JUDGEMENT TENDENCY AND FUZZY INFERENCE MODEL RELATED TO REDUNDANCY OF FRAMED STRUCTURES AGAINST DISSAPEARANCE OF MEMBER

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In these days, some examples have been reported about the collapse of buildings structures by gravity as an outcome resulted from an accidental action or the excitation not prepared in the design process. A redundancy and a key-element has been taken from a viewpoint of assuring robustness of a structure even if it receives unexpected disturbance. In past study, a questionnaire survey for human judgments related to structural redundancy was done. From the results, an assessment method related to redundancy was proposed considering sensitivity and the number of plastic hinges. Also, a “2nd Limit Analysis” method combining the plastic analysis and deformation calculation has been proposed for the occurrence of the mechanical mechanism. In this study, a questionnaire investigation was performed to experts and non-experts about human judgments related to a structural redundancy of framed structures against disappearance of member. From the results, the judgment tendency presents the consideration of combination for the sensitivity index and collapse mode. By abstracting the rules of fuzzy inference about the classification of structural redundancy, the membership function was composed related to human judgement. Furthermore, the method of the determination of the key-element is proposed by reference of the proposed fuzzy inference model.

Keywords: Building collapse, Assessment method, Sensitivity index, Fuzzy theory.

1 INTRODUCTION

In these days, some examples have been reported about the collapse of buildings structures by gravity as an outcome resulted from an accidental action or the excitation not prepared in the design process. The world was shaken to witness the progressive collapse of WTC in 2001. In this case, the frame was crashed and collapsed completely, but it can also be considered that WTC had been standing for several hours after the collision and disappearance of the structural frame (FEMA-403 2002). A close-up of concepts, such as a redundancy and a key-element, has been taken from a viewpoint of assuring robustness of a structure even if it receives the unexpected disturbance.

The sensitivity analytical method related to structural redundancy was proposed. That method estimates the index of vertical load carrying capacity to member disappearance based on the plastic analysis (Ito et al. 2005). The index was defined as the ratio of the load carrying capacity after a member disappears to the original load carrying capacity. The sensitivity index $S.I.$ was defined in Eq. (1):
Where, $\lambda_0$ is the collapse load factor of the structure at original state, $\lambda_d$ is the collapse load factor of the structure at damaged state.

Also, in previous research on building redundancy, when a plastic collapse mechanism was formed after the disappearance of a member, the deformation of the framework caused a potential capacity of the member that was not assumed in the original state. A “2nd Limit Analysis” method combining the plastic analysis and deformation calculation has been proposed for the occurrence of the mechanical mechanism (Ito 2008).

In this study, a questionnaire investigation to propose the criteria was performed to experts and non-experts about human judgments related to a structural redundancy of framed structures after a certain member disappearance. In the questionnaire investigation, the results of 2nd Limit Analysis on the framed structures were exhibited, that is, the sensitivity index and the failure mechanism after a certain member disappearance were exhibited. By abstracting the rules of fuzzy inference about the classification of structural redundancy, the membership function was composed related to human judgement. Furthermore, the method of the determination of the key-element is proposed by reference of the proposed fuzzy inference model.

2 SENSITIVITY ANALYSIS ON MULTI-STORY FRAMED STRUCTURES

2.1 Analytical Model of Multi-story Framed Structures

Herein, the two 6-story planner frames with and without an outrigger truss is dealt as shown in Figure 1. These analytical models were applied to the sensitivity analysis.

It is referred to as the story height $h$ of the frame, and the span length $2h$ ($h$ for the central short span length). The column over design factor or the beam-to-column moment capacity ratio at each story is taken 1.2 as a weak-beam structure. The plastic moment capacity of beams for the second floor through the fourth floor is taken commonly $1.2M_0$, or 1.2 times fully-plastic moment $M_0$ for the fifth floor through the penthouse roof. The relationship $N_y = 64M_p/3h$ is also assumed for the plastic resistance, but the interaction between the axial and flexural plastic resistances is ignored. Also, the buckling of member is not considered. The plastic resistances of members are summarized in Table 1. Vertical loads are applied at each column top and each beam center as concentrated loads. The magnitude of vertical loads at the Roof floor and the penthouse roof floor are taken $1.5P_0$, that is, 1.5 times of the standard magnitude $P_0$ at other floors.

2.2 Sensitivity Index and Evaluation Index Related to the Failure Mechanism

The 2nd limit analysis is conducted on the previous analytical model in Figure 1. Evaluation indexes related to the failure mechanism are defined to consider the effect of tilting as shown in Eq. (2), Eq. (3) and Eq. (4).

$$S.I. = \frac{\lambda_0 - \lambda_d}{\lambda_0}$$ (1)

Index related to tilted room : $\nu_r = \frac{N_{tr}}{N_{r0}}$ (2)

Index related to horizontal deformation : $\nu_h = \frac{N_{nh}}{N_{n0}}$ (3)
Index related to vertical deformation

\[ \nu_v = \frac{N_{rv}}{N_{r0}} \]

Where, \( N_{r0} \) is the number of rooms, \( N_{tr} \) is the number of tilted rooms, \( N_{n0} \) total number of the node, \( N_{nh} \) is the number of nodes moved horizontally, and \( N_{nv} \) is the number of nodes moved vertically. Figure 2 shows the relation of the sensitivity index \( S.I. \) and the number of damaged member and those indexes at the plastic failure mechanism formation after a member disappearance (Table 1).

### Table 1. Member properties.

<table>
<thead>
<tr>
<th>story</th>
<th>Member</th>
<th>Moment strength</th>
<th>Yield axial strength</th>
<th>Bending stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1～3</td>
<td>Beam 2-4st</td>
<td>1.2( M_0 )</td>
<td>25.6 ( M_0/h )</td>
<td>0.314 ( M_0 )</td>
</tr>
<tr>
<td></td>
<td>Column 1-3st</td>
<td>1.44( M_0 )</td>
<td>30.7 ( M_0/h )</td>
<td>0.377 ( M_0 )</td>
</tr>
<tr>
<td></td>
<td>Truss 3rs</td>
<td>-</td>
<td>12.2 ( M_0/h )</td>
<td>-</td>
</tr>
<tr>
<td>4～7</td>
<td>Beam 5-PHR</td>
<td>( M_0 )</td>
<td>21.3 ( M_0/h )</td>
<td>0.263 ( M_0 )</td>
</tr>
<tr>
<td></td>
<td>Column 4-R</td>
<td>1.2( M_0 )</td>
<td>25.6 ( M_0/h )</td>
<td>0.314 ( M_0 )</td>
</tr>
<tr>
<td></td>
<td>Truss 4-R</td>
<td>-</td>
<td>12.2 ( M_0/h )</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 2. Sensitivity index vs. deformation related failure mechanism.

### 3 QUESTIONNAIRE INVESTIGATION

#### 3.1 Outline of Questionnaire Investigation

In this study, a questionnaire investigation to propose the criteria was performed to experts and non-experts about human judgments related to a structural redundancy of framed structures after a certain member disappearance. In the questionnaire investigation, the results of 2nd Limit Analysis
on the framed structures were exhibited, that is, the sensitivity index and the failure mechanism after a certain member disappearance were exhibited. This investigation asked whether the condition of the result of the sensitivity analysis is permitted or not.

3.2 Jobs and Sample Size of Respondent

At the questionnaire investigation, the job of respondents was asked. The kinds of jobs are categorized as following. An “expert” includes the structural designers and researchers. A university student of the department of architecture is categorized as “architectural student.” And the others are categorized as “non-experts.”

Total sample size of respondents is 201, which includes 57 experts, 27 architectural students, and 117 non-experts.

3.3 Questionnaire Items

In the questionnaire investigation, the results of sensitivity analysis on the framed structures as shown in Figure 3 were exhibited, that is, the sensitivity index S.I. and the failure mechanism after a certain member disappearance were exhibited. This investigation asked whether the condition of the result of the sensitivity analysis is permitted or not. The respondents answer the numerical value about the permission as 5-grades; 1: “not permitting”; 3: “neither permitting or not”; 5: “permitting”. And this questionnaire asked the weights for the parameter, the sensitivity index, and the failure mechanism. Furthermore, the questionnaire asked what is important about collapse mode.

![Figure 3. The fourteen-models exhibited at the questionnaire investigation.](image)

3.4 Questionnaire Result

Herein, this paper only deals with questionnaire of “experts”. Figure 4 shows the relations of the numerical value of the questionnaire results vs. sensitivity index. Table 2 shows importance ratio during judgement related to redundancy. Table 3 shows importance ratio during judgement related to failure mode. According to these figures and tables, it is desirable to evaluate the redundancy by considering the failure mode and deformation.
4 FUZZY INFERENCE MODEL

4.1 Index Related to Redundancy

From the results of Figure 4, it is found that the permission of the condition presented by sensitivity analysis results would not be judged by reference of the individual factor. Furthermore, it can be said that the combination of these factors is regarded as the important for the judgment. So then, the permission model related to the judgments is approximated by use of the combination index related to redundancy, which index is abbreviated as R.I.’ (Redundancy Index). That is, the fuzzy inference model is not directly expressed by use of the individual factor, the sensitivity index, and the number of damaged members. It is intermediate expressed by use of the combination index R.I.’. Herein, the combination index R.I.’ is presented as following formula in Eq. (5);

\[
R.I.' = \frac{1}{1/(w_1S.I.) + 1/(w_2f)}
\] (5)

Where \( w_1 \) and \( w_2 \) are weight parameters S.I. and f, and the f is the evaluation index related to the failure mechanism and defined in Eq. (6):

\[
f = a_1n + a_2v_r + a_3v_h + a_4v_v
\] (6)

\( w_1 \) and \( w_2 \) are weight parameters S.I. and f, and \( a_1 \sim a_4 \) are coefficients determined from Table 3. The relation of the index R.I.’ and the questionnaire results are shown in Figure 6. From the results of Figure 7, the response rate of “not permitting” increases as the index R.I.’ increases.

4.2 Membership Function

The membership function for the questionnaire results would be approximated by the fuzzy model, which is widely used in the fuzzy inference theory (Figure 5). Herein, the approximated membership functions \( m_B \) are presented as in Eq. (7):

\[
m_B(R.I.) = \frac{C_1}{1 + \exp\left(\frac{R.I.-C_2}{C_3}\right)} + C_4
\] (7)

Where, the \( C_1 \sim C_4 \) are the undetermined coefficients. These coefficients are determined by the least square method by used of the questionnaire results. And the \( C_1 \sim C_4 \) and coefficient of determination are presented in Table 4. The comparison of the abstracted membership functions.
and the questionnaire results are shown in Figure 7. From the results of Figure 7, the response rates decrease as the index R.I.' increases. It could be said that the index R.I.' can reflect the tolerance for the judgment related to the redundancy.

![Figure 5. Fuzzy inference model for tolerance related to redundancy.](image)

![Figure 6. Relation of R.I. vs answer ratio (experts).](image)

![Figure 7. Contour of questionnaire results.](image)

Table 4. The $C_1$~$C_4$ and coefficient of determination (experts).

<table>
<thead>
<tr>
<th></th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$C_3$</th>
<th>$C_4$</th>
<th>Coefficient of determination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tolerance</td>
<td>21173</td>
<td>0.1267</td>
<td>0.0168</td>
<td>2175</td>
<td>0.616</td>
</tr>
<tr>
<td>Acceptable</td>
<td>523.4</td>
<td>0.0471</td>
<td>0.0063</td>
<td>0.0958</td>
<td>0.803</td>
</tr>
<tr>
<td>Neither</td>
<td>0.0635</td>
<td>0.0053</td>
<td>0.0018</td>
<td>0.0501</td>
<td>0.557</td>
</tr>
<tr>
<td>Unacceptable</td>
<td>17.31</td>
<td>0.01081</td>
<td>0.0261</td>
<td>0.5576</td>
<td>0.576</td>
</tr>
</tbody>
</table>

5 CONCLUSION

As a result of the questionnaire, it was confirmed that the respondents tended to place importance not only on the member sensitivity but also on the deformation in the collapse mechanism. Furthermore, by abstracting the rules of fuzzy inference about the classification of structural redundancy based on the questionnaire results, the membership function is composed related to human decision-making. The index related to the redundancy is proposed, that index is defined by the combination of the sensitivity index and the failure mechanism.

References

