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REPRODUCTIVE ANALYSIS OF FULL-SCALE SHAKING TABLE TESTS OF WOODEN HOUSES USING QUALITY ENGINEERING

Tokikatsu Namba[1], Takafumi Nakagawa[2], Yuji Kado[3], Atsuo Takino[4], Hiroshi Isoda[5]

ABSTRACT: Since the Great Hanshin-Awaji Earthquake in Japan, many full-scale shaking table tests have been conducted for the purpose of analysing the seismic performance of wooden houses. Therefore, the knowledge obtained in the experiment needs to be fed back to the simulation such as structural analysis. However, as a premise that makes them possible, it is indispensable to be able to perform reproductive analysis. In this study, as reproductive analysis, we tried the data assimilation using quality for seismic response analysis of wooden houses engineering.

KEYWORDS: Data assimilation, Reproductive analysis, Full-scale shaking table test, Quality engineering

1 INTRODUCTION

Since the Great Hanshin-Awaji Earthquake in Japan, many full-scale shaking table tests have been conducted for the purpose of analysing the seismic performance of wooden houses [1]. The purpose of these experiments was to determine the seismic performance of the houses and to establish analysis methods. If there is an analytical method that can reproduce the behaviour, it will be possible to determine the seismic performance of the building without conducting experiments. However, if a time history response analysis is conducted in advance by simple addition of load-deformation relationships of individual walls, the response deformation tends to be larger, i.e., the performance of the building at the time of the experiment often exceeds the prediction. As a result, the parameters of walls and joints are reviewed to obtain parameters that match the experimental results, and the parameters will be compared before and after the review to consider the reason for the increase in the capacity. The review is performed manually while considering the reason for the increase, but it is a time-consuming process, and even if the failure process of the obtained solution is different, the inter-story displacement may happen to be similar to the experimental results.

This study discusses a data assimilation method, rather than trial and error, for the review process. Data assimilation is a method of finding parameters that are consistent with observations [2]. This method has been developed primarily in the field of weather forecasting, and it has also been applied to the development and validation of mathematical models in meteorology, climatology, geophysics, geology, and hydrology. In recent years, data assimilation has also been applied to numerical simulations in the fields of geophysics and biology to improve the reliability of numerical simulations [3,4]. In the fields of architecture and civil engineering, it is also known as "system identification," a theory for identifying the modal properties and analytical parameters of structures by observing their response to earthquakes and using microtremor measurements [5]. For example, Nakamura et al. (2000) proposed and validated method for identifying layer stiffness and damping of shear mass system structures using actual earthquake records [6]. In wooden houses, studies have been conducted to estimate layer stiffness by microtremor observation [7]. But there have been few research cases of system identification of nonlinear behaviour of wooden houses, which is the target in this study. As mentioned above, there are several studies on estimating seismic performance by analysis and reproducing experimental results that are closely related to the parameters. For example, Sugiyama et al. (1987), in a static load test of a two-story wood-frame frame house, compared the seismic capacity during a full-scale experiment with the estimated bearing capacity calculated from an experiment on a single wall, and reported that the capacity during the experiment was about 30% greater than the estimated capacity [8]. Miyoshi et al. (2001) reported that static loading force and shaking table experiments on a two-story wood-frame frame house estimated the load-deformation relationship in shaking table experiments by adding up wall experiment and found that it was possible to estimate about 90% of the stiffness up to 1/75 rad, but not the maximum capacity and toughness in the large-deformation region [9]. Comparing the results of shake table tests of several full-scale wooden houses with the calculation results of adding up the load-deformation relationships of all the walls of those structures, Isoda et al. (2021) reported that the capacity during full-scale

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[1] Tokikatsu Namba, RISH, Research Institute for Sustainable Humanosphere, Kyoto university, Japan, tokikatsu_namba@rish.kyoto-u.ac.jp
[2] Takafumi Nakagawa, RISH, Kyoto university, Japan, nakagawa@rish.kyoto-u.ac.jp
[3] Yuji Kado, JAXA, Japan Aerospace Exploration Agency, Japan, kado.yuji@jaxa.jp
[4] Atsuo Takino, Osaka Institute of Technology, Japan, atsuo.takino@oit.ac.jp
[5] Hiroshi Isoda, RISH, Kyoto university, Japan, hisoda@rish.kyoto-u.ac.jp

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shake table tests was larger than the addition results, about 1.2 times larger at small deformations and about 1.5 times larger at large deformations [10]. It is not easy to accurately estimate the performance of a full-scale shaking table test from experiments for individual walls. In most of these previous studies, shear deformation of each floor is the target. In this study, on the other hand, a three-dimensional analytical model that includes the behaviour of joints, rather than a shear system model that only covers the response of the layers, was constructed to present the damage of each part in detail. In other words, the number of parameters to be considered is enormous.

Here, we focused on quality engineering to reduce the computational complexity in data assimilation and to more efficiently assimilate analytical parameters from shaking table tests. Quality engineering is a statistical method based on the design of experiment method and is sometimes called the robust design method [11]. Developed to improve product quality, orthogonal tables are employed to analyse a large number of variables with a relatively small number of experiments, for example [12]. And inferences obtained using orthogonal tables are said to yield results similar to those obtained by exhaustive examination, and have recently been applied in various fields, such as biotechnology. In the data assimilation method using quality engineering, parameters are defined by multiplying a correction factor with the nominal value set to 1 by the actual physical property value, and the parameters are reproduced by manipulating the correction factor [13].

Based on the quality engineering, this study attempted to establish a method for searching parameters in an analytical model that can accurately reproduce the response of a shake table test. By analysing the results obtained from the actual performance during the full-scale shaking table test and the results of elemental experiments for each seismic element, the main objective of this study is to discuss points and problems that have not been considered in previous studies and to help improve the accuracy of future seismic simulations.

2 EXPERIMENT

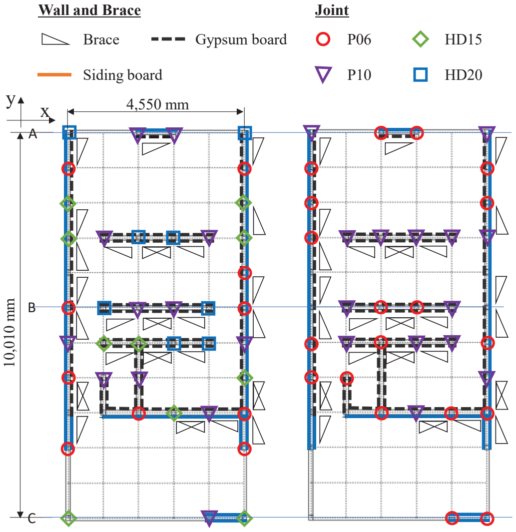
The full-scale shaking table experiment targeted in this study was conducted as part of the Ministry of Land, Infrastructure, Transport and Tourism-subsidized project "Design Method Verification Project for 3-Story Wooden Frame Construction" [14]. There were four specimens, each with different wall amounts, joints, and their arrangement, etc. The target specimens to be analysed in this study are specimens 1 and 2 (Figure 1), which have the same plan and elevation plan, but the design of the joints is different (Figure 2). Both are three-story wood-frame frame construction buildings with a plan dimension of 4.55 m x 10.01 m and an eave height of 8.905 m.

3 NUMERICAL ANALYSIS

3.1 Analysis model

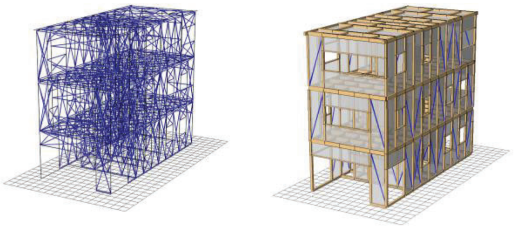
In this study, we used "wallstat" [15], an analysis software based on the discrete element method, was used for the time history response analysis. The individual element method is an analysis method for discontinuous bodies such as collapsed bedrock, but the authors have proposed an analysis method using a three-dimensional framework model that can trace the collapse of a wooden house16). Figure 3 shows the analytical model. The number of nodes is 1716 and the number of springs is 3050. The shaft members were assumed to be beam elements, and the bending strength was set to 60 N/mm^2, considering the actual values of the glued laminated wood used in the test specimens. Young's modulus was set to the value based on JAS for each member, respectively.

***Figure 1**: The specimen of the test*



(a) Specimen No.1 *(b) Specimen No.2*

***Figure 2**: Plan views at the 1st floor of the specimen*



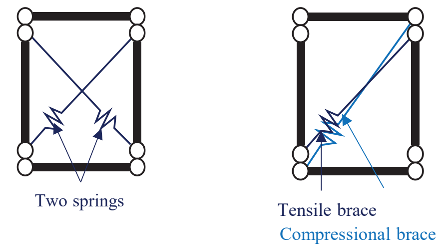
(a) Beam and truss elements *(b) Overview*

***Figure 3**: Analysis model (1716 Nodes, 3050 elements)*

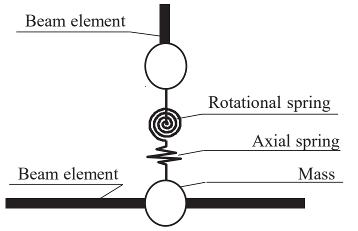
The shear resistance of the wall and brace were modelled as shown in Figures 4(a) and (b), with bracing substituted by truss elements for the walls and two truss elements for the fascia walls with separate load-deformation relationships on the tensile and compressive sides. Each spring acts only in the compression and tension directions. The joints were modelled with rotational springs, compressional and tensile springs (rigid against shear), as shown in Figure 4(c). The skeletal curves were defined based on the results of flexural and tensile tests of the joints. The tensile spring was assumed to be a spring with slip-type characteristics, and the compressional spring was assumed to be an elastic spring. The rotational spring acts independently in the strong and weak axial directions. Figure 5 shows the skeleton curve of the walls and braces, and the skeleton curves of the tensile and rotational springs. The resilience characteristics of the walls and braces are the bilinear + slip skeleton curve [15] (Figure 6), which is used as a simple modelling method for walls of wooden houses, while the tensile and rotational springs are defined as slip-type history characteristics.

The input seismic motion was the acceleration measured at the center of the shaking table; the time history of acceleration at 100% BSL and the acceleration response spectrum are shown in Figure 7. As in the experiment, the seismic motion was input in the order of 90% BSL to 160% BSL.

Numerical integration was performed using the average integration method with a step of every 10^{-5} seconds. Viscous damping was set to 2% with instantaneous stiffness proportional to the instantaneous stiffness, and zero damping was set when the instantaneous stiffness was negative. The weight of each layer was set to be equal to the weight measured in the full-scale shake table test by distributing half of the wall load to the upper and lower layers at the center of each floor height. (1F: 50.1 kN, 2F: 103.1 kN, 3F: 104.3 kN, RF: 61.2 kN)

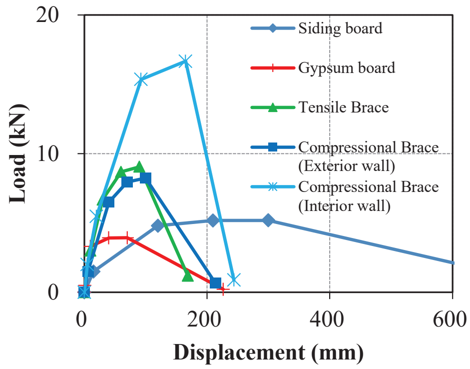


(a) Wall (Braced springs) *(b) Brace*

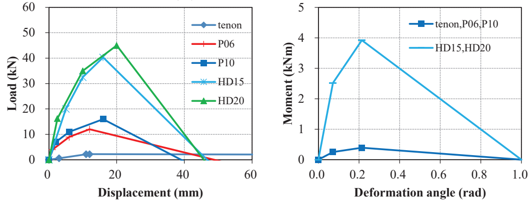


(c) Joint

***Figure 4**: The details of the elements*



(a) Wall and brace



(b) Tensile spring *(c) Rotational spring*

***Figure 5**: The backbone curves of the springs*

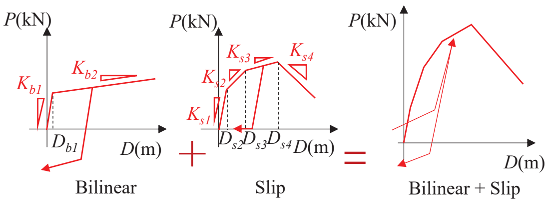
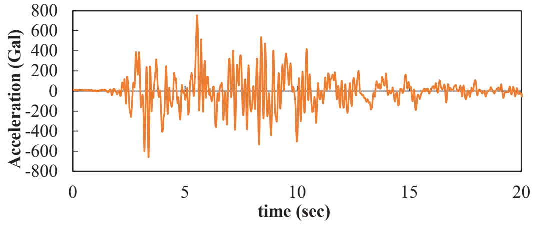
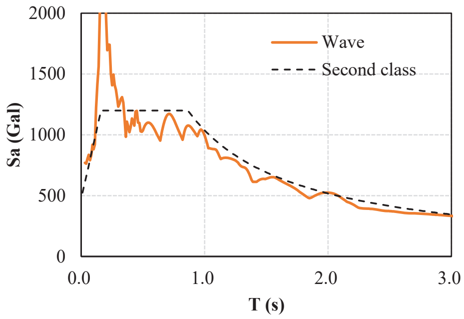


***Figure 6**: Hysteresis rule of the wall and brace*



(a) Time history curve



(b) Spectrum acceleration

***Figure 7**: Outline of the BSL wave*

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3.2 Analysis and experimental results

The time history response analysis was performed with analytical parameters based on the elemental tests. Figure 10 shows the test image of the BSL160% BSL and a simulation image of the same time in the time history response analysis. In the full-scale shaking table test, almost all of the column leg joints pulled out in specimen 2, and the entire building slid sideways. In specimen 1, the column legs did not pull out, but instead the damage was concentrated in the walls, resulting in the collapse of the building due to a 1F collapse. On the other hand, in the simulation, both specimens 1 and 2 collapsed and did not reproduce the experiment.

4 REPRODUCTIVE ANALYSIS

4.1 Outline of data assimilation

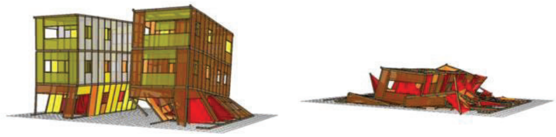
To analyse responses of the test, a 3-D simulation program "wallstat" was used. Figure 3 provides an overview of the data assimilation using orthogonal arrays. First, various skeletal curves are created by multiplying the parameters that simulate elemental experiments by correction factors (1. Definition of the parameters). These parameters are set as the skeletal curves for the springs in the analytical model, and multiple analyses are conducted (2. Numerical analysis). The results of the multiple analyses are compared with the experiments, and the correction factor range are analysed (3. Comparison). Then, the factor ranges are narrowed down by reviewing the initial range (4. Narrowing down the range of factor). Data assimilation was attempted by repeating this flow multiple times. In this study, we were able to obtain accurate results by repeating this process three times.

4.1.1 Definition of the parameters

In this study, mainly focusing on the input parameters for the walls, braces and joints, correction factors were multiplied to set the skeleton curve of the spring. The correction factor multiplied to the parameters are indicated in Figure 10.

Taguchi methods are statistical and based on the design of experiments (DOE), also called quality engineering to improve the quality of manufactured goods [16]. In the theory, the orthogonal array (OA) is a factorial-based approach combining statistical and engineering techniques [17]. The Taguchi technique employs OAs to analyze numerous variables with fewer experiments [18]. Moreover, inferences from the reduced number of experiments apply to the entire experimental region spanned by control factors and levels [19]. Therefore, this method allows data assimilation of many parameters without too much numerical analysis. Therefore, OAs in the Taguchi method was applied to conduct the time history response analysis. The OA is a type of general fractional factorial design. It is a highly fractional orthogonal design based on a design matrix proposed by Taguchi and allows one to consider a selected subset of combinations of multiple factors at multiple levels. OAs are balanced to ensure that all levels of all factors are considered equally. Therefore, the factors can be evaluated independently, despite the fractionality of the design. In this study, 12 eleven-level factors and the orthogonal array, which is to examine the effects of those factors and called L121, were adopted. In L121, to clarify all effects of 12 eleven-level factors, 121 combinations are planned. Table 5 shows two orthogonal arrays (L121) that targets the 11 significant analytical parameters of rotational springs and young's modulus, along with the factor levels of the coefficient. The correction factors were set as 11 levels, equally spaced from minimum to maximum. In the numerical analysis, we multiplied the coefficient and the property. If we try to conduct all combinations, 9.85×10^{24} (= (1112)2) cases are simulated. Using combination of two OAs, 14641 (=1212) cases are needed.

(a) Full-scale shaking table test



Step 1 Step 2

(b) Pre-analysis

Figure 8: *Movie snapshots in BSL160%.*

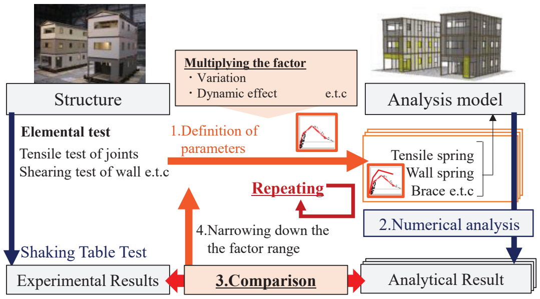
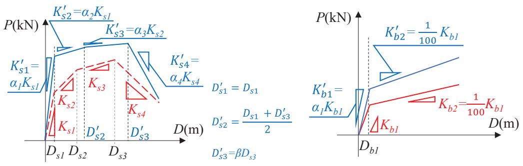


Figure 9: *Flow diagram of data assimilation.*



(a) Slip (b) Bilinear

Figure 10: *Definition of backbone curves.*

4.1.2 Numerical analysis

The analyses planed in phase 1 were conducted using JAXA's HPC "JSS3" [20]. Using a common computer will take 600 days but using the supercomputer JSS3, it took 15 hours to complete 14,641 analysis cases.

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4.1.3 Comparison

Focusing on the inter-story displacement, shear force, and uplifts deformation of walls measured in the full-scale shaking table tests, four model validation criteria related to the difference between the analytical and experimental results, shown below, were calculated for each case of analysis (14641 cases).

(i) Total distance of points on the graph in the load-deformation relationship for each layer

Draw the load-deformation relationship and sum the distances between the plots in the analysis and the plots in the experiment at all times. The interlaminar deformation was measured in 7 streets for each layer, but three streets, one at both ends and the center street, were targeted for the inter-story drift, and all the summed values were calculated. (Equation-(1))

$$nSm = \sum_{k=1}^{3}\sum_{i=0}^{20}\sqrt{({}_{anmk}D_i - {}_{exmk}D_i)^2 + ({}_{anmk}Q_i - {}_{exmk}Q_i)^2} \qquad (1)$$

where *exmkDi*: inter-story drift in the *m*-story *k*-street in experiment at *i* second, *anmkDi*: inter-story drift in the *m*-story *k*-street in analysis at *i* second, *exmkQi*: shear force at in the *m*-story *k*-street in experiment, *anmkQi*: shear force in the *m*-story *k*-street in analysis.

(ii) Inter-story drift in each layer

The difference in Inter-story drift between the analytical and experimental results for all layers at all times when the earthquake motion was input was summed for each sampling period of 0.01 (s). The inter-story displacement was measured at seven streets in each layer, and calculations were made for three streets: the streets at both ends and the center street. (Equation-(2))

$$nDm = \sum_{k=1}^{3}\sum_{i=0}^{20}\left|{}_{anmk}D_i - {}_{exmk}D_i\right| \qquad (2)$$

(iii) Shear force in each layer

The difference between the analytical and experimental results for the layer shear force was calculated at all times when the earthquake motion was input. (Equation-(3))

$$nQm = \sum_{k=1}^{3}\sum_{i=0}^{20}\left|{}_{anmk}Q_i - {}_{exmk}Q_i\right| \qquad (3)$$

(iv) Uplift deformation of walls in 1F (14 locations)

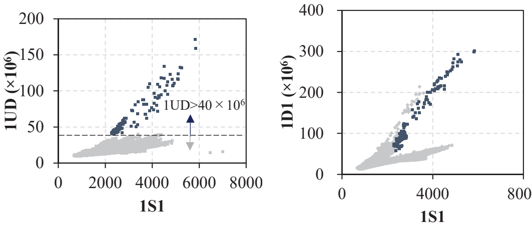
The difference of uplift deformation of 1-story walls between the analysis and the experiment was summed up at all times. The difference of load-deformation curves between layers was evaluated in (1). However, if the results of the lifting of the legs were different, it could not be said that the three-dimensional behaviour during the experiment was reproduced, so the uplift deformation was also included in the evaluation. (Equation-(4))

$$nUD = \sum_{l=1}^{14}\sum_{i=0}^{20}\left|{}_{anl}UD_i - {}_{exl}UD_i\right| \qquad (4)$$

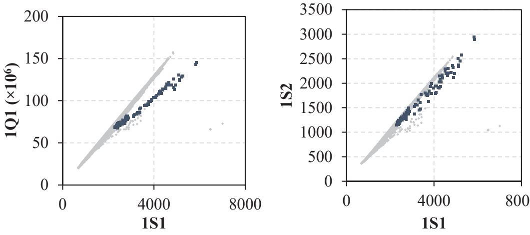
Where, *anlUDi* : the uplift deformation of wall leg at point l in the analysis at i second, and *exlUDi* : the uplift deformation of wall leg at point l in the experiment.

These values are calculated separately for BSL90% and 160%, and the difference between the analytical and experimental results is evaluated to create a factorial effect diagram. For all criteria, the closer the values are to zero, the smaller the difference between the analytical and experimental results.

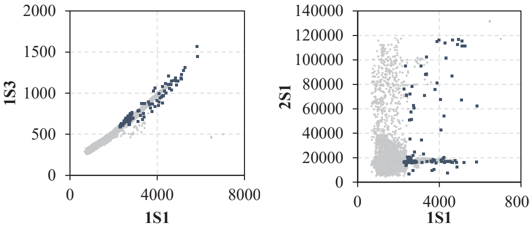
A comparison of the calculated results of each model validation for 14,641 analysis cases is shown in Figure 11. The horizontal axis of each figure is 1S1, which is the distance between the points on the graph for the load-deformation curve in 1F at BSL90%, and the values on the vertical axis are changed. In (a), the vertical axis is 1UD targeting the uplift deformation at BSL90%, with values of 1UD greater than 40 x 10^6 shown in black and others in grey plot. The same trend can be seen in graphs (b) and (c), where the vertical axes are 1D1 and 1Q1 for inter-story drift and shear force in 1F, and the graphs are generally polarized with black values of 1UD greater than 40 x 10^6 and grey values for the other points. The positive correlation can be confirmed from (d) and (e). On the other hand, (f) shows that there is no significant correlation between 1S1 and 2S1.



(a) 1S1 and 1UD *(b) 1S1 and 1D1*



(c) 1S1 and 1Q1 *(d) 1S1 and 1S2*



(e) 1S1 and 1S3 *(f) 1S1 and 2S1*

Figure 11*: Comparison of evaluation (Wall_K_s1 of the Specimen No.1)*

4.1.4 Narrowing down the range of factor

The results of the analysis were evaluated using a factorial effect diagram in quality engineering. This figure is used to identify input parameters that are sensitive to output parameters and to analyse the range of correction factors that reduce the difference between experimental and analytical results. To minimize the difference between the analytical and experimental results, the next step is narrowing the factor range of each parameter. From the results in this phase 3, we can make the graph of factorial effect for each parameter, and we can narrow the ranges of other parameters to move to the second cycle. For the next, the same procedure was conducted, and the ranges were narrowed down using the figures. In the presentation, detailed results and the process will be discussed.

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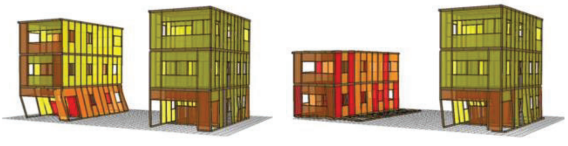
5 RESULT AND DISCUSSION

Figure 12 indicates comparison of the images from the full-scale shake table test, and reproductive analysis, respectively. In the test, almost all of the column legs were uplifted in specimen 2 and the entire building slid, while in specimen 1, the column legs did not pull out, but instead the damage was concentrated in the walls and the building collapsed. In reproductive analysis, the same behaviour of the test was confirmed and the proposed method in this study was verified. As for the load-deformation curves, similar results were got.

(a) Full-scale shaking table test



Step 1 *Step 2*

(c) Reproductive analysis

Figure 12: *Movie snapshots in BSL160%.*

6 CONCLUSIONS

In this study, we tried the reproductive analysis of the full-scale shaking table test on two 3-story wooden houses to verify the validity of the proposed data assimilation method using quality engineering. The reproducibility of the analysis confirmed the validity of the data assimilation method, as it was able to track the experiment behaviour well.

ACKNOWLEDGEMENT

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