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City-scale simulation of wooden house collapse prediction using the ASI-Gauss Code

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A large number of wooden houses collapsed in the 2011 off the Pacific coast of Tohoku earthquake and Tsunami and the 2016 Kumamoto Earthquake. The large amount of debris from the collapsed houses not only blocked the roads and hindered the immediate evacuation, but also caused delays in the recovery and reconstruction due to the time and cost required to remove the debris. For example, there is a high risk of earthquakes and tsunamis of the same or greater magnitude in the Tokai and Tonankai regions, and it is important to assess in advance the total amount and spread of debris that could be generated in the event of a major earthquake, and to prepare a recovery plan for post-disaster emergencies. The ASI-Gauss Code, which is a finite element method of beam elements that can analyze the progressive collapse of a framework structure, is used to predict the damage and collapse of houses caused by earthquakes. Here, in order to demonstrate the validity of the proposed technique, we attempted to reproduce the damage in the Furukawa area of Osaki city during the 2011 off the Pacific coast of Tohoku Earthquake and compared the results with damaged reports.

Key Words : *ASI-Gauss Code, Wooden House Model, City Model, Seismic Response Analysis*

1. INTRODUCTION

A large number of wooden houses collapsed in the 2011 off the Pacific coast of Tohoku Earthquake and Tsunami and the 2016 Kumamoto Earthquake. The large amount of debris from the collapsed houses not only blocked the roads and hindered the immediate evacuation, but also caused delays in the recovery and reconstruction due to the time and cost required to remove the debris. In other words, this hindered an effective recovery process. In the future, there is a high risk of earthquakes and tsunamis of the same or greater magnitude in the Tokai and Tonankai regions, and it is important to assess in advance the total amount and spread of debris that could be generated in the event of a major earthquake, and to prepare a recovery plan for post-disaster emergencies. Based on the above background, this study aims to establish a series of tools for predicting the damage and collapse of wooden houses caused by earthquakes using the ASI-Gauss method, which is a kind of finite element method for progressive collapse analysis of frame structures, by modeling the entire city based on GIS data including building information.

In this study, estimation of seismic ground motions in the surface layer using RO model, and earthquake damage prediction tool combined with ASI-Gauss method for wooden house of entire urban area and are developed. Lastly, we attempted to reconstruct the damage in the Furukawa area of Osaki City, Miyagi Prefecture, during the 2011 off the Pacific coast of Tohoku Earthquake and confirmed its validity by comparing it with damage reports.

2. METHODOLOGY

ASI-Gauss method used in this study is a type of Finite Element Method that uses Timoshenko beam elements for finite deformation elastoplastic analysis. By adaptively shifting numerical integration point during elastoplastic analysis, a single member can be divided into two elements and elastoplastic analysis can be performed with high accuracy as well as reducing the computational cost. Also, by modeling with beam members, we can easily do member fracture and member contact analysis. Plasticity is determined by substituting the cross-sectional forces at both ends of the element into the yield function. In this study, M_x, M_y, N are bending moment of x, y axes and axial force respectively and defined as the yield function shown in the following equation.

$$f_y = \left(\frac{M_x}{M_{x0}}\right)^2 + \left(\frac{M_y}{M_{y0}}\right)^2 + \left(\frac{N}{N_0}\right)^2 = 1$$

Here, sub 0 indicates the total cross-sectional plasticity value when each cross-sectional force component acts alone on the member cross-section. In case of members that are considered as fractured, stiffness is set as 0, and the cross-sectional forces stored in the element are instantly released in the next step. This allows the analysis of collapse phenomena.

3. ANALYSIS MODEL PREPARATION

Fig-1 shows an example of modelling a wooden house. To simplify the modelling of houses of arbitrary shape, automatic modelling was carried out by using the cube-shaped units shown in Fig. 2. The unit consists of four elements - columns, walls, beams, and floors - and each element was assigned an appropriate physical property value. Here, the face members such as walls and floors were modelled using beam elements, and braces were installed to provide shear stiffness. The stiffness and bearing capacity of each element is fitted to skeleton curve (see Fig-3), which shows the relationship between layer shear forces and interlaminar deformation angles based on the building standard for each construction age.

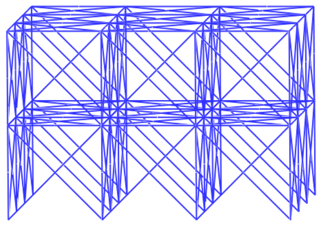


Fig-1. Timber house model.

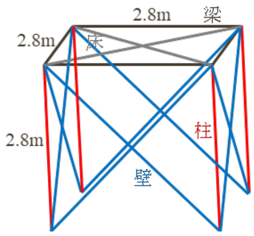


Fig-2. Unit

As shown in Fig-3, the skeleton curve is simplified as a three-linear model with two break points, and the inter-layer deformation angle shows elastic behavior up to 1/120 rad, with 1/30 rad considered to be the fracture initiation point. All non-rigid floor elements, i.e. columns and brace elements, were assumed to be fully elastoplastic.

For setting the weight of each component, the weight per floor area for each representative construction age was referred to from the "Japanese Building Disaster Prevention Association, Seismic Retrofitting Support Centre designated by the Minister of Land, Infrastructure, Transport and Tourism, 2012 Revised Edition of Seismic Diagnosis and Reinforcement Methods for Wooden Houses" shown in Table-1. The weight of each component (columns, beams, walls, and floors) was determined by distributing the roof weight on the second floor between the beam and floor components and the external and internal wall weight between the column and wall components. Similarly, on the ground floor, the floor weight and load carrying capacity were allocated to the beam and floor members, and the external and internal wall weight to the column and wall members.

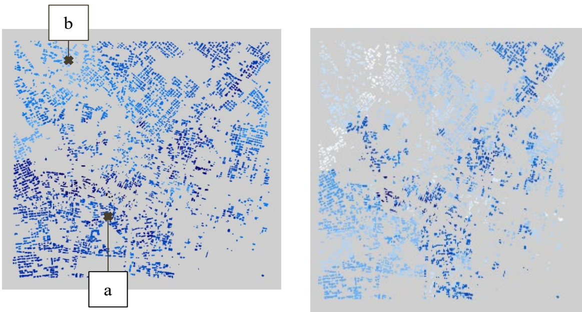
Building	Very heavy	Heavy	Light
Roof	2.40	1.30	0.95
Outer wall	1.20	1.20	0.75
Inner wall	0.45	0.20	0.20
Floor	0.60	0.60	0.60
Loading weight	0.60	0.60	0.60
Building standard year	1959	1981	2000

Table 1. Simplified weight table for houses (per floor area, kN/m^2)

4. SEISMIC MOTION INPUT

The input seismic motions were estimated by applying the method of Morikawa et al. This method is one of the methods for estimating the acceleration time history (incident waves) that should be input to the engineering base when the surface acceleration time history at a certain point and the surface ground properties immediately below the engineering base are known.

The distribution of the maximum response acceleration of the input earthquake motion is shown in Fig-3. The seismic motions were evaluated at 451 sites and the house model was given the seismic motions evaluated at the nearest neighbor sites. As shown in the Fig-3, the maximum response acceleration tends to be dominated by the NS component compared to the EW component over the entire domain. Furthermore, the North-East and South-West regions show a tendency to have particularly large NS components of acceleration, while the North-West is a region where both acceleration components are small. The fact that damage to houses tended to be concentrated in the south-west and scattered even in the north-west, where the maximum acceleration is relatively small, suggests that the assessment of earthquake damage to houses cannot be measured only by the maximum response acceleration.



(a) NS component (b) EW component

Fig-3 Distribution of maximum response acceleration

5. ANALYSIS CONDITION

(1) Target area and analysis environment

The target city for this study is Furukawa, Osaki City, Miyagi Prefecture. The area was the site of the 2011 Tohoku earthquake, which caused damage to many wooden houses. The analysis model composed of beam elements (hereafter referred to as the Furukawa model) is shown in Fig. 4.

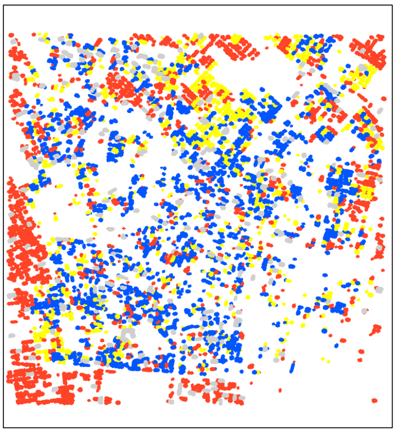
Fig-4. Aerial view of the Furukawa model

Area: 1.86 km x 1.69 km, number of buildings: 4,405, number of elements: 2,172,546, number of nodes: 1,165,744. The entire city can be analyzed as a whole, but if contact between buildings is not considered, the buildings are defined as independent problems, so the scale of area can be divided into approximately equivalent smaller areas that can be analyzed. In this study, it is classified into four sub-domains to improve the computational efficiency. The computational environment used was the Kyoto University supercomputer system Camphor2, 1 node, 64 threads, with a real time of 20 s (number of analysis steps: 10,000). The average time required for the four compartments was 65.91 hours, which means that a large-scale analysis of the entire city is possible to be carried out within a few days.

(2) Construction age

In wooden houses, the construction age has a strong correlation with the bearing capacity. In this study, model bearing capacities according to three construction dates (1959, 1981 and 2000) are considered, and it is necessary to assign a corresponding bearing capacity to each model. However, it is often difficult to obtain information on the date of construction, so some method of estimation had to be used. For this reason, this study used GSI aerial photographs (taken between 1947 and 2006) to estimate the approximate date of house completion by comparing the condition of houses from several eras.

The procedure is outlined as follows: 1) the building center coordinates, shape, area and number of floors are obtained from the 2010 residential map data; 2) the building location is obtained from GSI aerial photograph data taken at five different times (1947, 1961, 1975, 1993 and 2006) and given the coordinates; 3) the building information from the older photographs is used as a reference and the new buildings obtained from the next photograph are assumed to have been completed during that year of photography.



Blue: year 1959　Yellow: year 1981
Red: year 2000　Grey: Non-wooden houses

Fig-5. Estimated building standard date

For example, building that is absent from an aerial photograph taken in year X and present in a subsequent aerial photograph taken in year Y is judged to have been completed between X and Y. The results of the estimation of the construction age given by the above procedure are shown in Fig-5. Color in the diagram indicates the date of building standard dates. However, models with a large number of nodes and floor area larger than that of a typical wooden house are classified as non-wooden houses and given a robust load-bearing capacity. In terms of the distribution of construction ages, it is observed that there are many models complying with the 1959 standards in the central part of the analysis area, whereas there are many models complying with the newer standards in the outer part of the analysis area.

(3) Seismic setup

In this study, the acceleration waveforms created by the method described in Chapter 4 were converted into displacements and subjected to seismic analysis as forced displacements at the base of the ground floor members. Displacement time histories were prepared by integrating the acceleration time histories using the linear acceleration method, and velocity and displacement time histories were calculated. The baseline was adjusted so that the velocity at the end of the duration was zero for the given acceleration time history to avoid a monotonic increase in residual displacement after the seismic motion was applied.

(4) Calculation of the level of damage

In post-earthquake damage surveys, house damage levels are assessed using visual assessment criteria. In this study, in order to objectively assess the damage to a house as much as possible in accordance with the damage criteria in the field, an automatic classification of the damage level into five levels (total destruction, major partial destruction, partial destruction, partial damage and no damage) was investigated according to the analysis results of the ASI-Gauss method. For this purpose, the percentage of damage was quantified from the ratio of the number of components judged to have yielded or fractured to the total number of components

$$\text{damage ratio} = \frac{\Sigma\,\text{deduction}}{\Sigma\,\text{initial point}} \times 100$$

$$\Sigma\,\text{initial point} = 2N + 1n$$

$$\Sigma\text{deduction} = 1N_{yielding} + 2N_{break} + 0.5n_{yielding} + 1n_{break}$$

Here, the total number of columns is N and the total number of bracing members is n. Based on the idea that the columns are the most important members to make the house self-supporting and the braces are the equivalent elements of the walls, which are mainly expected to provide shear stiffness, the weight of the columns was set as twice that of the braces and initial point and deduction were given. The deduction for fracture was set as twice the yield, as the member releases all internal forces after fracture, whereas it can retain the yield stress as a fully elastoplastic state after yielding. Based on the above definitions, the damage ratio was set to 100% when all components had broken, with higher ratios indicating more severe damage to the house. The level of damage to houses was determined into five levels: totally destroyed, majorly destroyed, partially destroyed, partially damaged and undamaged.

6. CITY-SCALE HOUSE COLLAPSE PREDICTION SIMULATION

Using the analytical modelling procedures and methods described up to this point, simulations were carried out to predict house collapses across the city.

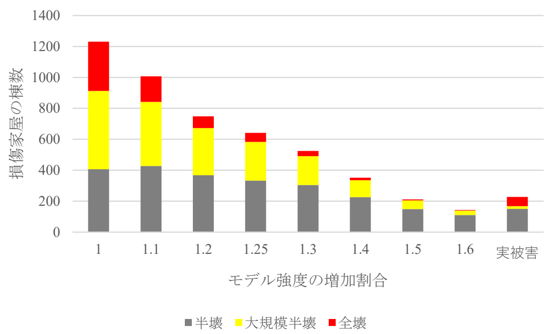


Fig-6. Percentage increase in model strength and number of damaged houses

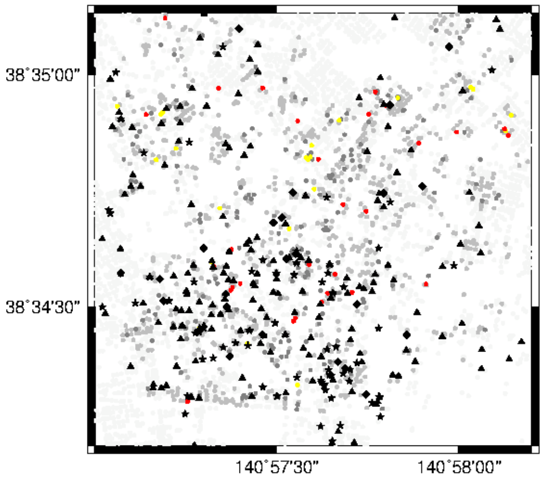


Fig-7. Analysis results with uniform waveform input

The relationship between the percentage increase in material strength and the level of house damage is summarized in Fig-6. Although an increase in strength by a factor of about 1.50 showed good agreement when focusing on the number of all damaged houses, an increase in strength by a factor of about 1.25 was equivalent to the actual damage when focusing only on the number of houses that were totally destroyed. An increase of 1.25-1.50 times is also considered reasonable as a parameter for a real wooden house, including cosmetic walls and finishes. On the other hand, there is still room for improvement, especially in simplified models for automatic house modelling, which do not reflect detailed information about the house and do not consider the effects of wall mass, finishes, post-construction renovation and reinforcement, among others.

Next, in order to check the effects of different input seismic characteristics, a simulation was also carried out in which the observed waveforms at JMA Furukawa were applied to all houses. The results are shown in Fig-7. There was almost no damage in the South-Central to South-West area, and damage occurred almost exclusively to older houses of the construction age. These results support the idea that the proper assessment of surface ground motions amplified by the engineering bedrock is important for the prediction of house damage and that the seismic modelling procedure presented in Chapter 4 was effective.

7. CONCLUSION

In this study, seismic motion estimation in surface ground using the RO model is combined with the ASI-Gauss method to develop a city-scale seismic damage prediction tool for wooden houses.The method of estimating seismic motions in surface soils using the RO model has so far been validated and gives reliable ground motions. A series of tools for simulating the prediction of house collapses in a city is proposed by combining the ASI-Gauss method. The proposed simulation tool showed good results in collapse analysis of various types of buildings. The estimation of material properties was partly based on skeleton curves estimated from the results of destruction test on houses consisting only of structural members, and there are concerns that the model has lower stiffness than the actual wooden houses, which includes cosmetic walls and finishes. Accordingly, although the natural period of the wooden house model consisting of simple units was somewhat longer than that of a typical wooden house, it was confirmed that the natural period of each building standard model was sufficiently within the practical range of values. Using the house models described above, an analysis model for the Furukawa area of Osaki City was automatically generated from GIS data, and seismic analyses were carried out for each house with the earthquake ground motions of the Great East Japan Earthquake estimated by the RO model. Models with stiffness and material strength identified from skeleton curves resulted in greater damage than actual damage. Therefore, by increasing only the material strength by a factor of 1.25 to 1.50, a realistic damage estimation was achieved, demonstrating the potential of the developed tool. Further comparisons with actual damage survey reports and aerial photo data will be carried out to improve the accuracy of the analysis and develop the tool into a more reliable tool.

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REFERENCES

[1] Daigoro Isobe : Progressive Collapse Analysis of Structures - Numerical Codes and Applications, Elsevier, eBook ISBN:9780128130421, Paperback ISBN:9780128129753, 2017.喜々津仁密，中川貴文，奥田泰雄，坂田弘安：日本版 改良藤田スケールの開発－木造戸建て住宅の DOD と 推定風速の概要－，平成 27 年度日本風工学会年次研 究発表会，pp.117-118, 2015.

[3] 日本建築防災協会，国土交通大臣指定耐震改修支援センター：2012 年改訂版 木造住宅の耐震診断と補 強方

法.
[4] Hitoshi Morikawa, Kahori Iiyama : A Method to Find an Appropriate Input Motion Using a Given Motion on Ground Surface, Journal of Earthquake and Tsunami, 2021.
[5] 飯山かほり，盛川仁，市村強，堀宗朗，山崎義弘，坂 田弘安，大野晋，柴山明寛：都市の地震応答シミュレーションのための木造建物モデル設定に関する一検 討，日本建築学会，構造工学論文集 Vol.64B，2018 年