ABSTRACT

Recommendations for Limit State Design (LSD) published by Architectural Institute of Japan (AIJ) last year demonstrate that the target reliability, which is a basis for determining design criteria, depends upon users’ choice. However, it is difficult to determine how much performance levels should be set. Code calibration is one of the acceptable ways to set target reliability levels for multi-performance (limit states) of buildings. It can maintain the continuity of old and new design codes, and social acceptability of existing buildings’ performance level. In this context, the paper presents how to calibrate the existing design codes in Japan and to discuss the target reliability levels. For some of combined load cases, code calibration of existing structural design codes in Japan will be implemented in the paper and reliability indexes which the existing codes implicitly require will be shown, and finally the results are expected to be fully utilized for the AIJ LSD of buildings.

INTRODUCTION AND BACKGROUND

With development of the design methods, Limit State Design (LSD) based on the probabilistic analysis has been gradually accepted by practitioners. Recommendations for LSD published by AIJ in Japan last year, indeed, have made the great step for practical use of LSD of buildings in Japan. The recommendations suggest that the target reliability depends on users to make the design more flexible (AIJ 2002).

How to set the target reliability for various limit states is, however, now a central issue. There is no reference value for the target levels. Code calibration of existing design codes, which has been adopted in the US and EU in the past when the new design method was
developed, is an effective and reasonable way. Therefore, this paper illustrates how to calibrate the existing design codes which prevails in Japan and demonstrates calibration results.

REVIEW OF TARGET RELIABILITY INDEX OF CURRENT LSD IN VARIOUS COUNTRIES

For LSD, it is necessary to specify target reliability index. As reference for practitioners, Table 1 gives a brief review and comparison of target reliability indexes of current LSD in various countries. The data in Japan is for the limit state design of steel frame (AIJ 2002).

<table>
<thead>
<tr>
<th>Country</th>
<th>Target reliability Index of ULS</th>
<th>Target reliability Index of SLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>US(Galambos 1982)</td>
<td>2.0-3.0 in 50 years</td>
<td></td>
</tr>
<tr>
<td>EU(EUROCODE 1 1993)</td>
<td>3.8-4.7 in 50 years</td>
<td>1.5—3.0 in 1 year</td>
</tr>
<tr>
<td>China(MCC 2002)</td>
<td>2.7-4.2 in 50 years</td>
<td>0—1.5 in 1 year</td>
</tr>
<tr>
<td>Japan(AIJ 2002)</td>
<td>1.5-2.5 in 50 years</td>
<td>1.1—2.0 in 1 year</td>
</tr>
</tbody>
</table>

METHOD FOR CODE CALIBRATION

The process of evaluating reliability index required by existing design codes is called code calibration (Pinkham 1978). It is one of the acceptable ways to set the target reliability levels for multi-performance (limit states) of buildings. With the calibration to the existing building, the distribution of reliability indices will be obtained. This is the purpose of the current study and is included the calibration of the members and elements (beams, columns, walls, connections) of different structural types under selected load combinations. Then the value of reliability indices can be recommended for different structural types such as RC, steel, tall buildings or low rise buildings etc.

Suppose the load combination is \( D_n + L_n + E_n \), and \( R_n \) is resistance, as an illustration example, when \( D_n, L_n \) and \( E_n \) respectively denote load effects for dead load, live load and seismic load. The seismic load effect is taken as a principal load effect, while others are regarded as secondary load effects. Here, Turkstra’s empirical law is adopted. The design equations of limit state of Allowable State Design (ASD) and LSD are respectively written as:

\[
\frac{R}{\nu} \geq D_s + L_s + E_s \quad (1)
\]

\[
\phi R_s \geq \gamma_D D_s + \gamma_L L_s + \gamma_E E_s \quad (2)
\]

where \( \phi \) is a safety factor used in ASD, \( \phi, \gamma_i \) are, respectively, the resistance and load factors in LSD, subscript \( n \) denotes a nominal value of load effect. Then taking the sign of equality in Eq.1 and substituting \( R_n \) in the Eq. 1 into Eq. 2, and dividing two sides by \( D_n \), the following equation is obtained:
The above equation implies that a member section with $R_n$ which is designed according to the ASD requirement (equality in Eq. 1 is assumed) is related to the LSD requirement. Since the resistance as well as load factors, namely $\gamma_i$, are related to a reliability index, it is possible to find the reliability index required by the ASD together with the corresponding load and resistance factors from Eq. 3. This equation can be solved with respect to the reliability index because the nominal load effect $D_n$, $L_n$, and $E_n$ and a safety factor $\phi$ are already given in the ASD format.

Let $\kappa_i = \mu_e / \mu_p$, $\kappa_e = \mu_e / \mu_p$, and $b_o = D_o / \mu_D$, $b_i = L_o / \mu_L$, $b_e = E_n / \mu_E$. The following equation can be solved with respect to a reliability index which the ASD requires.

$$\phi v(1 + \frac{L}{D} + \frac{E}{D}) = \gamma_o + \gamma_i \frac{L}{D} + \gamma_e \frac{E}{D}$$

(3)

where $\gamma_X$ represents the mean value ratio of the load effect $X$ to the dead load effect, and $b_X$ represents the ratio of a nominal value to the mean value of each load effect $X$. The process for finding reliability index will include the following steps.

1. **The first step**, we have to specify distributions of all load and resistance available in the existing standards or literatures. This step must be done once for various structural types and load combinations. Then they are all approximated into statistical values of logarithmic distributions according to the AIJ recommendation. At this step, the each load effect by structural analysis is derived.

2. **The second step**, after the preparation in the first step, computed are all the separation factors and load and resistance factors which are the function of reliability index. As we can see, the Eq. 4 only includes the variables of safety factor $\phi$ and reliability index $\phi$. Solving Eq. 4 with the prespecified safety factor $\phi$, reliability index can be obtained. The approximate but practically accurate procedure for the separation factors, load and resistance factors as functions of the reliability index has been proposed in the recent literature (Mori et al, 2002) and has been adopted in AIJ-LSD recommendations.

Finally, we can find the reliability indices under different load combinations that characterize the level of reliability inherent to the current design practice.

RESULTS OF CODE CALIBRATION

In the following two examples, beams of standard floor and roof are checked under the conditions of Ultimate Limit State (ULS) and Serviceability Limit State (SLS). The flexure moment of the beam is selected as load effect here. Load combination $D_n+L_n$ and $D_n+L_n+E_n$ are taken. For load combination $D_n+L_n$, $L_n$ (extraordinary live load $L_e$) is the principal load effect, while $D_n$ (dead load) is the secondary load effect. As to the case of $D_n+L_n+E_n$, $E_n$ (earthquake load) is the principal load effect, while $D_n$ (dead load) and (sustained live load $L_s$) are the secondary load effects. For the case of ULS, the 50-year maxima of the load intensity is used to characterize the principal load, while the annual maxima of the load intensity is used to characterize the secondary loads. For the case of SLS, the annual maxima of the load intensity is
used for both principal and secondary loads.

Building Frames for Calibration

The example of a RC structure is taken from appendix 2 attached in Standard for Structural Calculation of Reinforced Concrete Structures (AIJ,1988). It is a 3-story office building located in Tokyo. The analyzed beams are G9 and RG9 which locate in the 2nd floor and roof respectively. Figure 1 shows the flexure moments of beams G9 and RG9, under the dead load, live load and earthquake load.

![Fig. 1. Flexure Moments of Beam G9 and RG9 under Dead, Live and Earthquake Load](image)

The example of a steel structure is taken from Limit State Design of Steel Frames (AIJ, 2002). It is a 9-story office building with one story basement in Osaka. The beams to be analyzed are G2 and RG2 which locate in the 3rd floor and roof respectively. Figure 2 shows the flexure moments of beams G2 and RG2, under the dead, load live load and earthquake load.

![Fig. 2. Flexure Moments of Beam G2 and RG2 under Dead, Live and Earthquake Load](image)
Statistical properties on both structural resistance and load variables are required in order to develop probability-based design criteria. The statistical information required is the probability distribution of each load and resistance variable and estimates of its mean and coefficient of variation (COV). According to the recommendations (AIJ, 2002), summary of statistical data of resistance is listed in Table 2, and Table 3 gives the statistical data of loads that are adopted in this paper.

Table 2. Summary of Statistical Data for Resistance

<table>
<thead>
<tr>
<th>Designation</th>
<th>$\frac{\mu_s}{S_n}$</th>
<th>$V_R$ (COV)</th>
<th>Probability Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinforced Concrete, Flexure</td>
<td>ULS 1.26, 0.11</td>
<td>Log-Normal</td>
<td></td>
</tr>
<tr>
<td>SLS 1.20, 0.11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel, Flexure</td>
<td>1.25</td>
<td>0.07</td>
<td>Log-Normal</td>
</tr>
</tbody>
</table>

Table 3. Summary of Statistical Data for Loads

<table>
<thead>
<tr>
<th>Load</th>
<th>$\frac{\mu_s}{S_n}$</th>
<th>$V$ (COV)</th>
<th>Probability Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D$</td>
<td>1.0</td>
<td>0.1</td>
<td>Gauss</td>
</tr>
<tr>
<td>$L_e$</td>
<td>0.45</td>
<td>0.8</td>
<td>Gumbel</td>
</tr>
<tr>
<td>$L_s$</td>
<td>0.45</td>
<td>0.4</td>
<td>Log-Normal</td>
</tr>
<tr>
<td>$E$</td>
<td>0.16</td>
<td>0.85</td>
<td>Fréchet</td>
</tr>
</tbody>
</table>

Example of RC Beam

The reliability indices of beam G9 and RG9 are found, under the two limit states, ULS and SLS.

Load combination of $D_n+L_{n}$

The nominal ratio of dead to live load is 0.3 and 0.2 for G9 and RG9 respectively. Following the calibration process, the curves of reliability indices varying with the safety factor for ULS and SLS, which are shown in Figure 3, is obtained. It shows that reliability index increases with the safety factor as used in the traditional design (such as ASD). For both USL and SLS, reliability index with low $L_n/D_n$ (0.2 for RG9) is larger than that with high $L_n/D_n$ (0.3 for G9). It is attributed to that the dead load with the smaller COV comparing to live load is dominant. It shows that reliability index of SLS is larger than that of ULS. Note that $\theta$ in LSD is measured for 50 years while $\theta$ in SLS for 1 year.

Figure 4 shows the relationships between the reliability index and $L_n/D_n$ for ULS with different safety factors. It shows that reliability index decreases with the increasing of $L_n/D_n$. Reliability index of ULS ($\theta$ = 1.0) ranges from 0.8 to 1.0 when $L_n/D_n$ varies from 0.3 to 0.2. For the case of SLS, the relationships is similar, while reliability index ($\theta$ = 1.5 for SLS) ranges from 4.3 to 4.1.
Load combination of $D_n+L_n+E_n$. The curves of reliability indices varying with $E_n/D_n$ for ULS and SLS, are shown in Figure 5. For ULS the safety factor is set to 1.0, while it is set to 1.5 for SLS according to the recommendations. From Fig. 5, it can be seen that the curve is almost the same for G9 and RG9 under ULS or SLS. Because for the load combination $D_n+L_n+E_n$, $E_n$ is the principal load, $\beta$ is insensitive to $L_n/D_n$. The reliability indexes of SLS are larger than those of ULS, similar to the case of load combination $D_n+L_n$.

Example of Steel Beam

The reliability indices of beam G2 and RG2 are also found, under the two limit states, ULS and SLS.

Load combination of $D_n+L_n$. The nominal ratio of the dead to the live load is 0.5 and 0.2 for G2 and RG2 respectively. Following the calibration process, the curves of reliability indices varying with safety factor for ULS and SLS, which are shown in Figure 6, is obtained. It shows that reliability index increases with the safety factor as used in the traditional design. For both USL and SLS, reliability index with low $L_n/D_n$ (0.2 for RG2) is larger than that with high $L_n/D_n$ (0.5 for G2). It is attributed to that the dead load with the smaller COV comparing to live load is
dominant. It can be seen that reliability index of SLS is larger than that of ULS from Fig. 6. Note that in LSD is measured for 50 years while in SLS for 1 year.

Figure 7 shows the relationships between reliability and $\frac{L_n}{D_n}$ under ULS with different safety factors. It shows that reliability index decreases with the increasing of $\frac{L_n}{D_n}$. Reliability index of ULS ($\sigma=1.2$) ranges from 2.7 to 1.8 when $\frac{L_n}{D_n}$ varies from 0.5 to 0.2. For the case of SLS, the relationship is similar, while reliability index ($\sigma=1.0$ for SLS) ranges from 2.6 to 2.4.

![Fig. 6. $\sigma$ vs. $\sigma$](image)

![Fig. 7. $\sigma$-L$_n$/D$_n$](image)

Load combination of $D_n+L_n+E_n$. Following the calibration process, the curves of reliability indices varying with $\frac{L_n}{D_n}$ for ULS and SLS, which are shown in Figure 8, is obtained. For ULS the safety factor is set as 1.2, while it is set as 1.0 for SLS according to the recommendations. From Figure 8, it can be seen that the curve is almost the same for G2 and RG2 under ULS or SLS. Because for the load combination $D_n+L_n+E_n$, $E_n$ is principal load, $\sigma$ is insensitive to $\frac{L_n}{D_n}$. The reliability indexes of SLS are larger than those of ULS, similar to the case of load combination $D_n+L_n$.

![Fig. 8. $\sigma$-E$_n$/D$_n$](image)

The results for RC and Steel, is almost similar, as we can see from the above. However, they are slightly different, as discussed in the following.

Discussion
Load combination of $D_n + L_n$ The nominal ratio of the dead load to the live load $D_n + L_n$ is 0.2 and 0.2 for RG9 (RC) and RG2 (S) respectively.

In the above examples, the reliability indexes of both RC beam and steel beam are increases with the safety factor. However, the reliability index of steel beam (RG2) is larger than that of RC beam (RG9), although $L_n/D_n$ is almost the same. The curves of the relationship between the safety factor and reliability index for the RC beam and steel beam are shown in Figure 9. Figure 10 shows the curve of $\beta$ vs. $L_n/D_n$. It is partly because of the COV of resistance for steel is smaller than that of RC.

![Figure 9](image1.png) \hspace{1cm} ![Figure 10](image2.png)

Load combination of $D_n + L_n + E_n$ Figure 11 shows the curve of $\beta$ vs. $E_n/D_n$ for both RC beam and steel beam under ULS. Both of curves become constant with the increase of $E_n/D_n$. However, reliability index of steel beam is larger than that of RC beam. It is because in the existing design for RC, the safety factor is set to 1.0 under ULS, while it is set to 1.2 for steel structure.

![Figure 11](image3.png)

Figure 12 shows the curve of $\beta$ vs. $E_n/D_n$ for both the RC beam and the steel beam under SLS. On the contrary to the result of ULS, reliability index of steel beam is smaller than that RC beam. It is because in the existing design for RC, the safety factor is set to 1.5 under SLS, while
it is set to 1.0 for steel structure.

![Graph](attachment:image.png)

**Fig. 12.** \( \beta \) vs. \( E_n/D_n \) for SLS

**CONCLUSIONS AND FURTHER STUDY**

This paper is intended to give a brief review of code calibration and describes a reliability analysis procedure for developing probability based design criteria in Japan. As we can see from the above examples, target reliabilities may be established by reviewing the levels of reliability inherent to those existing standards which have resulted in the past as day-to-day design practice. The examination of reliabilities of existing design criteria indicates that the reliability varies according to materials, member types, and failure modes, and load combinations. The major difference between the conventional ASD and probability-based LSD adopting the load and resistance factors lies in the theory and the way of reasoning. The probability-based limit state design philosophy has a number of advantages over traditional ASD, while ASD is relatively simple, a constant level of reliability is not achieved for different set of values of the same loads because the same factor of safety is applied to both permanent and time-varying loads. Moreover, the allowable stress format may be unsafe when load effects counteract one another.

It has become apparent that it would be highly desirable to establish a more unified strategy of design for all materials and more specifically (Ellingwood et al. 1982)

From the above two examples of code calibration, the following conclusion can be obtained.

1. Reliability indexes of both RC beam and steel beam under SLS are larger than that of ULS with the same load combination. For load combination \( D_n + L_n \), reliability indexes increase with safety factor, while decrease with the increasing of \( L_n / D_n \). For load combination \( D_n + L_n + E_n \), reliability indexes decrease with the increasing of \( E_n / D_n \), and become constant.

2. For RC beam, reliability indexes range from 0.8 to 1.0 with \( L_n / D_n \) varying from 0.3 to 0.2 under ULS for load combination \( D_n + L_n \) (safety factor is 1.0), while they range from 4.3 to 4.1 under SLS (safety factor is 1.5). Reliability indexes range from 1.2 to 2.0 ULS for load combination \( D_n + L_n + E_n \) (safety factor is 1.0), while they range from 3.3 to 5.7 under SLS (safety factor is 1.5).
3. For steel beam, reliability indexes range from 1.8 to 2.7 with $L_n/D_n$ varying from 0.2 to 0.5 under ULS for load combination $D_n+L_n$ (safety factor is 1.2), while they range from 2.4 to 2.6 under SLS (safety factor is 1.0). Reliability indexes range from 1.5 to 2.5 ULS for load combination $D_n+L_n+E_n$ (safety factor is 1.2), while they range from 2.8 to 4.4 under SLS (safety factor is 1.0).

4. Reliability indexes of steel beam for both ULS and SLS are larger than those of RC beam under load combination $D_n+L_n$, while it is difference under load combination $D_n+L_n+E_n$. that is, reliability indexes of steel beam are larger than those of RC beam for ULS, while it is contrary for SLS.

To implement the LSD in Japan, it is necessary to calibrate the existing building designed by existing codes. With the code calibration, we can maintain the continuity of old and new design codes for practitioners, and social acceptability of exiting buildings’ safety. For the further study, it is necessary to study where these reliabilities are in current design and where they are likely to fall, in order to perform the necessary calculations leading to a coordinated set of specific load factor values.

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