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EXPERIMENTAL AND NUMERICAL STUDY ON DYNAMIC PROPERTIES OF FRICTION-RESISTANT DRY-MASONRY STRUCTURES

S. Dorjpalam[1], H. Kawase[2], K. Yamaguchi[3], and S.O.Citak[4]

[1] *Structural Engineer, PhD*
[2] *Professor, Disaster Prevention Research Institute, Kyoto University, Kyoto, Japan*
[3] *Professor, Grad. School of Human-Environment Studies, Kyushu University, Fukuoka, Japan*
[4] *Research Engineer, Ohsaki Research Institute, Tokyo, Japan*
Email: saruuld@yahoo.com, kawase@zeisei.dpri.kyoto-u.ac.jp, yamaguchi@arch.kyushu-u.ac.jp, and citak@ohsaki.co.jp

ABSTRACT :
Dynamic properties of friction-resistant dry-masonry SRB-DUP (Steel Reinforced Brick based on Distributed Unbond Prestress) structures and structural elements are studied through experimental tests and numerical simulation analyses. First, dynamic tests are conducted on masonry wall elements, and basic dynamic properties are found. Next, a numerical model is formulated using micro-modeling technique, where constituent materials (bricks and reinforcing steel elements) are modeled as separate entities. The model is verified by analyzing the experimental wall models. Then simulation models of various wall elements are built and analyzed. Based on the analyses results a macro-model of a real size structure is built and analyzed for strong ground motion records. We found that the SRB-DUP structure shows quite strong seismic resistance.

KEYWORDS:
Friction-resistant, Reinforced Masonry, Numerical Modeling, Simulation, FEM Analysis, Environmentally Friendly Structural System

1. INTRODUCTION

A friction-resistant type dry masonry system called SRB-DUP has been being developed and studied in Kyushu University, Japan, for a decade now. SRB-DUP stands for Steel Reinforced Brick based on Distributed Unbond Prestress and is a structural system, which uses steel plates and bolts for bonding bricks to each other by introducing prestress in bolts (Figure 1). The purpose of this arrangement is to construct a re-usable yet earthquake resistant structure.

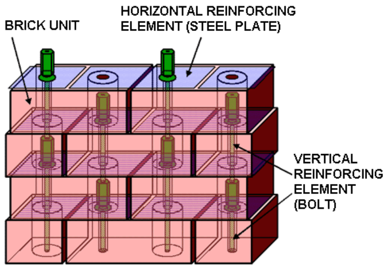


Figure 1 SRB-DUP masonry system (Matsufuji 2000; 2005)

Conventional brick-mortar masonry is one of the most widely used structural systems especially in developing countries due to simplicity of its construction techniques and availability of raw materials locally. However, it is avoided in seismically dangerous regions due to its devastating history in past earthquakes. SRB-DUP masonry, as one form of reinforced masonry, offers a great alternative as it does not only possesses good seismic resistance, but also it is one of few green new structural systems to emerge in the wake of environmentally friendly construction and sustainable urban development issues. Because the materials are not glued to each other, they are easily disassembled and can be reused, thus saving energy and reducing construction waste.

Until now SRB-DUP studies were focused on improvement of construction methods, performing of material tests, static and dynamic tests of structural elements, and development of design analytical formulas (Mastufuji et al. 2005; Yamaguchi 2004; Dorjpalam 2005). Several experimental SRB-DUP houses were built and are being monitored (Matsufuji et al. 2005). This particular study aims at grasping dynamic properties of SRB-DUP structures and structural elements through dynamic tests, numerical modeling, and simulation analyses.

The experimental tests show that SRB-DUP has good ductility (Yamaguchi 2004), and we were lucky to observe a two-story experimental SRB-DUP masonry house to survive to the strong motions of 6^- (in terms of JMA seismic intensity) during the 2005 West off Fukuoka Earthquake, which caused only a very minor crack in a brick at an entranceway (Kawase 2006). However, we do not have much real life evidence of its safety during strong earthquakes, except for that rare example, mostly due to relatively recent invention of the system.

Adequately verified simulation models can give insight into behavior of SRB-DUP structures in case of an earthquake, and that is what we attempt doing in our research.

2. SCOPE OF THE STUDY

First, in-plane shaking table tests on SRB-DUP wall elements were carried out to obtain basic dynamic properties of the walls for further use in verification analyses of the numerical model. The numerical model was formulated on general purpose finite element code ADINA using micro-modeling technique, where constituent materials (bricks, steel plates, and steel bolts) are modeled as separate entities. The model was verified using static (Yamaguchi 2004) and the dynamic test results.

Next, models of SRB-DUP wall elements of different sizes were built and analyzed for push-over loads. Based on the results of the push-over analyses a “spring” model of a real two-story house was built and verified by comparing with microtremor measurement results of the same building. Finally, simulation analyses of the building were performed for several strong ground motion records using SAP2000 software.

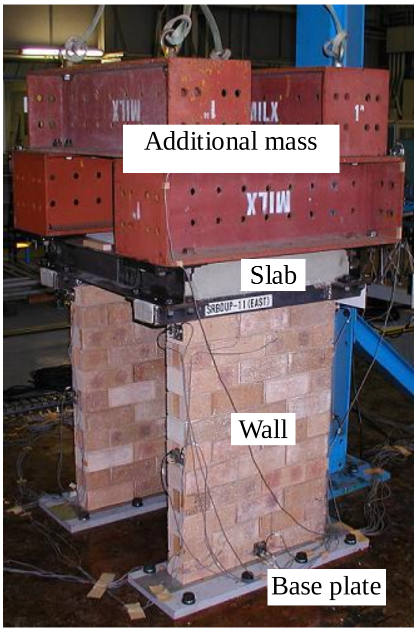
3. DYNAMIC TESTS ON WALL ELEMENTS

SRB-DUP masonry wall specimens were tested in the shaking table laboratories of Kyushu University and Shimizu Corporation. Coal fly ash mix red clay hollow bricks with size 220x110x85 mm, 1 mm thick steel plates and bolts of 12 mm diameter were used in the masonry (Figure 2). The average prestress introduced in each bolt is set to 7 kN. This prestress induces average 0.64 N/mm^2 compression in bricks, which is approximately 1/42 of the brick’s compression strength.

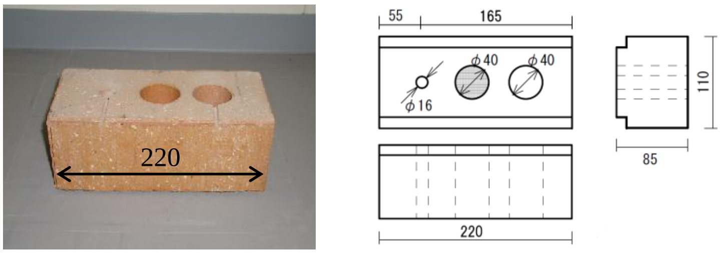
The specimens consisted of two parallel walls fixed at the bottom to the table via base plates with bolts, and connected at the top through a rigid concrete slab, which also served as a mass (Figure 2). Specimens of three different heights, 6-layer high (Length x Height = 660x516 mm^2), 11-layer high (660x946 mm^2) and 16-layer high (660x1136 mm^2) were tested. The specimen top masses varied from 215 kg to 315 kg and 650 kg.

The specimens were excited with sinusoidal sweep signals with frequency ranging from 2 Hz to 50 Hz or 2Hz to 400 Hz in in-plane direction for about one minute. This excitation was repeated for each specimen with accelerations gradually increasing from 1 m/s^2 up to 10 m/s^2. Some of the specimens were also subjected to 1995 JMA Kobe Observatory (JMA Kobe) NS component record scaled to be 2 m/s^2, 4 m/s^2 and 8 m/s^2.

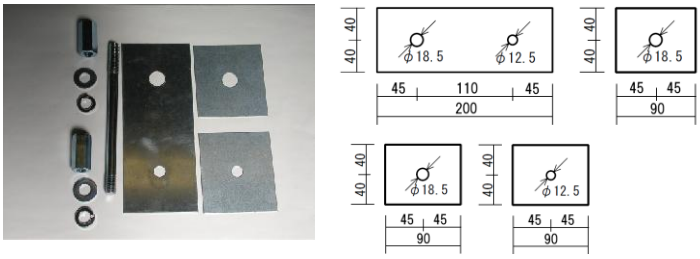
Predominant frequencies and damping values found from the experiment are collected in Table 1.



(a) Test setup (11-layer wall specimen)



(b) Brick



(c) Reinforcing steel
(Nuts, round and spring washers, bolt, plates)

Figure 2 Shaking table test setup and materials

Table 1 Natural frequencies and damping results

Type	Mass, kg	Natural frequency, Hz	Rayleigh damping	
			α	β
6-layer	215	73.55/80.03	2.505	0.00017
	315	68.80	3.279	0.00020
11-layer	215	51.33	1.604	0.00020
	315	43.17	2.248	0.00022
	650	21.32/29.56	0.630	0.00048
16-layer	650	15.76/20.89	0.302	0.00032

Several notes on cracking and damage pattern observed during the tests shall be briefly mentioned. The nature of cracks in bricks is brittle, but in SRB-DUP masonry as a whole the response was not brittle. Cracks in the SRB-DUP wall specimens appeared at different locations over the wall, thus avoiding localized, abrupt, brittle failure type, and securing more ductile overall behavior. Also, there was not much sliding between the layers observed during the shaking test, whereas it was a case in quasi-static tests (Yamaguchi 2004).

4. FORMULATION OF THE MODEL

4.1. Geometry

Bricks were modeled using a 3D-solid 8-node element; steel plates – “plate” element; bolts – “beam” element with the initial prestress of 7 kN as it was designed in the experiment.

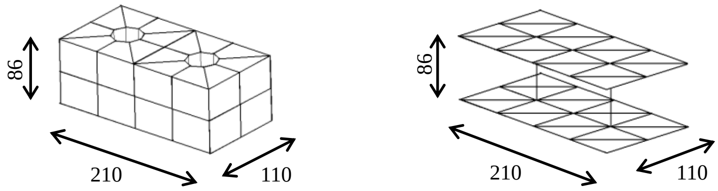


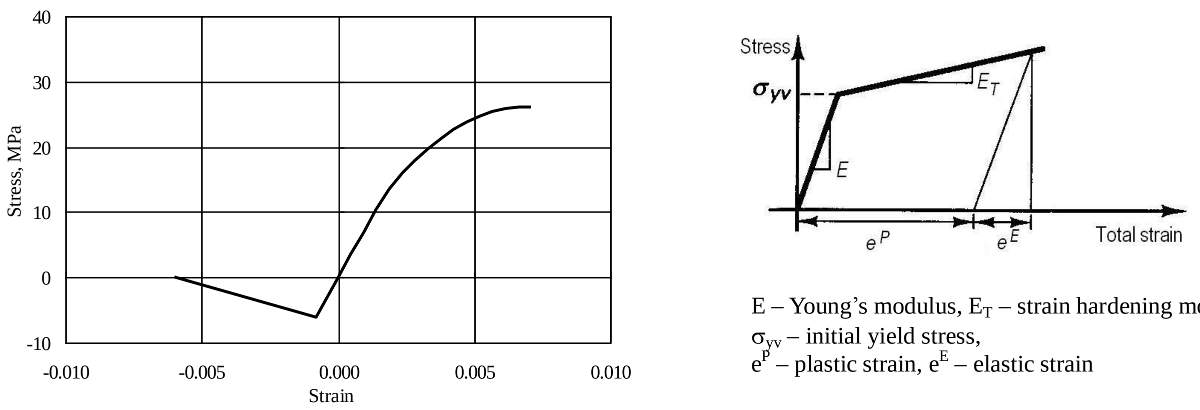
Figure 3 Brick, bolt, and plate elements

In this study the nodes of two adjacent bricks are coupled, that is, they are joined and move together. So are the nodes of adjacent plates.

We assume that slip is concentrated in the interlayer joints. For the modeling of brick-plate interface ADINA's "contact surface" elements are adopted and their interaction is represented by Mohr-Coulomb criteria. Friction coefficient φ=0.3 was adopted in previous studies of analytical formulations for shear strength of SRB-DUP masonry (Yamaguchi 2004). In our analyses we employ the same value of 0.3 for the dynamic friction coefficient, and the static friction coefficient of value 0.9 was determined to fit the static test results discussed later in 5.2.

4.2 Material model

Bricks were modeled with material property defined in ADINA as the "concrete" material type, which has a simple nonlinear stress-strain formulation (Figure 4) with tensile failure at relatively small principal tensile stress and compression crushing failure at relatively higher compression. Softening common for brittle materials like brick was not modeled due to convergence difficulties. In unloading the initial Young's modulus was used.



E – Young's modulus, E_T – strain hardening modulus,
σ_{yv} – initial yield stress,
e^P – plastic strain, e^E – elastic strain

(a) Brick (b) Steel

Figure 4 Stress-strain curves for brick and steel materials

The steel material for both plate and bolt elements is presented by plastic-bilinear model with kinematic hardening. The values of material properties used in the analyses are given in Table 2, and were determined from material laboratory tests (Yamaguchi 2004).

Table 2 Properties of SRB-DUP masonry materials used in analyses

Property	Brick	Bolts	Plate
Young's modulus, MPa	6000.00	208000.00	195000.00
Initial yield stress, MPa	-	435.70	273.70
Tensile strength, MPa	6.21	521.40	369.60
Strain hardening modulus E_T	-	2700.00	100.00
Poisson's ratio	0.19	0.20	0.20

5. NUMERICAL MODEL VERIFICATION

5.1 Dynamic tests of wall elements

Figure 5 shows an example of 6-layer dynamic test wall specimen and how it was modeled using ADINA.

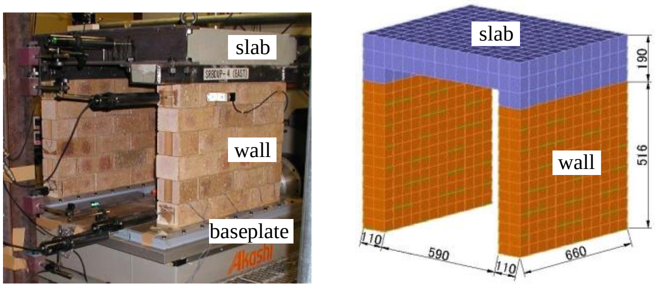


Figure 5 6-layer wall specimen and its model

Table 3 Fundamental frequency values (Hz)

Specimen	Experiment results	FEM analysis
6-layer (mass 215 kg)	73.55/80.03	72.61
6-layer with steel plates (mass 315 kg)	68.80	67.41
11-layer (mass 215 kg)	51.33	54.93
11-layer with steel plates (mass 315 kg)	43.17	48.98
11-layer with steel profiles (mass 650 kg)	21.32/29.56	30.30
16-layer with steel profiles (mass 650 kg)	15.76/20.89	21.39
31-layer, out-of-plane shaking test (Yamaguchi, 2004)	3.5	5

It can be seen from Table 3 that the model reproduces one of the main dynamic characteristics, the fundamental frequency well, although little discrepancies are observed for the 11-layer (mass 215 kg and 315 kg) wall specimens. The experimental results for these two walls are less stiff than the models' results. The walls were tested on a small-size shaking table, and the weights of the concerned two walls were comparatively heavier than those of the other specimens measured on the same table. Thus we may suspect that the table might not have been able to provide an adequate fixation, especially in a rocking motion.

5.2 Static test of 32-layer wall element

Also, a wall specimen subjected to a static horizontal load was modeled and verified. A series of static tests on SRB-DUP masonry wall specimens were conducted by Yamaguchi in Kyushu University, Japan (Yamaguchi 2004). A 32-layer SRB-DUP (Figure 6) wall specimen of size 960x2750 mm was modeled, analyzed and compared to the static test results. The results of the analysis and those of the test are shown in Figure 7. The model can follow the test results reasonably well.

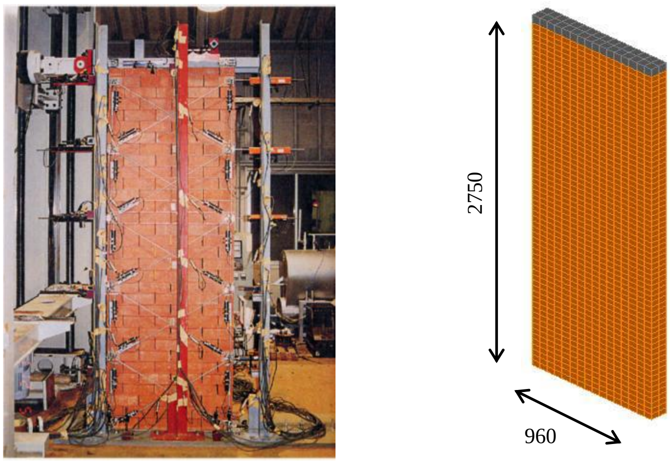


Figure 6 32-layer specimen (Yamaguchi 2004) and its model

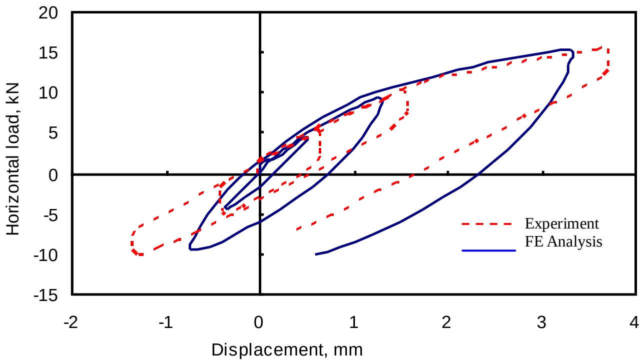


Figure 7 Shear stress and drift angle curve of the 32-layer wall's static experiment and analysis

According to the static test measurements (Yamaguchi 2004) the strains of bolts at the load levels shown in Figure 7 are still within the yielding limits of the steel material. Therefore the non-linearity of the test curve comes from the slip at horizontal joints. The analysis results also indicated the still elastic state of the bolts, and brick-plate interface friction parameters were adjusted to allow slip of the test levels.

6. REAL SIZE BUILDING MODELING

Assuming the above verifications of the model are acceptable the simulations of dynamic behavior of SRB-DUP masonry structural elements and real-size structures can be undertaken.

The main disadvantage of the micro-model is its computational time and computer capacity demands. To overcome this hurdle and simulate the response of a real-size building a more simplified model is proposed. SRB-DUP masonry is simplified to a "spring" system. A big-size wall is divided into smaller parts, wall elements, of less demanding sizes according to the configurational features (i.e. window and door openings). These smaller wall parts are represented by non-linear "spring" elements. The non-linear properties of a "spring" element are calculated by push-over analyses using a micro-model of a wall of the size that this particular "spring" element represents. The simplified system is similar to "lattice" model or "Spring-Lumped Mass" model.

6.1. A two-story experimental SRB-DUP house: microtremor measurements

Within the project several experimental SRB-DUP houses were built and monitored (Matsufuji et al. 2000; Yamaguchi 2004). Here we present one of them, namely 2-story house built in 2005 in Fukuoka, Japan (Figure 9). Microtremor measurements were conducted and fundamental frequencies were calculated in 2005, and again later in 2007. The results, which are given in Table 4, indicate unchanged stiffness of the building after passage of two years and even experiencing the JMA intensity of 6- ground motion (Kawase 2006). Compared to wooden houses (of similar configurations, not much differed in age), which have natural frequencies of about 6-8 Hz, the SRB-DUP masonry house is almost twice stiffer.

Table 4 Measured predominant frequencies (Hz)

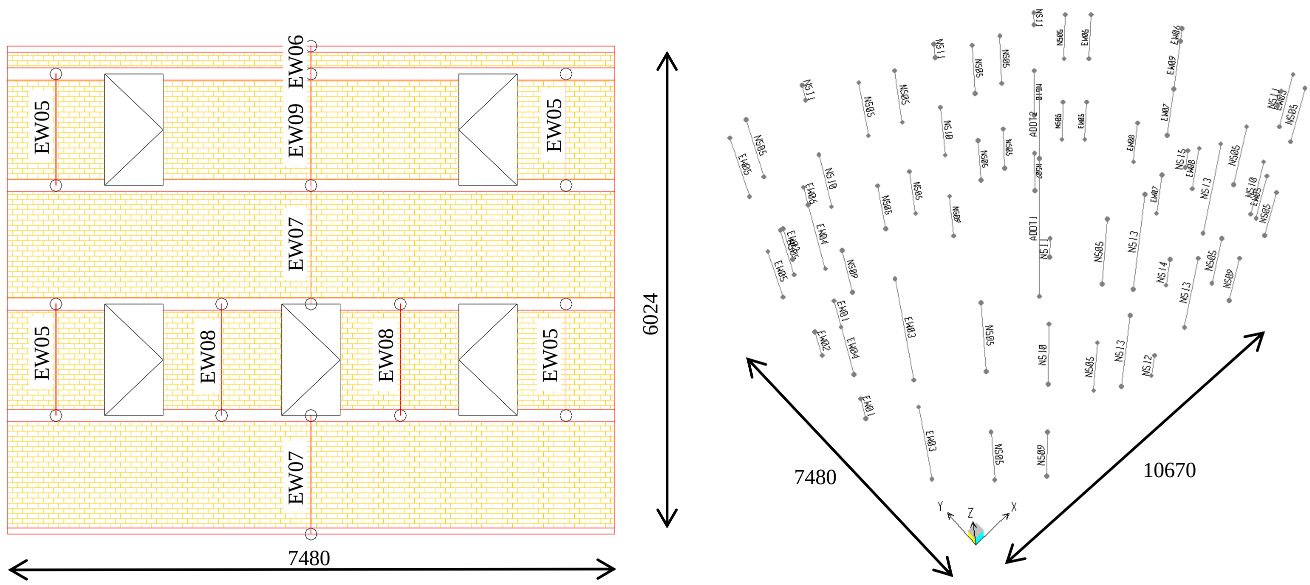
Measurement date	Ambient temperature, °C	NS direction	EW direction
May 2005	24.7	11.23	9.69
June 2007	24.4	11.25	9.75

a) Entrance façade b) First floor plan

Figure 8 Two-story experimental SRB-DUP masonry house built in 2005, Fukuoka, Japan

6.2. Model formulation

First, allocation of “spring” elements has to be decided. Though modeling of a wall element with an opening(s) is possible with the SRB-DUP micro-model, the building model or the walls were divided into smaller solid wall elements (with no opening) as shown in Figure 9. SAP2000 software was used in the analyses.



(a) East Wall (b) SRB-DUP house model

Figure 9 “Spring” element allocation

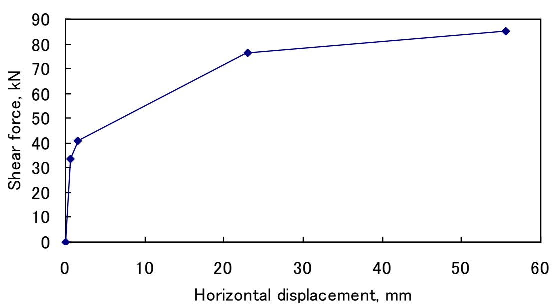


Figure 10 Skeleton curve adjusted from push-over analysis curve (EW05 element)

An example of a multi-linear skeleton curve of a spring element obtained from the push-over analysis of a representative wall element (EW05, 1100x1376 mm^2) is shown in Figure 10. The springs were provided with multi-linear plastic properties and Pivot stiffness degradation hysteresis model (Dowel et al. 1998).

6.2. Modal analysis

Using this "spring" model modal analysis was carried out, and the results are compared to the microtremor measurement results discussed previously (Table 5). The analysis results are very close to the measured results.

Table 5 Experimental house predominant frequencies, observed and simulated

	NS direction	EW direction
Microtremor measurement	11.40	10.33
Modal analysis result	11.46	10.26

6.3. Strong ground motion time history analyses

Dynamic analyses were carried out on the model using strong ground motions of 2005 Fukuoka West Earthquake (Magnitude 6^{-}), which resulted in very little displacement response of less than one cm at the roof level of the house, and 1995 Hyogo-ken Nanbu Earthquake (Magnitude 7.3), which resulted in 2 cm (1/300 radian) at the maximum, much smaller than a preliminary design safety deformation limit of 1/100 radian (Matsufuji 2005).

7. CONCLUSION

In this paper we introduced the numerical modeling of new friction-resistant dry-masonry (SRB-DUP). First, a micro-model for analyses of wall elements was introduced. Then, for analyses of a real-size structure a simplified "spring" model, material non-linear characteristics of which were obtained from push-over analyses of wall micro-models, was utilized. Using "spring" model a real structure was modeled and analyzed for two strong ground motion records. The displacement responses were in the limits of 2 cm (1/300 radian) in case of Kobe earthquake, which was still within the preliminary safety design value of 1/100 radian (Matsufuji 2005).

Though micro-model is a labor and time-expensive analysis model, it has one main advantage compared to all simplified methods especially in the case of SRB-DUP masonry modeling. In SRB-DUP masonry the energy is mainly dissipated by the friction and sliding between the layers, which are uniformly prestressed. In micro-model the friction and sliding energy dissipation is inherently modeled with introduction of interface elements (contact surfaces) and friction laws between them.

REFERENCES

Matsufuji, Y. et al (2000). Study on construction of sustainable housing system. Part 1: Concept of sustainable housing system and suitableness for DUP method with dry masonry work. *Summaries of technical papers of annual meeting*, Architectural institute of Japan, **A-1**, 683-692 *(In Japanese)*.

Yamaguchi, K. (2004). Design and performance of friction resistant dry masonry structural elements. *PhD Thesis*, Kyushu University *(In Japanese)*.

Dorjpalam, S. et al (2005). Experimental and numerical studies of nonlinear behavior of masonry wall elements. Part 2: In-plane shaking table test. *Journal of architecture and urban design, Kyushu Univ*. **8**, 35-40.

Kawase, H. (2006). 2005 Fukuoka West off Earthquake report. *COE newsletter* **3**, 1 *(In Japanese)*.

Tanaka, A. and Kawase, H. (2005). Construction of three-dimensional nonlinear dynamic models for wooden structures based on actual measurements and experiments. *Journal of structural and construction engineering* **592**, 121-128 *(In Japanese)*.

ADINA: Theory and modeling guide. Adina R&D Inc., 2006.

Analysis reference manual for SAP2000. Computers & Structures Inc., 2007.

Dowell, R. K. et al (1998). Pivot hysteretic model for reinforced concrete members. *ACI structural journal* **95**, 607–617.

Matsufuji, Y. (2005). Sustainable architecture. Shirojima Printing, Japan *(In Japanese)*.

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