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FRAGILITY CURVE FOR WOODEN BUILDINGS BASED ON RESPONSE ANALYSIS USING SEISMIC ASSESSMENT RESULTS IN KYOTO CITY

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ABSTRACT: In vulnerable urban areas, there is an index that shows the probability of being able to evacuate safely from the affected area to outside the district. The index is calculated statistically. In the calculation process, the percentage of building collapse within the district is determined using the fragility curve created based on the actual damage survey conducted during the 1995 Hyogo-ken Nanbu Earthquake. In principle, the assumed seismic motion and the individual seismic resistance of buildings differ depending on the district. In this study, we targeted Kyoto City, collected and modeled information on wooden houses in Kyoto City, and attempted to create a wooden building fragility curve for Kyoto City based on the results of response analysis for the assumed seismic motion. In addition, it is thought that during an earthquake, the collapse direction of buildings may not block roads. In the calculation process, the collapse rate of buildings is determined by building age using the fragility curve, and the collapse direction of buildings is not considered. Therefore, we conducted a collapse simulation of a group of buildings in a block in Kyoto City and confirmed the collapse direction of buildings and the resulting road blockage.

KEYWORDS: fragility curve, seismic assessment, vulnerable urban area, collapse simulation, Kyoto City

1 – INTRODUCTION

Kyoto City has many vulnerable urban areas formed by old wooden houses, narrow streets, or cul-de-sacs as shown in Figure 1. While they are known around the world as representative of the historic cityscape of Kyoto, there is a possibility that collapsed buildings will block roads during an earthquake, making evacuation difficult. In such vulnerable urban areas, there is an index that evaluates the collapse of buildings and the resulting blockage of roads in the event of an earthquake and indicates the probability of safe evacuation from the affected area to outside the district. The index is statistically calculated by referring to various items such as the width and length of roads in the district and the degree of earthquake resistance of buildings. In the current calculation process, the percentage of collapsed buildings in the district is determined using a fragility curve created based on an actual damage survey conducted during the 1995 Hyogo-ken Nanbu Earthquake [1]. Although the earthquake ground motions and individual seismic resistance of buildings may differ depending on the district in which the index is evaluated, this is not considered in the current calculation process. In this study, the city of Kyoto was selected as the target district for evaluation, and information on wooden buildings built in the city was collected and modeled.

In addition, during an actual earthquake, a street may not be blocked by the direction of building collapse, such as when a building leans against an adjacent building in a city block and avoids collapse, or when a building avoids collapse in the direction of the street. In the current calculation process, the percentage of building collapse is determined by building age using fragility curves, and the direction of building collapse is not taken into account. Therefore, we conducted a collapse simulation on a group of buildings assuming a city block in Kyoto City to confirm the collapse direction of buildings and the resulting road blockage.

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2 – FRAGILITY CURVE IN KYOTO CITY

2.1 ANALYSIS OUTLINE

2.1.1 NUMBER OF BUILDING TO BE ANALYSED

So far, fragility curves have been prepared for each year of construction of the subject building. Therefore, it was decided to divide the years after 2000 into "age A," 1981～1999 into "age B," 1971-1980 into "age C," 1925～ 1970 into "age D," and prior to 1925 into "age E." With the cooperation of Kyoto City, we obtained a total of 46 buildings, 25 of which fell into the age c category, 20 into the d category, and 1 into the e category, by referring to seismic assessment data. Since only one building was dated age E, it was treated as dated age D. On the other hand, since there was a lack of newer ages, we decided to treat it as d. On the other hand, since there was a lack of newer ages, the Association for Seismic Performance Visualization provided data for 25 buildings that corresponded to age A and could be analyzed as is. The seismic performance of age B is inferior to that of age A. Therefore, we first analyzed the load carrying capacity of age A, which is the same as that of age B. Therefore, we first checked the load capacity of the load-deformation curve for age A. Since many of the buildings had high performance, we divided the load capacity by 1.8 and multiplied it by 0.9 to consider aging and deterioration reduction. The value of 1.8 was adjusted so that the minimum value was 1.0, because the smallest wall capacity in the X direction (short side direction of the building) of the first floor of age A was about 1.8. In the end, a total of 96 buildings were included in the study.

2.1.2 ANALYSIS MODEL

The wooden buildings in Kyoto City were modeled using the analysis software “wallstat” [2] based on the seismic assessment data. The specifications of the walls and load-bearing elements were not clearly stated in the data, and there were some things that were unclear. In this study, we have made uniform assumptions and proceeded with the modeling. In the seismic assessment of Kyoto City, the buildings to be assessed are broadly divided into two categories, “wooden houses” and “Kyo-machiya,” based on differences in “construction method and construction period”[3]. The wooden houses targeted for seismic assessment in Kyoto City are defined as buildings that construction started before May 31, 1981, are no more than three stories high, and were constructed using either the Japanese post-and-beam construction method or framework wall construction method. The Kyo-machiya targeted for seismic assessment in Kyoto City are defined as buildings that construction started before November 22, 1950, are no more than two stories high, and were constructed using traditional methods. Of the 46 buildings for which we collected seismic assessment data, five buildings of Period correspond to Kyo-machiya, and the other 41 buildings correspond to wooden houses. Therefore, we changed the assumed specifications for wooden houses and Kyo-machiya. The assumed contents of the unknown specifications are shown in Table 1. In addition, for the Kyo-machiya of Period, we created a fragility curve separately from the wooden houses.

In the analysis, it is necessary to correctly grasp the seismic performance of the target building and reflect it in the analysis model. Therefore, in this study, we attempted to match the performance of the analytical model with the actual performance of the building. First, we adjusted the strength of the analytical model so that it matched the structural rating of the seismic assessment results. After that, since the structural rating is thought to be underestimated compared to the actual performance of the building, we multiplied the rigidity strength of the analytical model by a factor of 2.0 for the wooden house model and 1.5 for the Kyo-machiya model. These factors are based on the results of previous shaking table experiments [4].

Figure 1. Wooden Urban Areas in Kyoto City

Table 1: Assumptions about Unknown Specifications

Target Buildings	Elements		Specifications
Wooden Houses	Exterior wall		Mortar for Wooden Lath Base (Allowable shear capacity of wall 2.2kN/m)
	Interior wall		Gypsum Board (Allowable shear capacity of wall 1.1kN/m)
	Opening	Window	Allowable shear capacity of wall 0.6kN
		Door	Allowable shear capacity of wall 0.3kN
Kyo-machiya Houses	Exterior wall		Mud Wall (Allowable shear capacity of wall 2.4kN/m)
	Interior wall		
	Opening		Not to be considered as bearing capacity
Common to Wooden Houses and Kyo-machiya Houses	Joint		Equivalent to seismic standard joint I
	cross-section of component	Column and Foundation	105mm x 105mm
		Beam	105mm x 210mm
	Weight		Weight as stated in the data

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2.1.3 INPUT EARTHQUAKE MOTION

The input seismic motion was two waves with different pickup points as shown below.

(i) Assumed seismic wave (6061 Hanaori fault) in the Kyoto City Earthquake Damage Assumption (hereinafter referred to as "Assumed Wave 1"

(ii) Assumed seismic wave (5041 Hanaori Fault) in the Kyoto City Earthquake Damage Assumption (hereinafter referred to as "Assumed Wave 2")

For the assumed waves, a strong EW component is input as seismic motion in the X direction (short side direction of the building) of the analytical model. From the seismic assessment data of Kyoto City, it was found that many buildings have a higher superstructure rating in the Y direction (longitudinal direction of the building) than in the X direction, and in this report, the seismic motion input direction was set to the X direction in order to evaluate the building on the safer side.

The PGV (three-component composite) of each seismic motion was 117.2 cm/s for assumed wave 1 and 132.2 cm/s for assumed wave 2. The acceleration response spectrum of the earthquake motion (damping constant 5%) is shown in Figure 2.

2.2 FRAGIRITY CURVE DEVELOPING METHOD

Fragility curves were created by the following methods based on the literature [5]. (1) Perform response analysis using wallstat by varying the input magnification of seismic waves from 0.1 to 1.8 times. (2) Draw a scatter diagram with the vertical axis as the total destruction rate and the horizontal axis as the PGV of the seismic motion. (3) Make the PGV of the horizontal axis logarithmic. (In(PGV)) (4) Transform the total destruction rate on the vertical axis using the inverse cumulative distribution function. (5) Draw an approximate straight line using the transformed graph. (6) From the approximate curve, calculate the mean (median of normal distribution) and standard deviation. (7) Substitute the mean value and standard deviation obtained in (6) into the equation of lognormal distribution and create a fragility curve. Collapse" is defined as a maximum response deformation of 600 mm or more (maximum response deformation angle 1/5 rad) on any floor.

2.3 ANALYSIS RESULTS

The fragility curves for the assumed wave 1 and assumed wave 2 are shown in Figures 3 and 4. The fragility curves from Reference [1] are superimposed on the figures. The fragility curves for Kobe City and Kyoto City were different. Figure 3 shows that, for wave 1, the total destruction rates for ages a and b are extremely small and less than 10% even at 180 cm/s, but for ages c and d, the slope of the fragility curves is larger than in Reference 1. The total destruction rate at PGV90cm/s (the seismic intensity assumed when calculating the total destruction rate used in the process of calculating the degree of blockage in the district) was approximately 20% for age c, 50% for age d, and 85% for age d (Kyo-machiya). The Kyo-machiya house can be said to have low seismic performance because of its high total destruction rate at the same seismic intensity compared to the others, partly because it was assumed to be 1.5 times stronger than the other houses. Figure 4 shows that, as in the case of wave 2, the total destruction rates for ages a and b extremely small and 0% even at 180 cm/s. For age c, the total destruction rate was 0% at up to 120 cm/s. For age d, the total destruction rate was 0% even at 180 cm/s. In age c, the total destruction rate was 0% up to 120 cm/s, in age d, it was 0% at PGV 90 cm/s, and in age d (Kyo-machiya), it was about 20%.

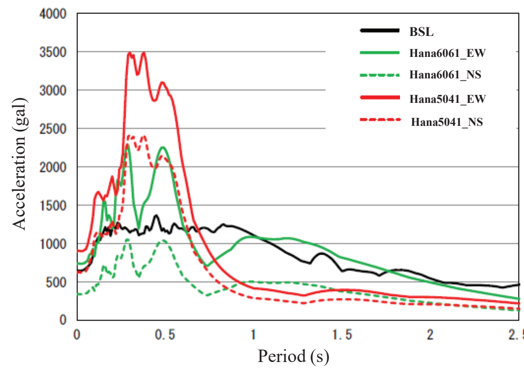

Figure 2. Acceleration Response Spectrum of Seismic Motion (Damping Ratio 5%)

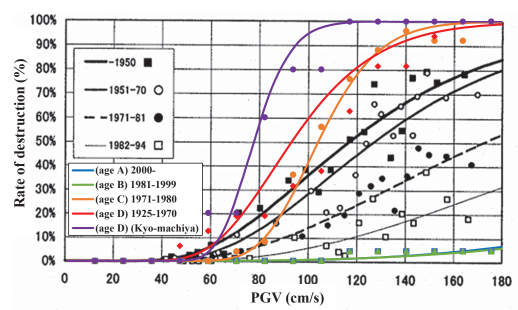

Figure 3. Fragility Curve by Building Age for Assumed Wave 1

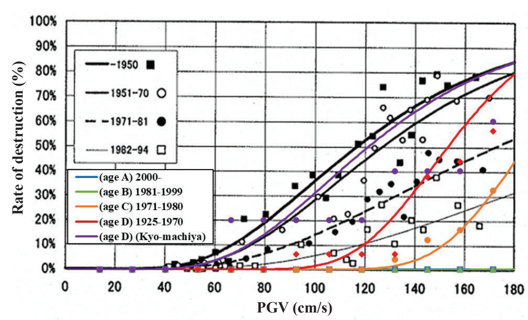

Figure 4. Fragility Curve by Building Age for Assumed Wave 2

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3– COLLAPSE SIMULATION IN KYOTO CITY

3.1 TARGET CITY BLOCK

Kyoto City selects "Priority Districts" based on its own criteria, which are based on the characteristics of the city's urban areas, after identifying densely populated urban areas based on the common criteria for determining densely populated urban areas in danger throughout Japan. Currently, there are 21 dense urban districts (approx. 730 ha) in Kyoto City, of which 6 priority districts (approx. 220 ha) have been selected (Kashiwano, Shoran, Ninna, Seishin, Demizu (North), and Rokuhara districts). In this study, four districts (Kashiwano, Shoran, Ninna, and Rokuhara) were selected out of the six priority districts, excluding two districts, Seishin and Demizu (North), which are expected to be able to eliminate dense urban areas by 2030, considering the situation of each district. The selection was based on data provided by the city of Kyoto, including building conditions (fireproof construction and age), road type and condition (section 2 road, non-road), and whether or not seismic retrofitting had been implemented. As a result, the Shoran district was selected as the target district, as it is a general district with a diverse mix of not only Kyo-machiya, but also ordinary houses, row houses, and non-housing, and the age of the buildings varies. The total number of buildings in the Shoran area is about 3,000, but it would be too large to include all of them, so we selected a portion of the district with less than 100 buildings as the target district. Figure 5 shows the Shoran District and the target city blocks.

3.2 METHOD OF EXTRACTING THE MODEL FROM SEISMIC ASESSMENT DATA

In creating the block model, we extracted the model to be applied to the block from the seismic diagnosis data. We obtained seismic diagnosis data for 605 wooden houses and 238 Kyo-machiya houses from Kyoto City. Kyoto City broadly categorizes buildings subject to earthquake resistance diagnosis into “wooden houses” and “Kyo-achiya” based on differences in “construction method and construction period”. They can also be divided into detached houses, row houses and apartment buildings according to the way they are built [6].According to the Kyoto City definition, a row house is a building with two or more living units that has a completely separate structure that does not allow internal access between adjacent living units or between living units that overlap above and below, and where the hallway, stairs, etc. are not shared by each living unit. A apartment building is a building that has two or more dwelling units, and has two or more common areas such as hallways, staircases, or entrances, which are shared by each unit. The buildings to be analyzed were classified into the following five types based on the “construction method and construction period”, “building type”, and “opening position” of the wooden buildings in Kyoto City.

- Type 1 (T1): The construction method and construction period are classified as wooden houses, the building type is a detached house or apartment building, and the A building with no openings on one of the four exterior sides of the first floor
- Type 2 (T2): The construction method and construction period are classified as wooden houses, the building type is a detached house or apartment building, and the building with openings on all four exterior sides of the first floor
- Type 3-1 (T3-1): The construction method and construction period are classified as wooden houses, the building type is a row house
- Type 3-2 (T3-2): The construction method and construction period are classified as a Kyo-machiya, and the building type is classified as a row house.
- Type 4 (T4): The construction method and construction period are classified as a Kyo-machiya, and the building type is classified as a detached house or apartment building.

When the 605 wooden houses were classified, 311 were classified as Type 1, 281 as Type 2, and 13 as Type 3-1. When the 238 wooden houses were classified in the same way, 25 were classified as Type 3-2 and 231 as Type 4.

There are a total of 30 buildings in the target area that are included in the analysis model. Figure 6 shows the area of the target area that is included in the analysis model. Figure 7 shows the classification of the buildings in the area included in the analysis model. There are old and new earthquake-resistant buildings, wooden houses built after 2000, and steel-frame buildings, and there is a mixture of buildings with one to three floors. The buildings we are looking at are located in a cul-de-sac, forming a relatively regular block surrounded by roads.

In order to create an analysis model for the entire block, it is necessary to extract the model that applies to each individual building in the target block from the seismic assessment data. To investigate this, we focused on seven buildings numbered 43 to 49, which are arranged in a row and have similar frontage dimensions, and conducted an analysis. From the seismic assessment data, we extracted 33 buildings classified as T1-2 and 12 buildings classified as T4-2, and analyzed them. As a result, there was no correlation between the assessment score, the coefficient of resistance C_B, and the year of construction. In addition, in wooden houses, the score for the first floor is lower than that for the second floor in the direction of the frontage where the entrance is located. The coefficient of capacity C_B in the direction of the frontage of a Kyo-machiya house

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decreases as the opening rate in the direction of the frontage where the entrance is located increases.

Therefore, in this study, for buildings in the target block that were built before 1981, we decided not to take the year of construction into account, and to extract buildings with similar dimensions in the front-to-back direction and similar appearances in the front direction with entrances as models from the seismic assessment data.

3.3 CITY BLOCK ANALYSIS MODEL

The model for 27 of the target buildings, excluding two two-story wooden houses built after 2000 (Building Nos. 57 and 64) and one S-structure building (Building No. 42), was duplicated due to the building classification, number of stories, approximate frontage and depth dimensions, etc. As a result, eight buildings were extracted from the seismic assessment data. Building No. 50, which is one of the 27 buildings, was considered to have a possibility that the interior of the building is bisected into north and south based on the exterior with two entrances obtained from the field survey and the building roof information obtained from Google Earth. Therefore, it was decided to treat the subject building as two buildings with frontage dimensions of two sentences in length and two models with frontage dimensions, building numbers 50-1 and 50-2.

Models for two two-story buildings (building numbers 57 and 64) and a three-story S structure (building number 42), both constructed after 2000, were not available from the seismic assessment data. Therefore, we decided to apply the model provided by the Association for Seismic Performance Visualization, which allows us to analyze a two-story wooden house built after 2000.

Using wallstat, we modeled eight buildings individually, which were extracted from the earthquake resistance diagnosis data. The earthquake assessment data contained detailed information on the specifications of the buildings, and we created the models based on this information. Of the target buildings, we extracted three-story wooden houses built in 1996 and 2004, and used them as models to which we applied three-story wooden houses with similar frontage and depth dimensions from the earthquake assessment data. However, when modeling the building as it was described in the seismic diagnosis documents, it was decided that the building's actual strength could not be evaluated in accordance with the year the building was constructed in the actual city block, and it was decided to apply a model that increased the wall strength by 1.54 times, referring to literature [7].

Individual models are arranged according to the frontage and depth directions of the subject building in the city block, the building layout, and the street width of the neighboring buildings in the city block. The city block analysis model is created as shown in Figure 8. Although some of the extracted models overlap among the target buildings in the city block, the orientation of the models in the city block in the frontage direction differs depending on their layout. Therefore, if the same extracted model has different orientations in the city block in the frontage direction, it is treated as a different model.

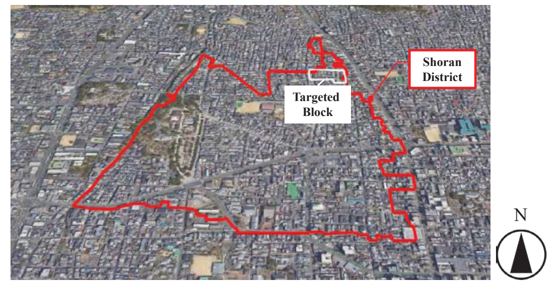
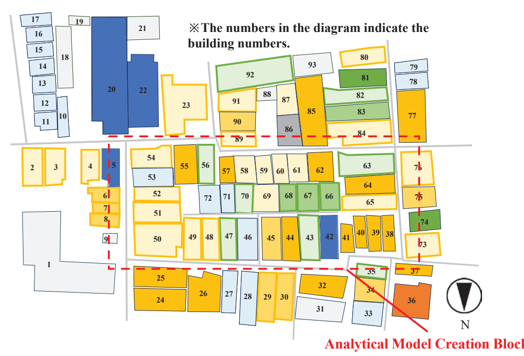


Figure 5. Shoran District and Target Block

Figure 6. Analytical Model Creation Block



legend

	Wooden Houses/Detached House/1-Story (T1-1)
	Wooden Houses/Detached House/2-Story (T1-2)
	Wooden Houses/Detached House/1-Story (T2-1)
	Wooden Houses/Detached House/2-Story (T2-2)
	Wooden Houses/Detached House/1-Story/Built after 1981
	Wooden Houses/Detached House/2-Story/Built after 1981
	Wooden Houses/Detached House/3-Story/Built after 1981
	Kyo-machiya Houses/Row House/1-Story (T3-2-1)
	Kyo-machiya Houses/Row House/2-story (T3-2-2)
	Kyomachiya Houses/Detached House/1-story (T4-1)
	Kyomachiya Houses/Detached House/2-story (T4-2)
	Wooden non-residential
	Concrete Block Construction/2-story
	Steel-framed construction
	Unknown

Figure 7. The Classification of The Buildings in The City Block

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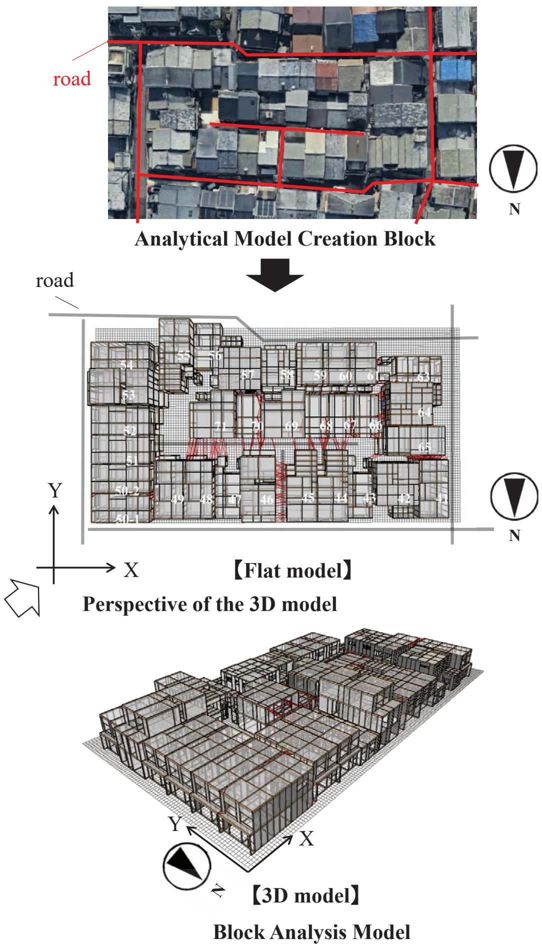

Figure 8. Analyzing and Modeling of City Blocks

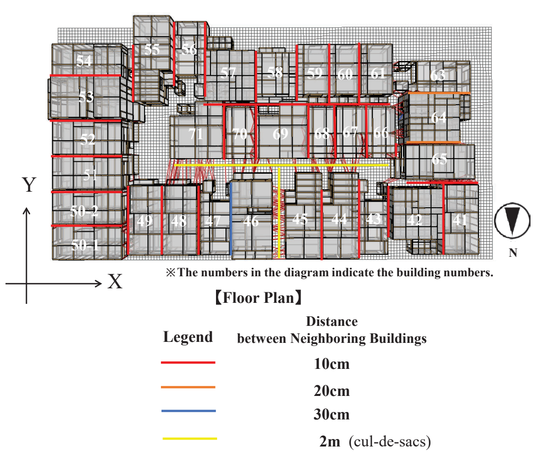

Figure 9. Distance between Neighboring Buildings

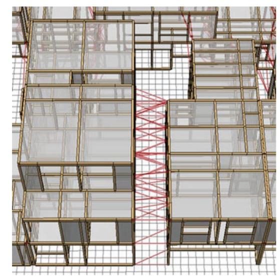

Figure 10. Distance between Neighboring Buildings

Figure 9 shows the distance between adjacent buildings between individual models in the town block model. The distance between adjacent buildings was visually confirmed or actually measured during the field survey. For areas where measurement was not possible, the distance was checked using Google Earth or other tools. Note that wallstat requires at least 10 cm of clearance between models and adjacent models when placing the models. Therefore, if the distance between adjacent buildings is 0 in the actual city block, the distance between adjacent buildings is set to 10 cm in the city block model.

In order to evaluate building-to-building collision assumed during an actual earthquake in the analytical model, gap elements were inserted between the individual models that make up the city block model to match the distance between adjacent buildings, as shown in Figure 10

3.4 COLLAPSE SIMULATION

3.4.1 INPUT EARTHQUAKE MOTION

As described in 2.1.3, the two assumed seismic waves 1 and 2 of the Kyoto City Earthquake Damage Assumption were input. The assumed waves were input in the triaxial direction, with the strongest EW component of the three components in the X direction of the city block model, the NS component in the Y direction, and the UD component in the Z direction.

3.4.2 COLLAPSE SOMULATION RESULTS

Figures 10 and 11 show the road blockage conditions that can be confirmed from the collapse simulation results for each input earthquake motion. The model in the collapse simulation results turns from gray to red, indicating a higher degree of fragility. For all earthquake motion inputs and directions, the road can be seen to be free from blockage as the building collapses in the frontage direction.

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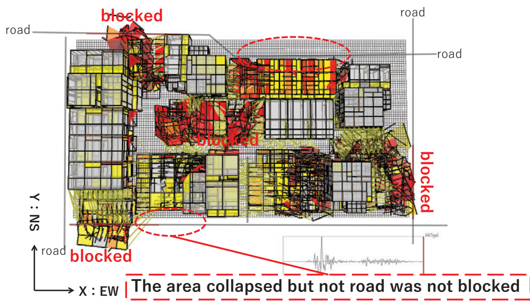

Figure 10. Road Blockage Situation in Assumed Wave 1

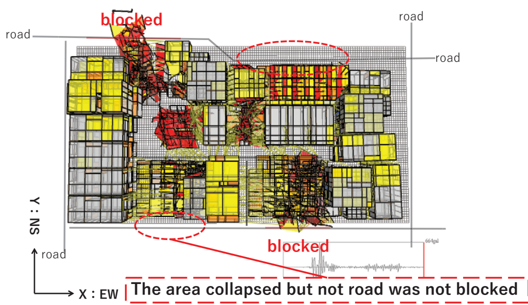

Figure 11. Road Blockage Situation in Assumed Wave 2

4 – CONCLUSION

Using the results of response analysis based on the assumed seismic motion of Kyoto City and a model of a wooden house built in the city, we created a fragility curve showing the damage to wooden buildings in the event of an earthquake in Kyoto City. The results differed from the curve for damage to wooden buildings in the event of an earthquake in Kobe City, which is used uniformly regardless of region in the current calculation method. In addition, as a result of conducting a collapse simulation of a group of buildings in a block in Kyoto City, we found that the direction of collapse of the buildings had a different effect on the situation of road blockage.

- By using the results of response analysis based on the assumed seismic motion, we were able to propose a method for creating building damage curves for each area. This method has the potential to be applied not only to Kyoto City, which is the subject of this study, but also to other areas. In addition, it was shown that the current method for calculating the degree of blockage within an area could be refined by updating the wooden building damage curve used in the calculation process to reflect regional characteristics, without changing the calculation method itself.
- The possibility of constructing a new method for calculating an indicator that differs from the current method was demonstrated by evaluating the road blockage situation while taking into account the direction in which buildings collapse using a method for simulating the collapse of urban areas.

5 – ACKNOWLEDGEMENT

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