A Reliability Analysis of In-service Reinforced Concrete Residential Structures

YUYING WANG, QIANG GAO and GUOPING ZHANG

ABSTRACT

Floor load and resistance of residential buildings, two important parameters for reliability analysis, pose direct influences upon the structural reliability. Based on the survey of floor live load of typical reinforced concrete residential buildings, strength of member materials, geometric parameters of reinforced concrete members and other resistance parameters, the reliability level of residential buildings is systematically studied, the standard value for floor live load and influences of the construction quality upon the reliability of residential buildings are analyzed, and primary causes of reduced reliability of reinforced concrete flexural members of residential buildings are obtained.

INTRODUCTION

Structure reliability can be defined as the probability that structures reach desired functions in the specified time and under specific conditions[1]. It’s being a dominant tendency for study and development of residential buildings in our country to research the structure reliability, improve the durability and practically guarantee the security of residential buildings. As important parameters for analyzing structure reliability, structural load and resistance are two direct influence factors. Through the investigation and statistic analysis of the floor live load of 100 households and 400 rooms in typical residential buildings in Chang Chun City, this paper studies its statistic parameters and probability distribution and, based on actual measurement and statistical analysis of material strength of newly-built residential buildings and geometric parameters of structural members, the variability of performances and geometric parameters of structural member
materials. On this basis, statistic parameters and reliability of the resistance of structural members as well as influences of the standard value for the floor live load upon the reliability of residential buildings are analyzed.

1 STATISTIC PARAMETERS OF STRUCTURAL MEMBER RESISTANCE OF RESIDENTIAL BUILDINGS

1.1 Indeterminateness of Structural Member Resistance

Resistance of structural members is not only the ability to resist effects of actions, including bearing capacity, rigidity and crack resistance etc. but also the bearing capacity in the reliability analysis of its ultimate state. Indeterminateness of resistance contains indeterminateness of material performances, indeterminateness of geometric parameters and indeterminateness of calculation mode. Generally, the resistance of structural members is a function of multiple random variables, so it is difficult to obtain statistical information of resistance directly and confirm the distribution pattern of statistical parameters and probability. Thus, statistical features and probability distribution of basic resistance parameters are confirmed through the statistic analysis of primary causes, and then statistical parameters of resistance and probability distribution mode are figured out using the functional relationship between resistance and influence factors.

Indeterminateness of the calculation mode of structural members refers to indeterminateness caused by the similarity basically assumed in the calculation of resistance and the uncertainty of the calculation formula, which is also called the error of the calculation mode. The indeterminateness of the calculation mode of structural members is expressed using random variable $K_p$, namely[2]:

$$K_p = \frac{R^e}{R^j}$$  \hspace{1cm} (1)

Where, $R^e$ is the actual resistance value of structural member, generally, it’s the experimental measured value or the accurate calculated value, and $R^j$ is the value of the structure resistance which is figured out using a normal formula with the actual value of material performance and geometric dimensioning.

Statistical parameters of random variable $K_p$ for indeterminateness in the calculation mode are provided in Code for Concrete Structure Design[3]. Through the contrastive analysis of the old code and the new, statistical parameters of random variable $K_p$ for calculating the indeterminateness of reinforced concrete structural members corresponding to existing Code for Concrete Structure Design are obtained as shown in Table I.
### TABLE I. STATISTICAL PARAMETERS OF RANDOM VARIABLE $K_p$ OF REINFORCED CONCRETE STRUCTURAL MEMBERS.

<table>
<thead>
<tr>
<th>Stress state</th>
<th>89 Code</th>
<th>Revision</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\mu_{K_p}$</td>
<td>$\delta_{K_p}$</td>
</tr>
<tr>
<td>Axial tension</td>
<td>1.00</td>
<td>0.04</td>
</tr>
<tr>
<td>Axial compression</td>
<td>1.00</td>
<td>0.05</td>
</tr>
<tr>
<td>Eccentric compression</td>
<td>1.00</td>
<td>0.05</td>
</tr>
<tr>
<td>Bending</td>
<td>1.00</td>
<td>0.15</td>
</tr>
<tr>
<td>Shearing</td>
<td>1.00</td>
<td>0.15</td>
</tr>
</tbody>
</table>

### 1.2 Statistical Parameters Of Resistance Of Structural Members

Considering the indeterminateness of the calculation mode, the resistance of structural members is figured out using Equation (2):

$$R(t) = K_p R_p(t)$$

Where, $R(t)$ is the random process of resistance; $K_p$ is the random variable of indeterminateness of the calculation mode; $R_p(t)$ is the calculated resistance of structural members. Obviously, the key of establishing the random process model of structure resistance is to determine the mean function and the standard deviation function of resistance. The standard deviation of resistance is figured out using the error propagation formula:

$$\sigma_{R_p} = \left\{ \sum_i \left( \frac{\partial R}{\partial X_i} \right)^2 \sigma^2_{X_i} \right\}^{\frac{1}{2}}$$

Where, $X_i$ is the random variable of $R_p$, and $\frac{\partial R}{\partial X_i}$ is the value of the partial derivative from the mean value.

According to the above method, Table II shows statistical parameters $K_p$ and $\delta_p$ of resistance of reinforced concrete members under unstressed state. Other than axial tension members, the mean value of resistance of structural members under other stress states decreases in different degrees compared with the statistical values in the 1970s and 1980s, while the variation increased sharply.
TABLE II. STATISTICAL PARAMETERS OF RESISTANCE $R$ OF REINFORCED CONCRETE STRUCTURAL MEMBERS.

<table>
<thead>
<tr>
<th>Stress state</th>
<th>89 Code</th>
<th>Analysis result of measured data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$K_R$</td>
<td>$\delta_R$</td>
</tr>
<tr>
<td>Axial tension</td>
<td>1.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Axial compression</td>
<td>1.33</td>
<td>0.17</td>
</tr>
<tr>
<td>Micro-excentral compression (short column)</td>
<td>1.30</td>
<td>0.15</td>
</tr>
<tr>
<td>Macro-excentral compression (short column)</td>
<td>1.16</td>
<td>0.13</td>
</tr>
<tr>
<td>Bending</td>
<td>1.13</td>
<td>0.10</td>
</tr>
<tr>
<td>Shearing</td>
<td>1.24</td>
<td>0.19</td>
</tr>
</tbody>
</table>

2 STATISTICAL PARAMETERS OF LOAD OF RESIDENTIAL BUILDINGS

[4] shows the proposed value of the standard floor live load value of a design reference period of 50 years (1.6 kN/m²) and 100 years (1.92 kN/m²). Table III shows major statistical parameters of residential structure load, $K$ is the ratio between the average load value and the standard value.

Table III. STATISTICAL PARAMETERS OF LOAD OF RESIDENTIAL BUILDINGS.

<table>
<thead>
<tr>
<th>Type of load</th>
<th>$\mu$</th>
<th>$\sigma$</th>
<th>$K_G$ or $K_O$</th>
<th>$\delta_G$ or $\delta_O$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead load (load code[5])</td>
<td>―</td>
<td>―</td>
<td>1.060</td>
<td>0.070</td>
</tr>
<tr>
<td>Floor live load of residential building</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0 (normal load value)</td>
<td>1.288</td>
<td>0.300</td>
<td>0.644</td>
<td>0.233</td>
</tr>
<tr>
<td>1.6 (50 years of design reference period)</td>
<td>1.100</td>
<td>0.292</td>
<td>0.688</td>
<td>0.265</td>
</tr>
<tr>
<td>1.92 (60 years of design reference period)</td>
<td>1.224</td>
<td>0.292</td>
<td>0.638</td>
<td>0.238</td>
</tr>
</tbody>
</table>

3 INFLUENCES OF THE VALUE OF FLOOR LIVE LOAD UPON THE RELIABILITY OF RESIDENTIAL STRUCTURE

Generally, dead load+ floor live load is the loading combination of residential structure. The floor live load is random in space and the value seriously affects the reliability index of the residential structure. Influences of the reliability of the residential structure are analyzed with different values of the floor live load.
The structural design is expressed using Equation [5]

\[ \gamma_0 (\gamma_G S_G + \gamma_Q S_Q) \leq R / \gamma_R \]  

(4)

Where, \( \gamma_0 \) is structural importance factor, \( \gamma_G \) is the dead load partial factor, \( S_G \) is the standard value effect of dead load, \( \gamma_Q \) is the partial factor of floor live load, \( S_Q \) is the standard value effect of floor live load, \( R \) is the standard value of structure resistance, and \( \gamma_R \) is the partial factor of resistance.

When the ratio \( \rho = S_G / S_Q \) between the standard value effect of the variable load and that of the dead load changes, the value of reliability index \( \beta \) changes. If \( \rho \) is fixed, the absolute value of the load effect does not affect \( \beta \). Therefore, the specific design value is not required in the analysis of \( \beta \), various stress states in practical projects can be summarized with the ratio of the load effect \( \rho \) as the variable parameter.

As per the standard value of the floor live load of residential buildings 1.60 kN/m2 and 1.92 kN/m2 respectively in a design reference period of 50 years and 100 years given in [1], and that in existing load codes 2.0 kN/m2, \( \beta \) corresponding to \( \rho \) of 14 basic members and all load values is calculated, the mean value is the reliability index of each member. The computed results show that the mean value of \( \beta \) of ductile failure members is higher than the target reliability index of ductility, while that of brittle failure members is higher than the target reliability index of brittleness; the standard value of the floor live load directly affects the reliability level of structure. As for the floor live load in a design reference period of 50 years, the proposed value 1.60 kN/m2 can meet the requirements of the target reliability index, and the reliability index obtained is much higher than the target value.

### 4 RELIABILITY ANALYSIS OF REINFORCED CONCRETE BENDING MEMBERS

Bending members are major stressed members in concrete structure, damages will result in serious consequences. The reliability of residential structures is analyzed below with reinforced concrete bending member as an example.

[1] shows a random model of the resistance of reinforced concrete bending members, it’s visible that attenuation laws of resistance increase shortly and then decreases.

According to Code for Concrete Structure Design, the bending capacity of single reinforced concrete beam can be expressed using Equation[6].
\[ R = K_p R_p = K_p f_y A h_0 [1 - \frac{\xi}{2}] = \frac{\gamma_0 (1.2 + 1.4 \rho)}{1 + \rho} \] (5)

As per the normative design structure, the reliability is independent of specific load value. According to the relation among the design value, the standard value and the mean value, the design can be translated into the mean value using Equation[7]:

\[ \mu_{f_y} = \frac{\gamma_s f_y}{1 - 1.625 \delta_{f_y}} \] (6)

In case that \(1 - \frac{\xi}{2}\) is fixed, the mean value and variable coefficient of resistance are figured out using Equation (7) and (8)

\[ \mu_R = \mu_{K_x} \mu_{f_y} \mu_{\lambda} \mu_{h_0} \left(1 - \frac{\xi}{2}\right) = \frac{\mu_{K_x} \mu_{h_0} \gamma_s (1.2 + 1.4 \rho)}{\left(1 - 1.645 \delta_{f_y}\right)(1 + \rho)} \] (7)

\[ \delta^2_R = \delta^2_{K_x} + \delta^2_{f_y} + \delta^2_{\lambda} + \delta^2_{h_0} \] (8)

The reliability of reinforced concrete bending members is calculated according to calculating parameters of resistance and statistical parameters given in Table IV, the results are shown in Table V.

**TABLE IV. CALCULATING PARAMETERS OF REINFORCED CONCRETE BENDING MEMBERS.**

<table>
<thead>
<tr>
<th>Computing method</th>
<th>HRB335 rebar</th>
<th>Steel area</th>
<th>Effective depth of section</th>
<th>Calculation mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Variable coefficient</td>
<td>Variable coefficient</td>
<td>Mean value multiple</td>
<td>Variable coefficient</td>
</tr>
<tr>
<td>Concrete code [3]</td>
<td>0.07</td>
<td>0.03</td>
<td>1.00</td>
<td>0.02</td>
</tr>
<tr>
<td>Actual measurement</td>
<td>0.04</td>
<td>0.03</td>
<td>0.96</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Table V shows that the reliability of bending member which is calculated according to the resistance obtained from investigation and statistics is obviously lower than that of normative design members due to differences between construction quality and design, as a result, the actual reliability of residential structures fail to reach the designed value.

5 CONCLUSIONS

(1) Different values of floor live load of residential buildings pose great influences upon the structure reliability analysis; the higher the value is, the higher the reliability index and the structure reliability level are.

(2) The structure resistance is lower than the design resistance as a result of construction quality, and the reliability level of reinforced concrete bending members is far lower than the target value. Thus, improving the construction quality is an important measure to guarantee the design reliability and safety of structure.

REFERENCES