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Study on damage estimation by machine learning of relationship between building response and damage

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Abstract

Post-earthquake use of buildings is required at hospital facilities that responds to disaster medical care and in measures for stranded persons, and so on. In the Great East Japan Earthquake, stranded persons were a major issue, and the building is required to promptly confirm the safety of the facility after the earthquake in order to accept stranded persons, and the need for structural health monitoring system is increasing in recent years. Many of these systems install accelerometers on each floor or every few floors in the building, estimate the building deformation by acceleration integration or mode analysis, and estimate the damage of each floor from story drift angle.

The authors speculated that the degree of building damage could be estimated directly by training with machine learning in advance the relationship between the acceleration data measured by accelerometers installed in the building and the degree of building damage. However, in order to create a learning model, a huge amount of training data including the results of damage is necessary, and observation records alone are insufficient. Therefore, we considered to create a learning model by conducting earthquake response analysis many times and using the analysis results and observation records as training data.

In this study, as the first step, we created a learning model using only the analysis results. Since the target building is preferably that with the observation records, to create training data, 3D model for seismic response analysis was created referring to the specimen used in the previous full-scale shake table experiment conducted in E-Defense for a steel 18-story building, and seismic response analysis with multiple seismic waves have been conducted.

Machine learning model is trained using the Fourier amplitude spectrum of each floor response acceleration obtained from the analysis results as input data, and the damage level of each floor as output data. The damage level of each floor is categorized into 3 levels based on the rate of structural member hinge occurrence.

As a result of machine learning with neural networks and Random Forest, it was found that the damage level of each floor can be estimated with accuracy of more than 80%. However, the estimated accuracy of the damage pattern that was infrequent in the training data was low. When the feature importance was evaluated with Random Forest, the importance of the Fourier amplitude spectrum corresponding to the position where the seismic response is not amplified tended to be high.

Keywords: building damage, earthquake, machine learning, neural network, Random Forest



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1. Introduction

Post-earthquake use of buildings is required at hospital facilities that responds to disaster medical care and in measures for stranded persons, and so on. In the Great East Japan Earthquake, stranded persons were a major issue, and the building is required to promptly confirm the safety of the facility after the earthquake in order to accept stranded persons. Thus, in 2013, Ordinance for Measures Concerning Stranded Persons was enacted by the Tokyo Metropolitan government. According to the final report by the Council for Measures on Stranded People Concerning the Capital Region Earthquake [1], it is required to judge within three hours of whether or not to stay in the building, and the need for structural health monitoring system is increasing in recent years. Many of these systems install accelerometers on each floor or every few floors in the building, estimate the building deformation by acceleration integration or mode analysis, and estimate the damage of each story from story drift angle. These types are also being introduced into real buildings as systems with some degree of reliability.

The authors speculated that the degree of building damage could be estimated directly by training with machine learning in advance the relationship between the acceleration data measured by accelerometers installed in the building and the degree of building damage. With this method, not only each story but also each member can be estimated. However, in order to create a learning model, a huge amount of training data including the results of damage is necessary, and observation records alone are insufficient. Therefore, we considered to create a learning model by conducting seismic response analysis many times and using the analysis results and observation records as training data. This paper represents the result of creation a learning model to estimate the degree of damage each story using only the analysis results as the first step.

2. Create Training Data

2.1 Target Building

Since the target building is preferably that with the observation records, to create training data, 3D model for seismic response analysis was created referring to the specimen used in the previous full-scale shake table experiment conducted in E-Defense for a steel 18-story building [2]. Table 1 shows the specifications of the created analysis model, Table 2 shows the eigenvalue analysis results, Fig.1 shows the analysis model diagram, and Fig.2 shows story shear force—story drift relationship of pushover analysis.

| Item | Specification | | | |
|--------------|--------------------------------|--|--|--|
| Structure | 18 story steel frame structure | | | |
| Gross weight | 4179kN | | | |
| height | 25.35m | | | |
| Plan Size | 6.0m×5.0m(2×3) | | | |
| scale | 1/3 | | | |

| Table $1 - S$ | Specification | of the | analysis | model |
|---------------|---------------|--------|----------|-------|
|---------------|---------------|--------|----------|-------|

| Table 2 – Eigenval | ue analysis results |
|--------------------|---------------------|
|--------------------|---------------------|

| mode order | Period | Frequency | Effective mass ratio | | | | |
|---------------|--------|-----------|----------------------|-------|-------|-------|--|
| (X-direction) | (sec) | (Hz) | Х | Y | Z | θZ | |
| 1 | 1.14 | 0.875 | 0.770 | 0.000 | 0.000 | 0.191 | |
| 2 | 0.37 | 2.681 | 0.138 | 0.000 | 0.000 | 0.034 | |
| 3 | 0.20 | 4.897 | 0.038 | 0.000 | 0.000 | 0.009 | |

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Fig. 1 - 3D model for seismic response analysis



Fig. 2 – Story shear force-story drift relationship of pushover analysis (X-direction)

2.2 Seismic Response Analyses

Training data is created by seismic response analysis with multiple seismic waves on the above analysis model. The ground motion used in the analysis is observed at K-NET Naruko station (MYG005), where the ground surface amplification peaked around the first mode period of the analysis model. 140 waves were selected from observation records with JMA seismic intensity of over 2.0 observed the period from January 1, 1996 to September 4, 2017. The analysis is performed in one direction (X-direction), and the maximum direction of composite vector of the horizontal two-direction of 140 waves is used. Fig.3 shows velocity response spectrums of all observation records.

17th World Conference on Earthquake Engineering, 17WCEE Sendai, Japan - September 13th to 18th 2020 17WCE 2020 1e-01 1e+00 1e+01 1e+02 Sv(cm/s) 1e-02 average h=0.05 0.01 0.02 0.05 0.10 0.20 0.50 1.00 2.00 5.00 Period(sec)

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Fig. 3 – Velocity response spectrums of 140 waves

The above observation record was standardized so that the maximum velocity was 115 cm/s, and a waveform was prepared for each 100 waves in 1% increments from an amplitude level of 1% to 100% (14,000 waves in total). In the experiment, since the test specimen was reduced to 1/3 scale compared to the one that assumed an 18-story building, the time-step of the ground motion was also scaled to $1/\sqrt{3}$. A case where the response becomes too large is regarded as an error case, and a result where the maximum story drift angle or the member ductility factor is too large is excluded from the training data. The case where the story drift angle exceeds 1/20 or the member plasticity exceeds 50 are excluded, and 12,770 cases remained. Fig.4 shows the maximum story drift angle distribution for 12,770 cases.



Fig. 4 – Maximum story drift angle distribution for 12,770 cases



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2.3 Input / Output Data

As the input data, the Fourier amplitude of the 1st to 19th floor acceleration data is adopted, considering that the response in the frequency domain is correlated with the damage to the building. The target frequency band was 0.5 to 3.0 Hz, 19×474 (0.00527 Hz steps) matrix data was used as input data. Fig.5 shows an example of Fourier amplitude spectrum when the amplitude is 100% in the seismic wave No.1.



Fig. 5 – Fourier amplitude spectrum (seismic wave No.1, 100% amplitude)

The output data was defined as the damage level of each story, and defined by the occurrence ratio of plastic hinges at the nodes on the upper and lower floors of each story. If a plastic hinge occurs (the member ductility factor exceeds 1.0) at any of the member ends in contact with the node, the plastic hinge is counted as having occurred at the node. The damage level was defined as three levels of plastic hinge occurrence ratio of 0%, 0 to 100%, and 100%. Figure 6 shows an example of determining the damage level and shows the frequency of each damage level on each story in 12,770 cases. It can be seen that the ratio of level 2 is lower than that of levels 1 and 3, and the damage level is tend to be higher in lower stories than in higher stories.



Fig. 6 – The damage level of each story



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3. Machine Learning

3.1 Learning Model

Learning is performed using three models, Multi-Layer Perceptron (MLP), Convolutional Neural Network (CNN), and Random Forest (RF). The learning model is set individually for each story damage level, and a total of 18 learning models are constructed. Fig.7 shows the network architecture of MLP and CNN. The number of decision trees created in RF are 400, and the number of features used to create each decision tree is determined by grid search. The training data is divided into the training set and the test set. Since the test set is need to be unknown seismic waveforms for the training set, No.1-35 seismic waves cases are prepared for the test set (3,154 case), and the other 105 waves cases are used as the training set (9,616 case), and training and evaluation are performed with the dataset.



Fig. 7 – The neural network architecture

3.2 Learning Result

The accuracy is evaluated for each learning model. Table 3 shows the result of comparing the predicted value and the measured value of each floor damage level of each learning model, and Fig.8 shows the result of comparing the accuracy of each learning model.



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| | MLP | | | CNN | | | | RF | | | | |
|---|---|--|---|---|---|---|---|--|--|--|--|--|
| | predicted | | Accuracy = | 0.8827 | predicted | | Accuracy = | 0.8786 | predicted | | Accuracy = | 0.9008 |
| | measured | 1 | 2 | 3 | measured | 1 | 2 | 3 | measured | 1 | 2 | 3 |
| 1F | 1 | 1027 | 72 | 5 | 1 | 1056 | 42 | 6 | 1 | 1040 | 64 | 0 |
| | 2 | 85 | 159 | 97 | 2 | 119 | 100 | 122 | 2 | 70 | 159 | 112 |
| | 3 | 43 | 68 | 1598 | 3 | 31 | 63 | 1615 | 3 | 2 | 65 | 1642 |
| | predicted | | Accuracy = | 0.8884 | predicted | | Accuracy = | 0.8859 | predicted | 1 | Accuracy = | 0.9039 |
| | measured | 1 | 2 | 3 | measured | 1 | 2 | 3 | measured | 1 | 2 | 3 |
| 2F | 1 | 1030 | 63 | 11 | 1 | 1074 | 0 | 30 | 1 | 1054 | 23 | 27 |
| | 2 | 54 | 95 | 94 | 2 | 101 | 1 | 141 | 2 | 63 | 47 | 133 |
| | 3 | 79 | 51 | 1677 | 3 | 86 | 2 | 1719 | 3 | 20 | 37 | 1750 |
| | predicted | | Accuracy = | 0.9017 | predicted | | Accuracy = | 0.9036 | predicted | 1 | Accuracy = | 0.9166 |
| | measured | 1 | 2 | 3 | measured | 1 | 2 | 3 | measured | 1 | 2 | 3 |
| 3F | 1 | 1152 | 30 | 39 | 1 | 1173 | 0 | 48 | 1 | 1166 | 2 | 53 |
| | 2 | 49 | 31 | 75 | 2 | 69 | 0 | 86 | 2 | 57 | 6 | 92 |
| | 3 | 91 | 26 | 1661 | 3 | 101 | 0 | 1677 | 3 | 53 | 6 | 1719 |
| | predicted | | Accuracy = | 0.8909 | predicted | | Accuracy = | 0.8944 | predicted | 1 | Accuracy = | 0.9115 |
| | measured | 1 | 2 | 3 | measured | 1 | 2 | 3 | measured | 1 | 2 | 3 |
| 4F | 1 | 1173 | 56 | 27 | 1 | 1207 | 0 | 49 | 1 | 1204 | 7 | 45 |
| | 2 | 56 | 44 | 91 | 2 | 85 | 0 | 106 | 2 | 58 | 17 | 116 |
| | 3 | 70 | 44 | 1593 | 3 | 93 | 0 | 1614 | 3 | 39 | 14 | 1654 |
| | predicted | | Accuracy = | 0.8725 | predicted | | Accuracy = | 0.8843 | predicted | 1 | Accuracy = | 0.9093 |
| | measured | 1 | 2 | 3 | measured | 1 | 2 | 3 | measured | 1 | 2 | 3 |
| 5F | 1 | 1202 | 79 | 18 | 1 | 1248 | 15 | 36 | 1 | 1235 | 56 | 8 |
| | 2 | 68 | 75 | 107 | 2 | 100 | 20 | 130 | 2 | 64 | 104 | 82 |
| | 3 | 53 | 77 | 1475 | 3 | 69 | 15 | 1521 | 3 | 37 | 39 | 1529 |
| | predicted | | Accuracy = | 0.8703 | predicted | | Accuracy = | 0.8627 | predicted | | Accuracy = | 0.9084 |
| - | measured | 1 | 2 | 3 | measured | 1 | 2 | 3 | measured | 1 | 2 | 3 |
| 6F | 1 | 1242 | 91 | 15 | 1 | 1262 | 76 | 10 | 1 | 1257 | 90 | 1 |
| | 2 | 69 | 187 | 100 | 2 | 91 | 95 | 170 | 2 | 51 | 214 | 91 |
| | 3 | 33 | 101 | 1316 | 3 | 34 | 52 | 1364 | 3 | 18 | 38 | 1394 |
| | predicted | | Accuracy = | 0.8618 | predicted | | Accuracy = | 0.8488 | predicted | | Accuracy = | 0.8982 |
| - | measured | 1 | 2 | 3 | measured | 1 | 2 | 3 | measured | 1 | 2 | 3 |
| 7F | 1 | 1265 | 102 | 2 | 1 | 1264 | 104 | 100 | 1 | 1260 | 109 | 0 |
| | 2 | 88 | 305 | 83 | 2 | 95 | 199 | 182 | 2 | 58 | 326 | 92 |
| | 5 predicted | 27 | . 134 | 1148 | 5 predicted | 22 | . 13 | 1214 | 5 predicted | 14 | 48 | 1247 |
| | predicted | 1 | Accuracy = | 0.8507 | predicted | 1 | Accuracy = | 0.8450 | picaletee | | Accuracy = | 0.8827 |
| 05 | measured | 1002 | 2 | 3 | measured | 1004 | 2 | 3 | measured | 1200 | 107 | 3 |
| 8F | 1 | 1283 | 109 | 1 | 1 | 1284 | 108 | 100 | 1 | 1266 | 127 | 0 |
| | 2 | 103 | 352 | 82 | 2 | 92 | 243 | 182 | 2 | 62 | 340 | 115 |
| | > predicted | 20 | 150 | 1008 | > predicted | 20 | 80 | 0.9510 | > predicted | 9 | 5/ | 0.8006 |
| | predicted | · · · · | Accuracy = | 0.8548 | predicted | 1 | Accuracy = | 0.8519 | predicted | · | Accuracy = | 0.8900 |
| OF | ineasureu 1 | 1264 | 110 | 3 | ineasured 1 | 1274 | 07 | 3 | ineasured 1 | 1262 | 110 | 3 |
| 96 | 1 | 1204 | 241 | 0 | 1 | 12/4 | 97 | 171 | 1 | 1203 | 250 | 106 |
| | 2 | 97 | 120 | 1001 | 2 | 93 | 82 | 1/1 | 2 | 01 | 539 | 1100 |
| | > predicted | 24 | Accuracy = | 0.8503 | > predicted | 20 | A coursey = | 0.8649 | > predicted | 5 | Accuracy = | 0.9033 |
| | | | Accuracy = | 0.6505 | | | | | ~ | | Accuracy = | (1.7(1.1.) |
| | measured | 1 | 2 | 3 | measured | 1 | 2 | 3 | measured | 1 | 2 | 3 |
| 10F | measured 1 | 1257 | 2 | 3 | measured | 1 | 2 105 | 3 | measured 1 | 1259 | 2 | 3 |
| 10F | measured 1 2 | 1 1257 90 | 2 115 327 | 3 0 90 | measured 1 | 1 1267 82 | 2 105 302 | 3 0 123 | measured 1 | 1 1259 44 | 2 113 382 | 3 0 81 |
| 10F | measured 1 2 3 | 1 1257 90 35 | 2 115 327 142 | 3 0 90 | measured 1 2 3 | 1 1267 82 29 | 2 105 302 87 | 3 0 123 | measured 1 | 1 1259 44 | 2 113 382 55 | 3 0 81 1208 |
| 10F | measured 1 2 3 predicted | 1 1257 90 35 | 2 115 327 142 Accuracy = | 3 0 90 1098 0.8237 | measured 1 2 3 predicted | 1 1267 82 29 | 2 105 302 87 Accuracy = | 0.8049 3 0 123 1159 0.8510 | measured 1 2 3 predicted | 1 1259 44 12 | 2 113 382 55 Accuracy = | 3 0 81 1208 0 8773 |
| 10F | measured 1 2 3 predicted measured | 1 1257 90 35 | 2 115 327 142 Accuracy = 2 | 3 0 90 1098 0.8237 3 | measured 1 2 3 predicted measured | 1 1267 82 29 | $\frac{2}{105}$ $\frac{302}{87}$ Accuracy = 2 | 0.8049 3 0 123 1159 0.8510 3 | measured 1 2 3 predicted measured | 1 1259 44 12 | 2 113 382 55 Accuracy = 2 | 3 0 81 1208 0.8773 3 |
| 10F | measured 1 2 3 predicted measured 1 | 1 1257 90 35 1 1284 | 2 115 327 142 Accuracy = 2 125 | 3 0 90 1098 0.8237 3 0 | measured 1 2 3 predicted measured | 1 1267 82 29 1 1294 | $\frac{2}{105}$ $\frac{302}{87}$ Accuracy = $\frac{2}{115}$ | 0.804) 3 0 123 1159 0.8510 3 0 | measured 1 2 3 predicted measured | 1 1259 44 12 1 1 1284 | 2 113 382 55 Accuracy = 2 125 | 3 0 81 1208 0.8773 3 0 |
| 10F | measured 1 2 3 predicted measured 1 2 | 1 1257 90 35 1 1284 121 | 2 115 327 142 Accuracy = 2 125 493 | 3 0 90 1098 0.8237 3 0 115 | measured 1 2 3 predicted measured 1 2 | 1 1267 82 29 1 1294 104 | $\frac{2}{105} \\ \frac{302}{87} \\ Accuracy = 2 \\ 115 \\ 511 \\ 110 \\ $ | 0.8049 3 0 123 1159 0.8510 3 0 114 | measured 1 2 3 predicted measured 1 2 | 1 1259 44 12 1 1 1284 54 | 2 113 382 55 Accuracy = 2 125 569 | 3 0 81 1208 0.8773 3 0 106 |
| 10F 11F | measured 1 2 3 predicted measured 1 2 3 | 1 1257 90 35 1 1284 121 45 | $\begin{array}{r} 2 \\ 115 \\ 327 \\ 142 \\ Accuracy = \\ 2 \\ 125 \\ 493 \\ 150 \end{array}$ | 3 0 90 1098 0.8237 3 0 115 821 | measured 1 2 3 predicted measured 1 2 3 | 1 1267 82 29 1 1294 104 24 | $\frac{2}{105} \\ \frac{302}{87} \\ Accuracy = \frac{2}{115} \\ \frac{511}{113} \\ \frac{11}{113} \\ \frac{11}{$ | 0.8049 3 0 123 1159 0.8510 3 0 114 879 | measured 1 2 3 predicted measured 1 2 3 | 1 1259 44 12 1284 1284 54 0 | $2 \\ 113 \\ 382 \\ 55 \\ Accuracy = 2 \\ 125 \\ 569 \\ 102 \\ 102 \\ 102 \\ 102 \\ 102 \\ 103 $ | 3 0 81 1208 0.8773 3 0 106 914 |
| 10F 11F | measured 1 2 3 predicted measured 1 2 3 predicted | 1 1257 90 35 1 1284 121 45 | 2 115 327 142 Accuracy = 2 125 493 150 Accuracy = | 3 0 90 1098 0.8237 3 0 115 821 0.8196 | measured 1 2 3 predicted measured 1 2 3 predicted | 1 1267 82 29 1 1294 104 24 | 2 105 302 87 Accuracy = 2 115 511 113 Accuracy = | 0.8049 3 0 123 1159 0.8510 3 0 114 879 0.8456 | measured 1 2 3 predicted measured 1 2 3 predicted predicted | $ \begin{array}{r} 1 \\ 1259 \\ 44 \\ 12 \\ 1 \\ 1284 \\ 54 \\ 0 \\ 1 \end{array} $ | 2 113 382 55 Accuracy = 2 125 569 102 Accuracy = | 3 0 81 1208 0.8773 3 0 0 106 914 0.8748 |
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| 10F 11F 12F | measured 1 2 3 predicted measured 1 2 3 predicted measured 1 1 1 1 1 1 1 1 1 1 1 1 1 | 1 1257 90 35 1 1284 121 45 | $\begin{array}{r} 2 \\ 115 \\ 327 \\ 142 \\ Accuracy = \\ 2 \\ 125 \\ 493 \\ 150 \\ Accuracy = \\ 2 \\ 110 \end{array}$ | 3 0 90 1098 0.8237 3 0 115 821 0.8196 3 0 | measured 1 2 3 predicted measured 1 2 3 predicted measured 1 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 1 1 1 1 1 1 1 1 1 1 1 | 1 1267 82 29 1 1294 104 24 | 2 105 302 87 Accuracy = 2 115 511 113 Accuracy = 2 2 115 511 113 Accuracy = 118 | 0.0079 0.0079 0.0070 | measured 1 2 3 predicted measured predicted measured 1 1 2 3 1 2 3 1 2 3 1 2 3 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 3 1 1 2 1 1 1 1 1 1 1 1 1 1 1 1 1 | 1 1259 44 12 1 1284 54 0 1 1354 | 2 113 382 55 Accuracy = 2 125 569 102 Accuracy = 2 114 | 3 0 81 1208 0.8773 3 0 106 914 0.8748 3 0 |
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| 10F 11F 12F 13F 14F 15F 16F | measured 1 2 3 predicted measured 1 2 2 3 predicted measured 1 2 2 2 2 2 2 2 2 2 2 2 2 2 | 1 1257 90 35 1 1284 121 45 1 1358 150 36 1 1491 210 11 1614 178 0 1 1859 184 0 1 1859 184 0 1 1 185 185 0 1 1 185 10 10 10 10 10 10 10 10 10 10 | 2 115 327 142 Accuracy = 2 125 493 150 Accuracy = 2 110 793 158 Accuracy = 2 70 993 178 Accuracy = 2 70 903 178 Accuracy = 2 70 903 178 Accuracy = 2 70 903 178 Accuracy = 2 70 903 1127 90 0 Accuracy = 2 70 903 1127 90 0 0 0 0 0 0 0 0 0 0 0 0 0 | 3 0 90 1098 0.8237 3 0 115 821 0.8196 3 0 115 434 0.8386 3 0 115 434 0.8386 3 0 0 115 434 0.8386 3 0 0 0 0 0 0 0 0 0 0 0 0 0 | measured 1 2 3 predicted measured 1 2 3 | 1 1267 82 29 1 1294 104 24 1 1350 115 14 149 138 0 1 1568 141 0 1 1568 141 0 1 1568 141 0 1 1568 141 0 1 1568 141 0 1 1568 141 0 1 1568 141 1576 1449 1350 0 1 1576 1449 1356 0 1 1576 1449 1356 0 1 1576 1449 1356 0 1 1576 1449 1356 0 1 1576 1449 1356 0 1 1576 1449 1356 0 1 1576 1449 1356 0 1 1576 1449 1356 0 1 1576 1449 1356 0 1 1 1 1 1 1 1 1 1 1 1 1 1 | $\begin{array}{r} 11 \text{ccuracy} = \\ 2 \\ 1005 \\ 302 \\ 87 \\ \text{Accuracy} = \\ 2 \\ 115 \\ 5111 \\ 113 \\ \text{Accuracy} = \\ 2 \\ 118 \\ \text{Accuracy} = \\ 2 \\ 118 \\ \text{Accuracy} = \\ 2 \\ 112 \\ 1078 \\ 2 \\ 100 \\ \text{Accuracy} = \\ 2 \\ 2 \\ 119 \\ 1213 \\ 100 \\ 2 \\ 2 \\ 119 \\ 1213 \\ 100 \\ 2 \\ 2 \\ 119 \\ 1213 \\ 100 \\ 2 \\ 2 \\ 1051 \\ 6 \\ \text{Accuracy} = \\ 2 \\ 2 \\ 35 \\ 1051 \\ 6 \\ \text{Accuracy} = \\ 2 \\ 2 \\ 32 \\ 32 \\ 32 \\ 512 \\ 0 \\ 100 $ | 3.007 3 0 123 1159 0.8510 3 0 114 879 0.8456 3 0 74 448 0.8486 3 0 277 150 0.8843 3 0 0.8843 0 233 0 0.8843 0 0.8843 0 0.9242 3 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 <t< td=""><td>measured 1 2 3 predicted 1 2 3 predicted 1 2 3 predicted 1 2 3 predicted 1 2 3 predicted 1 2 3 2 2 2 2 2 2 2 2 2 2 2 2 2</td><td>1 1259 44 12 1 1284 54 0 1 1354 67 0 1450 76 0 11 1450 0 1581 66 0 1 1870 74 0 1 2384 88 8</td><td>$\begin{array}{c} 2 \\ 113 \\ 382 \\ 55 \\ Accuracy = \\ 2 \\ 125 \\ 569 \\ 102 \\ 2 \\ 114 \\ 903 \\ 126 \\ Accuracy = \\ 2 \\ 111 \\ 103 \\ 126 \\ Accuracy = \\ 2 \\ 111 \\ 113 \\ 153 \\ Accuracy = \\ 2 \\ 106 \\ 1291 \\ 106 \\ 1291 \\ 106 \\ 1291 \\ 106 \\ 1291 \\ 106 \\ 6 \\ Accuracy = \\ 2 \\ 89 \\ 1115 \\ 6 \\ Accuracy = \\ 2 \\ 89 \\ 1115 \\ 6 \\ 6 \\ Accuracy = \\ 2 \\ 75 \\ 607 \\ 7 \\ 0 \end{array}$</td><td>3 0 81 1208 0.8773 3 0 106 914 0.8748 3 0 0 88 502 0.8808 3 0 0 88 3 0 0 0 88 3 0 0 0 0 0 106 914 0.8748 3 0 0 0 0 0 0 0 0 0 0 0 0 0</td></t<> | measured 1 2 3 predicted 1 2 3 predicted 1 2 3 predicted 1 2 3 predicted 1 2 3 predicted 1 2 3 2 2 2 2 2 2 2 2 2 2 2 2 2 | 1 1259 44 12 1 1284 54 0 1 1354 67 0 1450 76 0 11 1450 0 1581 66 0 1 1870 74 0 1 2384 88 8 | $\begin{array}{c} 2 \\ 113 \\ 382 \\ 55 \\ Accuracy = \\ 2 \\ 125 \\ 569 \\ 102 \\ 2 \\ 114 \\ 903 \\ 126 \\ Accuracy = \\ 2 \\ 111 \\ 103 \\ 126 \\ Accuracy = \\ 2 \\ 111 \\ 113 \\ 153 \\ Accuracy = \\ 2 \\ 106 \\ 1291 \\ 106 \\ 1291 \\ 106 \\ 1291 \\ 106 \\ 1291 \\ 106 \\ 6 \\ Accuracy = \\ 2 \\ 89 \\ 1115 \\ 6 \\ Accuracy = \\ 2 \\ 89 \\ 1115 \\ 6 \\ 6 \\ Accuracy = \\ 2 \\ 75 \\ 607 \\ 7 \\ 0 \end{array}$ | 3 0 81 1208 0.8773 3 0 106 914 0.8748 3 0 0 88 502 0.8808 3 0 0 88 3 0 0 0 88 3 0 0 0 0 0 106 914 0.8748 3 0 0 0 0 0 0 0 0 0 0 0 0 0 |
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Fig. 8 - Comparing the accuracy of each learning model

There is tendency that the accuracy of 6th to 13th stories is lower than that of the other stories in any of the learning model results. The damage level 2 is considered to have lower accuracy due to the small number of data itself, and the middle stories has a higher damage level 2 ratio than other stories, so the accuracy is likely to be lower. The higher stories (14th story or higher) have a higher accuracy, but this is a story where damage is unlikely to occur, so damage level 3 ratio is small and the ratio of damage level 1 is very large, so accuracy is high. As a comparison between the models, there is little difference in the accuracy between the two types of neural networks. On the other hand, Random Forest is more accurate on almost all floors than the other two models.

3.3 Feature Importance

In the random forest, the feature importance can be evaluated. Fig.9 shows, for the RF model of each story, the input data of the top 10 importance levels among the input data of the 19×474 Fourier amplitude. The importance is based on the degree of decrease in the Gini coefficient. Except for the prediction models from the 16th story to the 18th story, almost stories tend to have a higher importance of the Fourier amplitude in the band from first mode frequency (0.875 Hz) to about 1.00 Hz in the 1st to 4th floors. This suggests that most stories may be able to predict damage using only lower floor acceleration data without for all floors. On the other hand, on the 16th story model, the importance of the Fourier amplitude of 1.0 to 1.3 Hz on the 2nd to 7th floors is high, and on the 17th story model, the importance of the Fourier amplitude of 1.0 to 1.7 Hz on the 3rd to 10th floors is high. There is a tendency that the higher the target story, the higher the floor level and the frequency of the Fourier amplitude having the high importance. As for the 18th floor, since the damage level is 1 in all cases, indicating that the importance of the feature value is meaningless.



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Fig. 10 – The Fourier amplitude spectrum of each floor overlaid with feature of the top 10 importance levels (The whiter the higher the Fourier amplitude, the blacker the smaller)



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In order to confirm the relationship between the Fourier amplitude spectrum of each floor and the importance of the feature, Fig.10 shows a color map of the Fourier amplitude spectrum of each floor overlaid with feature of the top 10 importance levels (when the amplitude is 100% in the seismic wave No.1). It can be seen that, in addition to the tendency described in Fig.9, the position of the feature with high importance overlaps the band with a small Fourier amplitude. The Fourier amplitude at a frequency close to the first mode frequency of the ground motion is important, and the Fourier amplitude in an unresponsive frequency domain at above floors is also important. It is presumed that this learning model predicts damage based on the ground motion power at the first mode frequency of building and the acceleration amplitude in the frequency band not affected by the building response on the upper floor.

4. Conclusions

We speculated that it is possible to estimates the degree of building damage from acceleration data observed in buildings by training with machine learning the relationship between building response acceleration and building damage. Therefore, as the first step, machine learning was performed using the seismic response analysis results as training data. As a result, it was found that the analysis made it possible to estimate the damage of each story of the building from the acceleration data with accuracy of 80% or more by machine learning using a neural network or random forest. As a result of analyzing the importance of the feature, it was found that the ground motion power at the first mode frequency of the building and the acceleration amplitude in the frequency band not affected by the response of the building on the upper floor are important. The future task is how to solve the problem that the accuracy of the damage level with low occurrence frequency decreases because the occurrence frequency of each damage level greatly differs depending on the story. In addition, since this study is based on the analysis results, it will be necessary to verify in the future whether it is possible to make estimations using actual observation data.

5. Acknowledgements

Strong motion records were provided by NIED. For the building data, we used the experimental data of "Quantification of collapse margin of high-rise steel-framed buildings" from NIED "ASEBI".

6. References

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