tested are given in Table 2.

Table 2. List of specimens

No	Name	Description
1	SRB-DUP1	1st specimen 11-layers
2	SRB-DUP1A	1st speciment 11-layers with mass
3	SRB-DUP2	2nd specimen 11-layers (reuse materials)
4	SRB-DUP3	3rd specimen 11-layers (reuse materials)
5	SRB-DUP4	Shortened specimen 7-layers
6	SRB-DUP4A	Shortened specimen 7-layers with mass
7	SRB-DUP5	11-layers specimen (old bricks, new bolts)
8	SRB-DUP6	Shortened specimen 7-layers
9	SRB-DUP6A	Shortened specimen 7-layers with mass
10	SRB-DUP7	11-layer specimen
11	CBM1	13-layer conventional brick masonry
12	CBM2	7-layer conventional brick masonry

In general, all specimens can be divided into 4 groups. That is conventional tall (h/l=1.45), conventional short (h/l=0.78), SRB-DUP tall (h/l=1.45) and SRB-DUP short (h/l=0.78). Additional SRB-DUP masonry tests were performed to study re-usability of constituent materials. This quality of SRB-DUP system is considered one of the virtues of the system.

3.2 Input force

Second important thing in experimental study is to determine appropriate loads, which should be applied to specimens. Base excitation of sweep sinusoidal signals with frequency ranging from 2 to 400 Hz was applied to the specimen in in-plane direction for about 2 minutes. This excitation was repeated for each specimen with accelerations gradually increasing from 25 Gal up to 500 Gal for the short conventional brick masonry wall, while for the tall conventional brick wall up to 260 Gal, the limits when they break. For the SRB-DUP specimens the limits were imposed smaller then their actual strength, due to their heavy weight and safety limits of the shaking table. For that reason the short SRB-DUP wall was tested up to 390 Gal, and the tall SRB-DUP wall up to 240 Gal.

Damping was determined by free vibration tests, in which the table with the specimen was excited by a hummer, between test runs.

3.3 Measurement plan

Measurements were made assuming that the upper slab and the base slab approximately behave like rigid bodies. Acceleration (15 channels), displacement (6 channels), strains of bricks (6 channels) and bolts (14 channels) were recorded using accelerometers Akashi Pick-Up_V407, displacement transducers CDP100 and strain gauges PFL-30-11 or FLA-5-11 correspondingly. Experimental setup and locations of sensors for measuring displacement and acceleration are shown on Figure 2.

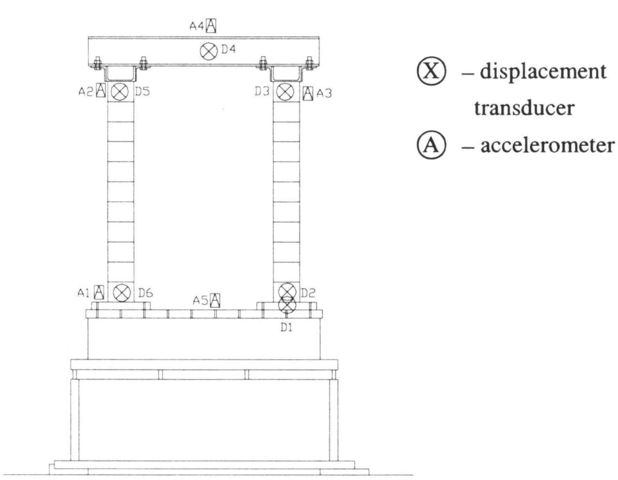

Fig.2 Locations of measuring devices

Sampling interval in data acquisition was 1 milliseconds. High-pass filter was applied to the acquired data.

4. Test Results

The tests were conducted at our shaking table laboratory, Kyushu University, from January 6 until June 2, 2005.

4.1 Predominant dynamic characteristics

Natural frequencies of the specimens were found by dividing absolute response acceleration spectra of the top point to the input acceleration spectra using Fourier transforms, that is transfer functions were calculated. As an example the transfer functions for in-plane motion of 50 Gal for all four specimens are shown on Figure 3.

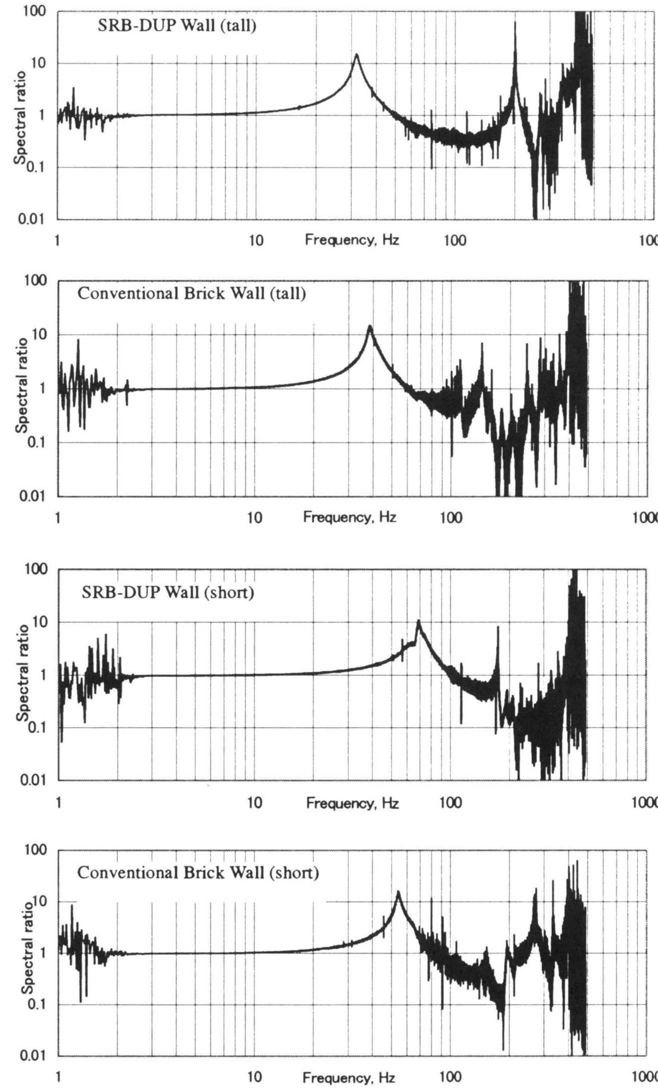

Fig.3 Transfer functions

Damping ratio of the test wall can be determined from free vibration test results using following formula [5]:

$$\zeta = \frac{1}{2\pi j} \ln \frac{\ddot{u}_i}{\ddot{u}_{i+j}}$$

Here, j is a number of cycles between peaks in the motion decrease from u_i to u_{i+j}.

Natural frequencies and dampings of four groups of wall specimens are given in the Table 3.

Table 3. Natural frequencies and damping

Specimen	Natural frequency, Hz		Damping
	In-plane	Out-of-plane	
Conventional tall	33	13	0.032
Conventional short	55	22	0.035
SRB-DUP tall	40	12	0.024
SRB-DUP short	70	26	0.027

The values in the table are initial values of natural frequency and damping. For all specimens natural frequencies decrease with increasing the input acceleration.

As it is shown in Figure 4, natural frequencies are gradually decreasing with increasing input force from 25 Gal to 240 Gal by up to 7% in case of SRB-DUP wall, and by up to 15% in case of conventional brick wall, before any visible crack occurs. SRB-DUP wall is stiffer than conventional masonry wall by about 1.2 times, and with increasing input acceleration its predominant frequency decreases in a slower rate. Also, the decline in natural frequencies for all specimens most accurately can be represented not by a linear function, but by quadratic polynomial (Figure 5).

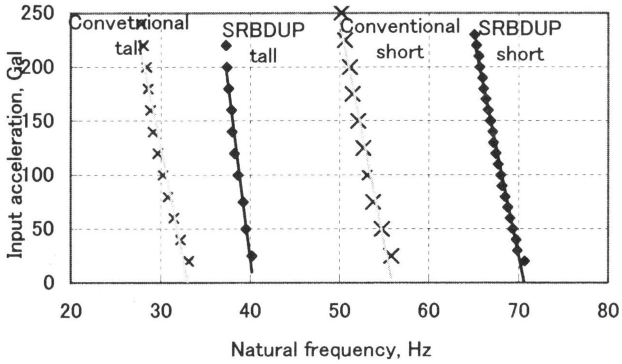

Fig.4 Change in predominan frequency

The decline in predominant frequency with increasing input acceleration may be caused by nonlinear behavior of masonry material, especially mortar (Figure 6).

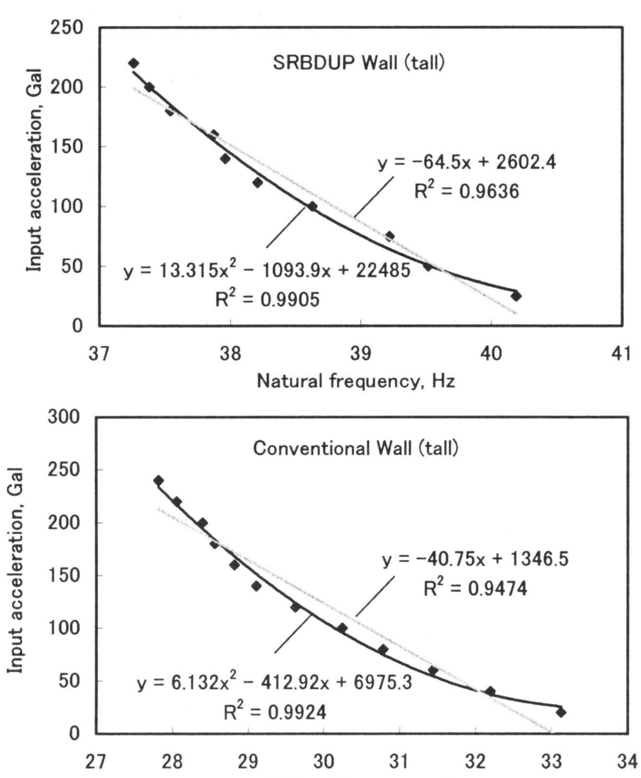

Fig.5 Correlation between natural frequency and input acceleration

The reason for the decrease in natural frequency for SRB-DUP wall could be due to bolt elongation. The bigger the force applied, the more the bolts elongate.

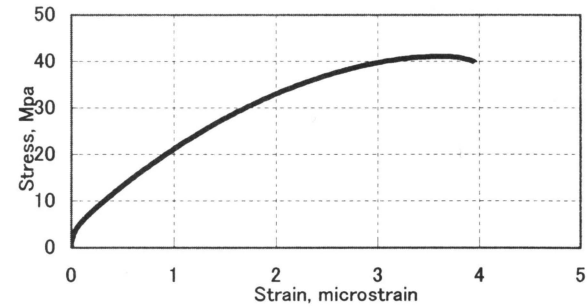

Fig.6 Mortar stress-strain curve: static test result [2]

In Figure 7 maximum strain induced in bolts of SRB-DUP tall wall were drawn with respect to the input acceleration. For example, bolt in SRB-DUP (tall) wall will be 0.14 mm longer at input acceleration of 240 Gal (since the working length of the bolt is 157mm), which reduces initial prestress of 7 kN by 0.2kN.

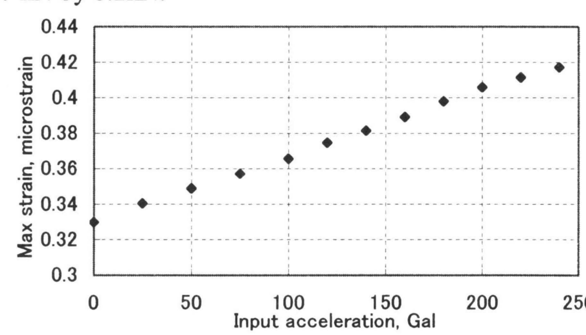

Fig.7 Strain in bolts (SRB-DUP wall)

Strain level in conventional masonry specimen bricks is still within the elastic linear limit. Figure 8 shows stress-strain curve of brick from static compression test, and Figure 9 shows input acceleration versus maximum strain in a brick at the bottom of a wall, recorded during a shaking table test.

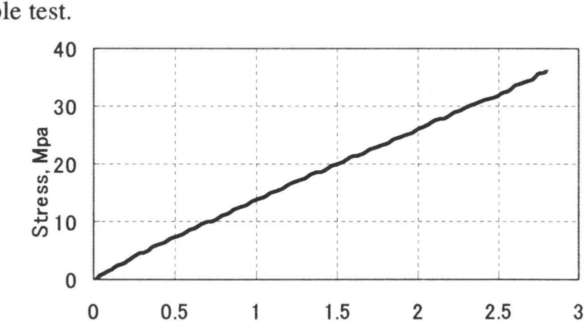

Fig.8 Conventional brick stress-strain curve: static test [2]

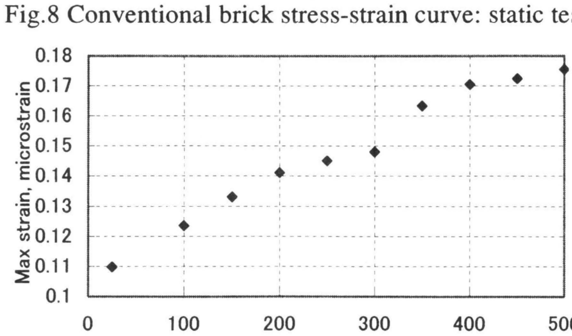

Fig.9 Strain in bricks (conventional wall)

Also in case of SRB-DUP wall specimen when smaller input acceleration is applied again the frequency of the structure returns to a higher value (Figure 10), although not exactly to the original value, which is probably due to development of initial cracks in the brick during construction or during first shaking. During successive runs (sets of inputs) the frequency decreased by about 2%, which is not significant.

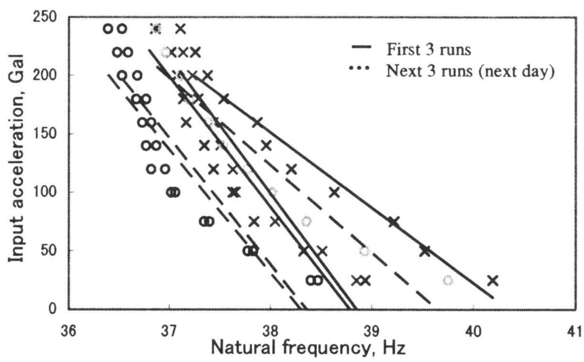

Fig.10 SRB-DUP Wall natural frequencies

Though small the decrease can be explained again by decrease in prestress, decrease of natural frequency may be due to heating up of bolts during numerious vibration. Coefficient of thermal expansion of steel and clay brick (see Table 4) differ more than twice. According to Yamaguchi's stiffness formula for SRB-DUP wall [6] 2% of frequency decrease can be caused by temperature change of about 20°C.

Table 4. Thermal properties of materials [7]

Material	Coef.of thermal expansion (average), 10^{-6}/C°
Clay brick	6.5
Structural steel	14
Concrete	10.5

4.2 Crack pattern or Damage Process

The damage was identified by means of two methods: visual observation of cracks appeared in specimen and change in natural frequency. After each shaking of given acceleration, cracks were accurately mapped (Figure 11).

An abrupt drop in natural frequency also can be an evidence of crack formation. In fact, one of the reasons for decrease of natural frequency discussed in 4.1 can be development of microcracks invisible to naked eyes. For example, in case of short conventional wall specimen, after first visible crack was observed on one of the parallel walls, the natural frequency droped and two distinctive peaks appeared at around 11 Hz and 47 Hz (Figure 12). Before the crack emergence there was only one peak in in-plane response transfer function (Figure 3). First crack appear at 300 Gal in short conventional wall, completely collapsing at 500 Gal, whereas the tall wall broke at 260 Gal.

The nature of cracks in conventional masonry specimen is shear and brittle, and the crack develop mostly in brick-

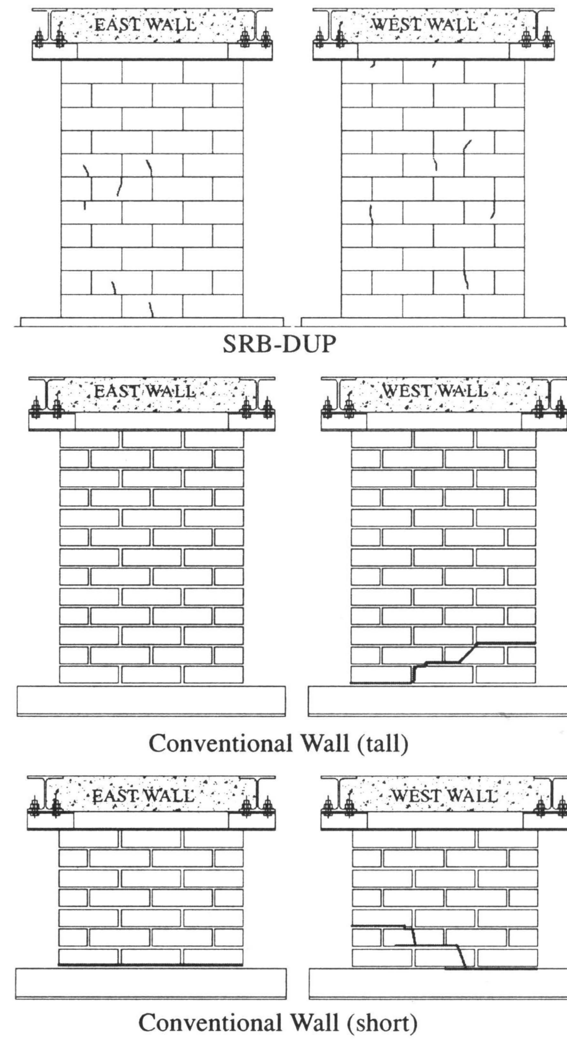

Fig.11 Crack pattern

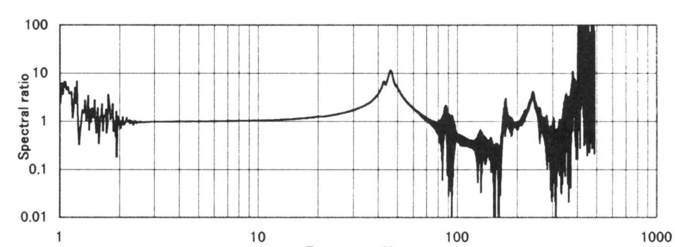

Fig.12 Transfer function after crack

mortar interface, the weakest part of conventional masonry. As for SRB-DUP wall, several cracks appear in the bricks (mostly along the middle of the brick) at the stage of prestressing during construction of the specimens. This is due to the imperfect surfaces of the bricks. Most other cracks appear during the first shaking, and again through the middle of the brick unit. It can be due to concentration of prestress accumulated during the construction due to brick surfaces were not perfectly flat. Additional cracks start to appear again at 300 Gal shaking in SRBDUP tall wall.

4.4 SRB-DUP`s reuse option

As it was mentioned above that SRB-DUP system represents environmentally friendly construction method, which is very important. Here we tested specimens starting from walls built entirely from new materials, and following first and second reuse of the materials up to 100 Gal. As we can see in Figure 13 the more we reuse the more torque we need to apply, which can be cause by deterioration though small of threads of bolts and nuts. Natural frequencies also tend to decrease by about 3.5% after the second reuse.

When reusing bricks, cracked units were replaced by new ones, allowing to reuse 86% of bricks used in specimen. As it was mentioned before the most cracks develop during construction and during first shaking, which is due to the imperfect shape of the brick units. Therefore, with good shaped bricks the cracks should be much less [8], and they could appear only if shaking will reach 300 Gal or more.

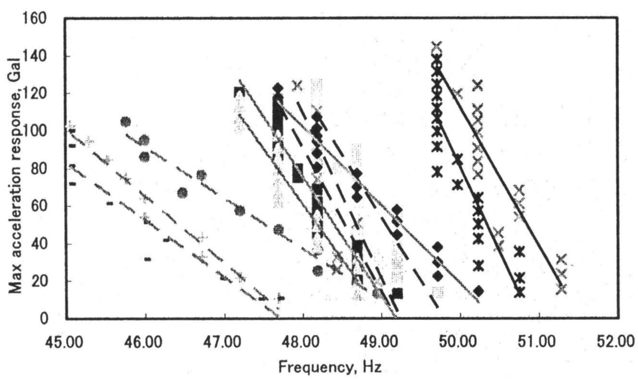

Fig.13 Natural frequencies and acceleration response of the wall specimens with reused materials

1[ST] specimen (new materials), torque 17.7 kN
2[nd] specimen (reuse of brick and steel hardwares), torque 22kN
3[rd] specimen (reuse of brick and steel hardwares for the 2[nd] time), torque 26kN
4[th] specimen (reuse of brick, new steel hardwares), torque 18.8kN

5. Microtremor measurement results

Microtremor measurements were done on specimens before and after the tests, and the results are very similar to that obtained from accelerometer results (Table 5).

Table 5. Natural frequencies obtained from microtremor measurements

Specimen	Natural frequency, Hz	
	In-plane	Out-of-plane
Conventional tall	33	14
Conventional short	50	25
SRB-DUP tall	40	12
SRB-DUP short	70	29

Also microtremor measurements were conducted on experimental SRB-DUP house [1], and natural frequencies were calculated (Table 6). Compared to wooden houses (of similar configurations, not much differed in age), which has natural frequencies of about 7-8 Hz [9], the SRB-DUP system masonry house is stiffer almost twice.

Table 6. Natural frequencies

Mode	Frequency	Direction
1	12Hz	NS
2	40Hz	NS
1	10Hz	EW
2	28Hz	EW

6. Conclusion

In-plane dynamic properties of SRB-DUP system masonry and conventional mortar masonry walls were studied. Results reveal that SRB-DUP walls are stiffer than conventional walls. Natural frequencies of all specimens decrease with increasing input acceleration, which can be due to nonlinear characteristics of mortar in conventional masonry, and due to steel bolt elongation and subsequent release of prestress, though very little, in SRB-DUP masonry.

The failure of conventional walls is brittle and abrupt, whereas SRB-DUP walls keep their integrity even after several cracks, making the system very ductile.

Stiffness of SRB-DUP wall did not deteriorate much even materials, brick and bolts, were reused from the structure shaken numerous times up to 100 Gal.

Data collected from the experimental study will be used further for development and verification of computational models for prediction of in-plane behavior of conventional unreinforced masonry and SRB-DUP system masonry structures.

References

1) **松藤泰典, 循環建築学講座**, 2005.

2) D.Saruul and H.Kawase, Experimental and Numerical studies of non-linear behavior of masonry wall elements. Part 1. Experimental Study, J.of Architecture and Urban Design, Kyushu University, no.6, pp.113-118, 2004.

3) J.H.Kim, Analytical implications on in-plane behavior of unreinforced masonry walls, Proceedings of the 3[rd] Diana world conference, Tokyo, Japan, pp.249-256, 2002.

4) M.Timozevic, Earthquake-Resistand Design Of Masonry Building, Imperial College Press, 2000.

5) A.K.Chopra, Dynamics of Structures, Prentice Hall Intl, 1995.

6) 山口太謙太郎 他 4, 分散型アンボンドプレストレスを用いた組積構造建物の常用設計に関する研究・壁体の面内剛性解析とその検証実験、学術講演梗概集、日本建築学会 A-1：679-680, 2000.

7) 樋口芳朗, 建設材料学, 東京 ： 技報堂出版, 1988.

8) 佐々木孝 他 4, 循環型住宅の施工に関する要素研究、学術講演梗概集、日本建築学会 A-1：691-692, 2000.

9) 田中宏明, 部材接合部の非線形特性を考慮した在来木造建物の挙動解析モデルの構築, 修士論文, 2004.

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