Cho *et al. Int J Concr Struct Mater* (2023) 17:12
https://doi.org/10.1186/s40069-022-00571-3

International Journal of Concrete Structures and Materials

RESEARCH Open Access

Structural Safety Inspection of Reinforced Concrete Structures Considering Failure Probabilities of Structural Members

Hae-Chang Cho[1], Sang-Hoon Lee[2], Seung-Ho Choi[3], Seong-Tae Yi[4], Won-Hee Kang[5] and Kang Su Kim[2*]

Abstract

Regular safety inspections of existing reinforced concrete (RC) structures are required according to the regulations and criteria set by each country. In South Korea, the safety inspection regulations provided by the Korea Infrastructure Safety and Technology Corporation (KISTEC) are followed. These regulations were developed based on fuzzy theory to avoid subjective decisions, and provide standardized deterioration grades for member types, floors, and the entire structure. However, the safety inspection regulation by the KISTEC often provides unconservative evaluation results. In particular, as the importance factors of beam and slab members are set lower than those of other members, there are cases in which deteriorations occurring in beams and slabs are not properly reflected in the floor level evaluation. In this study, to overcome such limitations, case studies were carried out and modified importance factors for structural member types were proposed considering the failure probabilities of each member type based on the reliability theory. The importance modification factor was calculated based on the strength ratio of structural members so that the more dangerous the members are, the more impact they give on the evaluation. Overall, compared to the KISTEC method, the proposed method provided conservative but practical assessment results, and it was found that the proposed importance factors can be very useful to properly reflect the effects of damaged members on the deterioration status evaluation of the floors and the entire structure.

Keywords: RC structure, Safety inspection, Structural reliability theory, Reliability index, Failure probability

1 Introduction

Reinforced concrete (RC) structures degrade over time due to various physical and environmental factors, and they need to be inspected regularly to avoid undesired consequences (KISTEC, 2009). In South Korea, the Korea Infrastructure Safety and Technology Corporation (KISTEC) mandates precision safety inspections of RC structures at least once every four to six years, according to the Safety for Infrastructure and Maintenance Plan, Notification (Ministry of Construction & Transportation of Korea, 2008). Generally, the inspection of an RC structure is carried out as a survey subject to the personal experience of an inspector, and it is difficult to find a systematic method from the literature. The only information found is the inspection method for RC structures provided by KISTEC, which was developed based on the study by Kim et al. (Kim et al., 2006). This method was developed to minimize the subjectivity of inspections and to provide standardized inspection grades considering structural safety and functionality (KISTEC, 2009). In this method, individual structural members are assigned evaluation grades between grades A (the best condition) to E (the collapse risk level), and importance factors are assigned to each of the 5 structural member types: walls, columns, girders, beams, and slabs. Importance factors

---

Journal information: ISSN 1976-0485 / eISSN 2234-1315

*Correspondence: kangkim@uos.ac.kr

[2] Department of Architectural Engineering and Smart City Interdisciplinary Major Program, University of Seoul, 163 Siripdaero, Dongdaemun-Gu, Seoul 130-743, South Korea
Full list of author information is available at the end of the article

are used to assign weights to each structural member type when obtaining the expected inspection grades of the floors and the entire structure. However, this method often provides unconservative evaluation results because the importance of slabs and beams among the member components is set lower than those of other members, that is, walls = 0.9, columns = 0.9, girders = 0.7, beams = 0.5, and slabs = 0.3. For example, even if the grades of slabs and beams are evaluated as risky levels, such as D or E, the overall grade of the whole floor or structure could be evaluated as B or C, due to the low importance assigned to the beams and slabs.

Additionally, unreasonable results can be obtained due to neglected load combinations. The inspection grade of a structural member type is determined using the ratio of the resistance of the member to the load applied on the member, and the safety inspection grade is weighted using the importance factor while evaluating the inspection grade of the entire structure. The importance factors provided by KISTEC were determined for a standard structure, and their values were proportional to the area of the load borne by the member. However, load combinations were not considered in this calculation. Since the loads acting on a structure have uncertainties, and non-dead loads, such as live loads, wind loads, and snow loads, have greater uncertainties than a dead load, RC structures experiencing relatively greater live loads compared to dead loads could yield unconservative inspection results.

Therefore, in this study, a structural reliability-based inspection method was proposed to overcome the limitations of safety inspection regulations developed by KISTEC. In this method, the failure probabilities of the members were calculated based on the applied load and resistance strength of the members, and modification factors for the importance factors of the members were proposed. Furthermore, the safety inspection of an RC moment resisting frame building was performed using the proposed method, and the rationality of the proposed method was demonstrated in comparison with the evaluation results obtained from the existing method.

2 Review of Korea Infrastructure Safety Corporation (KISTEC) Inspection Method

Concrete structures should have adequate durability performance during their intended service life, for which many design codes present durability evaluation methods or safety inspection methods. Japan Society of Civil Engineers (JSCE, 2007) provides a maintenance procedure consisting of inspection, deterioration prediction, evaluation, judgment, remedial measures, and recording. Public Works Department (PWD, 2013) provides a five-point color-coded building rating relating to the defects. Central Public Work Department (CPWD, 2002) has classes of damage and repair classification that are subdivided into five classes. Hong Kong Institute of Surveyors (Ho & Yiu, 2013) provides a list of defects that are categorized according to elements, such as surface durability, structural performance, fire safety, and drainage system. The inspection method of Building and Construction Authority (BCA, 2012) consists of two procedures which are visual inspection and full structural investigation. The inspection method for RC structures provided by KISTEC aims to minimize the subjectivity of the inspection that could be caused by an inspector, by introducing fuzzy theory (Zadeh, 1965) in its framework to effectively evaluate the safety status of a structure. Fuzzy theory has often been utilized to correlate data that are difficult to quantify, such as language variables, or to solve complex mechanisms that are difficult to analyze numerically. In civil engineering, it has been applied to the assessment of structures, fire inspection, and crack diagnosis (Cho et al., 2015, 2016, 2017a, 2017b; Kim et al., 2007). As shown in Table 1, the KISTEC inspection method consists of three inspection categories: (i) structural safety, (ii) condition and durability, and (iii) displacement and deformation, and each category has inspection items. The grade is calculated under each item, and used to derive a comprehensive grade. In the structural safety inspection, the grade of a structural member is determined using the strength ratio (= design strength (ϕR_n) / ultimate limit state load (Q_u)), based on the structural analysis results, and the grade of a floor is determined by calculating the expected value based on the importance of the members shown in Table 2 and Table 3 where the expected value can be determined through the Sugeno fuzzy measure and Choquet fuzzy integral (Choquet, 1954; Grabisch et al., 2010). Fuzzy measure is a theory that is used in the measure theory (Frank, 2001; Grabisch et al., 2010) when the additivity is not satisfied, and it has been developed

Table 1 Inspection items for RC structures (KISTEC 2009)

Inspection	Inspection item
Structural safety	Member strength
Condition and durability	Concrete compressive strength, member size
	Steel bar spacing, Cover depth
	Crack width
	Concrete carbonation depth
	Steel corrosion
	Chloride ion concentration
	Concrete core test
Displacement and deformation	Horizontal displacement
	Differential settlement

Table 2 Evaluation grades based on ratio of measured to designed member strength (KISTEC 2009)

Grade	Ranges of grades	Evaluation score
A	$SR \geq 100\%$ (in perfect condition)	1
B	$SR \geq 100\%$ (with slight damage)	3
C	$85\% \leq SR < 100\%$	5
D	$70\% \leq SR < 85\%$	7
E	$SR < 70\%$	9

SR = design strength (φR_n) / ultimate limit state load (Q_u)

Table 3 Weight factor of importance for RC frame structures (KISTEC 2009)

Members	Weight factor of importance
Column	0.9
Wall	0.9
Girder	0.7
Beam	0.5
Slab	0.3

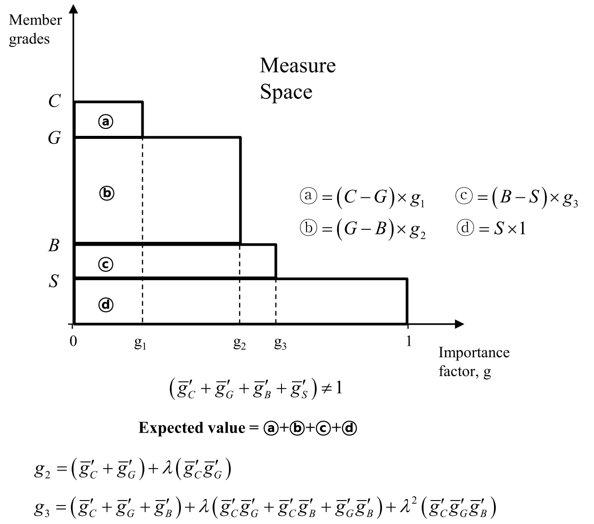


Fig. 1 Choquet integral

to measure the fuzzy set (Zadeh, 1965). Generally, in statistics, the sum of all expected values should be 1.0, but in the fuzzy measure space, the sum of the expected values is often not 1.0. Therefore, KISTEC uses the Sugeno fuzzy measure, which is a method that can artificially calculate the sum of expected values to be equal to 1.0, using λ-factors. When a structure consists of the following member types––columns (C), girders (G), beams (B), and slabs (S), the sum of the measure values, $g(C \cup G \cup B \cup S)$, can be expressed as follows:

$$\begin{aligned} g(C \cup G \cup B \cup S) = & g(C) + g(G) + g(B) + g(S) \\ & + \lambda\big(g(C)g(G) + g(C)g(B) + g(C)g(S) + g(G)g(B) + g(G)g(S) + g(B)g(S)\big) \\ & + \lambda^2\big(g(C)g(G)g(B) + g(C)g(G)g(S) + g(C)g(B)g(S) + g(G)g(B)g(S)\big) \\ & + \lambda^3\big(g(C)g(G)g(B)g(S)\big) \end{aligned} \tag{1}$$

where $g(C)$, $g(G)$, $g(B)$, and $g(S)$ are the importance factors of the columns, girders, beams, and slabs, respectively. KISTEC presents these values as fixed values of 0.9, 0.7, 0.5, and 0.3, respectively. Using these values and Eq. (1), λ is calculated as -0.988. The expected value can be calculated using an integral in the measure space. Although the Lebesgue integral (Frank, 2001) is used in a probability measure, it is not available in the fuzzy measure as it can only be used when additivity is satisfied, that is, the summation is 1.0. Choquet (Choquet, 1954) modified the Lebesgue integral and suggested a Choquet integral for the case where the additivity is not satisfied. KISTEC also used the Choquet integral to calculate the expected value. The Choquet integral is calculated by summing the subdivided areas along the y-axis in the measure space, as shown in Fig. 1. The distances along the x-axis that do not satisfy additivity, that is, the distance between 0 and g_2, and the distance between 0 and g_3, can be calculated using λ. The calculated expected value becomes the inspection result.

The inspection grade of the entire structure is calculated using the inspection grade of each floor, and the importance factor assigned to the floor. The detailed guidelines in the KISTEC regulations provide the following floor-specific importance factor (ζ):

$$\zeta = \frac{N - (n - 1)}{N}, \tag{2}$$

where N is the total number of floors in the structure, including the basement floors, and n is the corresponding floor number of the basement floors. The inspection grade of the entire structure can then be calculated using the Sugeno fuzzy measure, and the Choquet fuzzy integral.

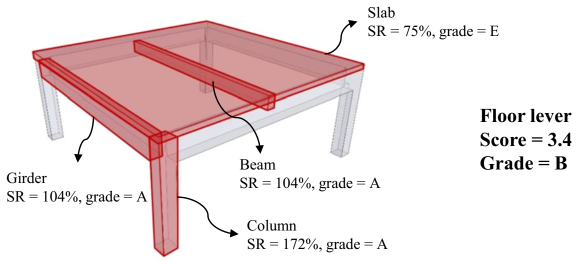
Table 4 Safety evaluation scores and grades from sample floors

Member grade				Floor level		Member grade				Floor level	
Column	Girder	Beam	Slab	Score	Grade	Column	Girder	Beam	Slab	Score	Grade
A	A	A	E	3.40	B	A	C	B	E	5.59	C
A	A	B	E	4.10	C	A	C	C	E	5.59	C
A	A	C	E	4.81	C	B	A	A	E	4.67	C
A	A	D	E	5.51	C	B	A	B	E	4.74	C
A	A	E	A	5.00	C	B	A	C	E	5.45	C
A	A	E	B	5.30	C	B	A	E	A	5.91	C
A	A	E	C	5.61	C	B	A	E	B	5.94	C
A	A	E	D	5.91	C	B	B	A	E	4.78	C
A	B	A	E	4.39	C	B	B	B	E	4.80	C
A	B	B	E	4.60	C	B	B	C	E	5.50	C
A	B	C	E	5.31	C	B	B	E	A	5.99	C
A	B	E	A	5.71	C	B	C	A	E	5.76	C
A	B	E	B	5.80	C	B	C	B	E	5.79	C
A	C	A	E	5.37	C	C	A	A	E	5.93	C

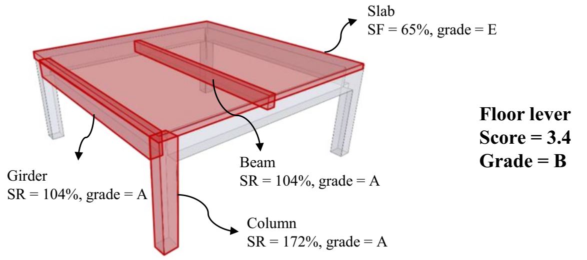
2.1 Limitations in the Inspection Method Suggested by KISTEC

To illustrate the limitations of the inspection method in the *Safety Inspection and Precise Safety Diagnosis: Detailed Guideline* provided by KISTEC, in this study, the floor inspection grades for a total of 625 combinations were calculated considering all possible grades from A to E, for each of the structural member types, that is, columns, girders, beams, and slabs.

Table 4 lists the results of 28 cases selected out of the 625 cases, where the individual member grades were unreasonably reflected in the floor grade. When the grades of column, girder, beam, and slab are A, A, A, and E, the scores can be calculated as 1, 1, 1, and 9, respectively, according to the KISTEC method presented in Table 2. In addition, from Table 3, the importance factors can be calculated as 0.9, 0.7, 0.5, and 0.3, respectively. Then, the score of floor level consisting of the column, girder, beam, and slab can be calculated as 3.40, based on λ and Choquet integral as shown in Fig. 1. Here, λ is determined through a fuzzy measure. The safety diagnosis method of KISTEC uses fixed values for the importance factors, as mentioned earlier, and the importance factors of beams and slabs are relatively low compared to those of columns and girders. Even when the grades of slabs or beams were E (risky condition, approaching collapse due to significant degradation in the member resistance), the floor grade was rated as C, which was above normal. Particularly, when the columns, girders, and beams were rated A, and the slabs were rated E, the total floor grade was B, which was unreasonably high. Additionally, KISTEC evaluates rates a member as E when the strength ratio ($\phi R_n/Q_u$) of the member is less than 75%. However, as shown in Fig. 2, there was a case where the strain ratio of the slab was 65%, indicating a very risky state, but it was simply considered to be the same as a strength ratio of 75%. Consequently, the inspection method provided by KISTEC does not reasonably reflect the effects of low-importance slabs or beams for floor inspection. Therefore, in this study, a structural reliability



(a) Slab SR = 75%



(b)Slab SR < 75 %

Fig. 2 Evaluation example for floor level using KISTEC method theory-based method was adopted to propose modification factors for the importance factors, which corrected the importance of the members with high failure probabilities and relatively less importance (Ang & Tang, 1990; Macgregor, 1983).

3 Proposed Method Based on Structural Reliability Theory

3.1 Structural Reliability Theory

Structural reliability theory is a probabilistic method used to assess the safety or reliability of structures (Freudenthal, 1947; Madsen et al., 1986), considering various uncertainties such as construction errors and load, and material strength variations. Madsen et al. assigned Levels I to IV for the reliability estimation methods as follows: Level I is a partial safety factor concept based on characteristic values (Freudenthal, 1947; Nowak & Szerszen, 2003; Szerszen & Nowak, 2003) applied to structural design codes; Level II is a method of modeling uncertain parameters using their partial descriptors such as means, standard deviations, and correlation coefficients; Level III is a method of using simulation techniques, such as Monte Carlo simulations, where random numbers are generated for random variables, and the failure probability or reliability is calculated based on the limit state status for each random set of variables; Level IV considers the consequences of failure and uses it for risk assessment; Level II uses the first-order reliability method (FORM) and second-order reliability method (SORM), which calculate failure probabilities or reliability indices (β) using a linear limit state function and a non-linear limit state function, respectively. The structural reliability theory has been used to determine the load factors and strength reduction factors, for example, in the American Concrete Institute (ACI Committee 318, 2019) and the Korea Concrete Institute (KCI, 2012) standards, and has also been applied to revise the safety factors of structural members or to perform risk analysis (Nowak & Szerszen, 2003; Szerszen & Nowak, 2003; Ellingwood et al., 1980; Chetchotisak et al., 2014; Kho et al. 2017; Cho et al., 2017a, 2017b; Nielsen & Sørensen, 2021).

In ACI 318–19, for the safe design of a structural member, the design strength (ϕR_n) is required to be greater than the ultimate limit state load, considering the load factors and strength reduction factors as follows:

$$\phi R_n \geq 1.4D, \tag{3a}$$

$$\phi R_n \geq 1.2D + 1.6L + 0.5(L_r \text{ or } S \text{ or } R), \tag{3b}$$

$$\phi R_n \geq 1.2D + 1.6(L_r\ or\ S\ or\ R) + (1.0L \text{ or } 0.5\text{S}), \tag{3c}$$

$$\phi R_n \geq 1.2D + 1.0W + 1.0L + 0.5(L_r \text{ or } S \text{ or } R), \tag{3d}$$

$$\phi R_n \geq 1.2D + 1.0E + 1.0L + 0.2S, \tag{3e}$$

$$\phi R_n \geq 0.9D + 1.0W, \tag{3f}$$

$$\phi R_n \geq 0.9D - 1.0E, \tag{3g}$$

where D is the dead load, L is the live load, L_r is the roof live load, S is the snow load, R is the rain load, W is the wind load, E is the horizontal and vertical earthquake-induced force, and ϕ is the strength reduction factor. International standards, such as KCI (KCI, 2012) and Eurocode 2 (EN 1992-1992-1 2004), have different values for the load factors and strength reduction factors in Eq. (3), but the load combinations have very similar forms. If a structural member is designed considering the load combination of only the dead and live loads from Eq. (3b), the safety factor (*SF*) becomes

$$SF = \frac{(1.2D + 1.6L)/\phi}{D + L} \tag{4}$$

and the limit state function (G) becomes

$$G = SF \cdot R_n - Q_u, \tag{5}$$

which is a function of the applied load ($Q_u = D + L$) and the resistance strength (R_n). This can be represented in a two-dimensional (2D) space, as shown in Fig. 3. The applied load and resistance strength are random variables, assuming that they have normal distributions. If they have non-normal distributions, they can be actually transformed into normal random variables through various transformation methods (Armen Der Kiureghian, 2022). The parameters of random variables, such as mean and standard deviation, are used to calculate the safety margin. For example, there can be 2 cases. The first case is in the failure state domain with the state of $R_1 < Q_1$. In this case, structural retrofitting can be implemented, or reducing the applied load can be a solution. The other case is in the safe state domain with the state of $R_2 > Q_2$. From Eq. (5), the mean and standard deviation of the safety margin (μ_g and σ_g, respectively) are calculated according to the linear combination of random variables, respectively, as follows:

$$\mu_G = SF \cdot \mu_{R_n} - \mu_{Q_u}, \tag{6}$$

$$\sigma_G = \sqrt{\left(SF \cdot \sigma_{R_n}\right)^2 + \sigma_{Q_u}^2}. \tag{7}$$

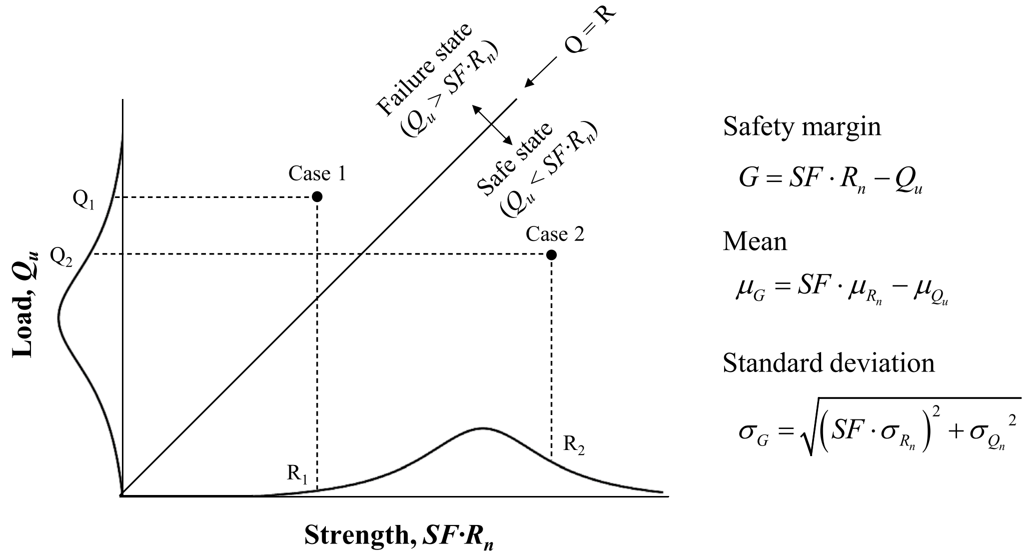


Fig. 3 Stractural reliability theory

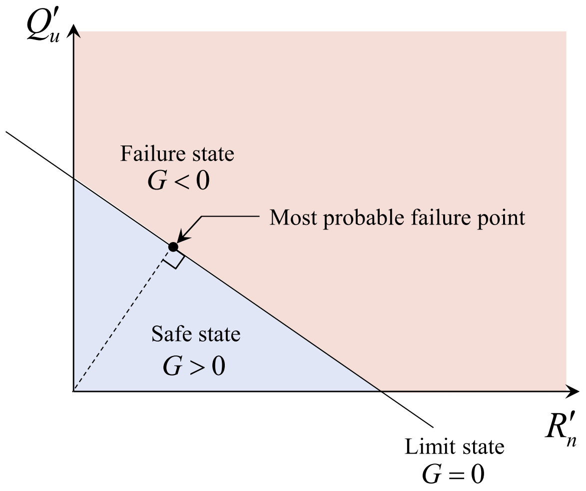


Fig. 4 Most probable failure point

As shown in Fig. 4, the random variables R_n and Q_u can be transformed into a normal distribution space as R_n' and Q_u', respectively, and the linear limit state function in Eq. (5) can be represented as a line in the figure. The shortest distance between the origin and the limit state function represents the reliability index (β), and the intersection point is called the most probable failure point (MPP). β is calculated as follows:

$$\beta = \frac{SF \cdot \mu_{R_n} - \mu_{Q_u}}{\sqrt{\left(SF \cdot \sigma_{R_n}\right)^2 + \sigma_{Q_u}^2}}. \tag{8}$$

μ_{Q_u} and $\sigma_{Q_u}^2$ differ according to the following load combinations:

$$D, \tag{9a}$$

$$D + L, \tag{9b}$$

$$D + L + S, \tag{9c}$$

$$D + L + W, \tag{9d}$$

$$D + L + E, \tag{9e}$$

$$D + L + S + W, \tag{9f}$$

$$D + L + S + E. \tag{9g}$$

If only the dead and live loads are used in the load combination, β is estimated as follows:

$$\beta = \frac{SF \cdot \mu_{R_n} - \mu_D - \mu_L}{\sqrt{\left(SF \cdot \sigma_{R_n}\right)^2 + \sigma_D^2 + \sigma_L^2}}. \tag{10}$$

SF can be estimated using the load factors provided in the standards, and the load factor ratio between the dead load and other loads, as shown in Eq. (4). In this study, the load factors and strength reduction factors provided in ACI 318–19 were adopted. The failure probability (P_F) and reliability index (β) have the following relationship:

$$P_F = \Phi(-\beta), \tag{11}$$

Table 5 Statistical parameters for load combinations (Szerszen & Nowak, 2003)

Load component	Bias	C.O.V
Dead load (cast-in-place)	1.05	0.10
Dead load (plant-cast)	1.03	0.08
Live load	1.00	0.18
Snow	0.82	0.26
Wind	0.78	0.37
Earthquake	0.66	0.56

Table 6 Statistical parameters of resistance, R_n (Szerszen & Nowak, 2003)

Structural type and limit state	Bias	C.O.V
RC beam (cast-in-place), flexure	1.114	0.119
RC beam (plant-cast), flexure	1.128	0.113
RC beam (cast-in-place), shear	1.159	0.120
RC beam (plant-cast), shear	1.170	0.116
RC slab (cast-in-place)	1.052	0.169
RC slab (plant-cast)	1.146	0.116
RC column (cast-in-place), tied	1.107	0.136
RC column (plant-cast), tied	1.102	0.134
RC column (cast-in-place), spiral	1.163	0.124
RC column (plant-cast), spiral	1.156	0.122

where $\Phi(\cdot)$ is the standard normal cumulative distribution function (CDF).

As expressed in Eq. (8), to calculate the failure probability of a structural member, it is necessary to know the resistance strength of the members, and the means and standard deviations of the applied loads, such as dead and live loads. In this study, as shown in Tables 5 and 6, the means and standard deviations of the applied loads, and the resistance strength of the members were determined based on the work done by Szerszen and Nowak (Szerszen & Nowak, 2003). The conversion formulae for Bias (b_x) and COV (c_x), to mean (μ_x) and standard deviation (σ_x), are as follows:

$$\mu_x = xb_x, \tag{12a}$$

$$\sigma_x = xc_xb_x, \tag{12b}$$

where x is the applied load or resistance strength.

3.2 The Proposed Inspection Method

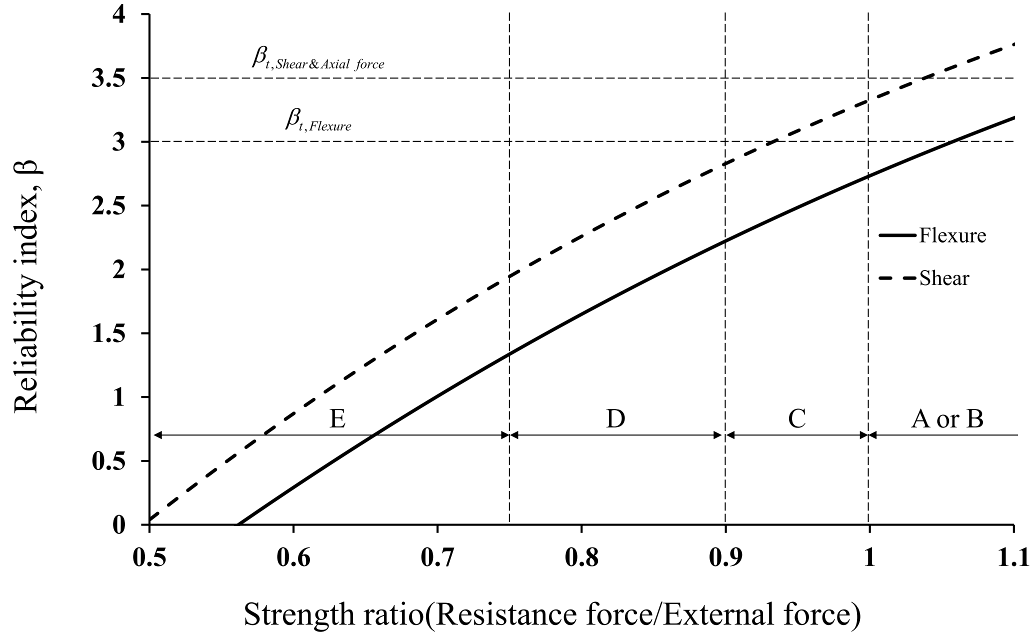
To overcome the limitations of the safety inspection regulations in KISTEC, a target reliability index (β_t) was set, and the importance of each structural member type was revised in case of $\beta < \beta_t$. Compared to shear and axial loads, which can be prone to sudden crack propagation or even sudden failure, bending moments to the structure are relatively much more ductile to failure. Considering these characteristics of the failure mechanisms, β_t was set to be 3.0 for structural members under bending, and 3.5 for members under shear and axial loads, which is a more conservative value. These target reliability indices are the values used to determine the resistance and load factors in ACI 318–19 and are derived by expert groups, such as the ANSI A58 load factor subcommittee and the ACI subcommittee 4, considering various databases and case studies (Macgregor, 1983). Using the ratio of β to β_t, the importance correction factor (α) was proposed as follows:

$$\alpha = 1 - \frac{\beta}{\beta_t}. \tag{13}$$

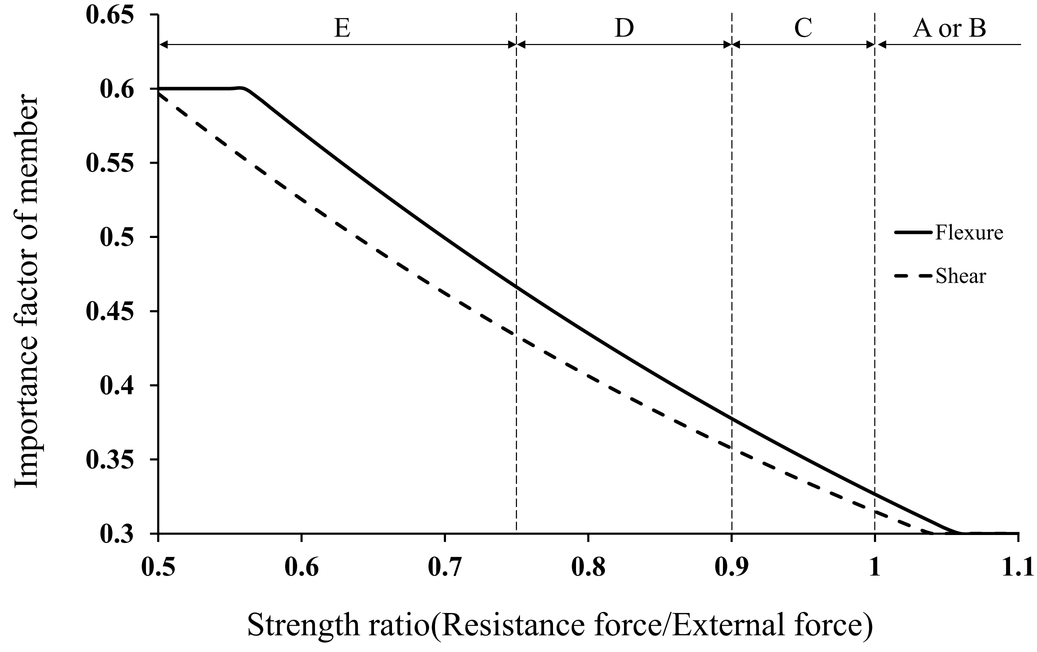
When $\beta = 0$, P_F is 50%, and when $P_F > 50\%$, α becomes 1. Additionally, when the resistance strength exceeded the applied load, it was considered to be sufficiently safe, and its importance did not change any further. In this study, the modified importance factor (η') for members is introduced, except for column, as follows:

$$\eta' = \eta \times (1 + \alpha) \leq 0.8, \tag{14}$$

where the modified importance was limited to 0.8. For a slab with a failure probability exceeding 50%, the importance factor was 0.6, which was twice the original importance factor of 0.3. Figs. 5, 6, and 7 present the importance factors and the reliability index (β) for slabs, beams, and girders, respectively, according to the strength ratio (i.e., member strength divided by required strength). It is noted that these cases are for the load combinations of $(D + L)$ expressed in Eq. (9b). As shown in Fig. 5a, β for the slab increased as the strength ratio increased, and when the strength ratio of the slab was 0.75 (grade E), the values of β for flexural and shear failures were estimated to be 1.34 and 1.95, respectively, which corresponded to P_F values of 9% and 3%, respectively. When the modified importance factors were applied, the importance factor could be estimated as shown in Fig. 5b, and the importance factor of the grade E slabs became equal to or greater than 0.433, which was 1.44 times the original importance factor of 0.3. As shown in Fig. 6, grade E beams had β values of 1.06 and 1.9 for flexural and shear failures, respectively, and the corresponding importance factors were modified to 0.728 and 0.9. Therefore, when the grade for the beams was E, the modified importance factor became approximately 1.56 times the original importance factor. As shown in Fig. 7, grade E girders had β values of 1.06 and 1.9 for bending and shear, respectively, which were similar to those for the



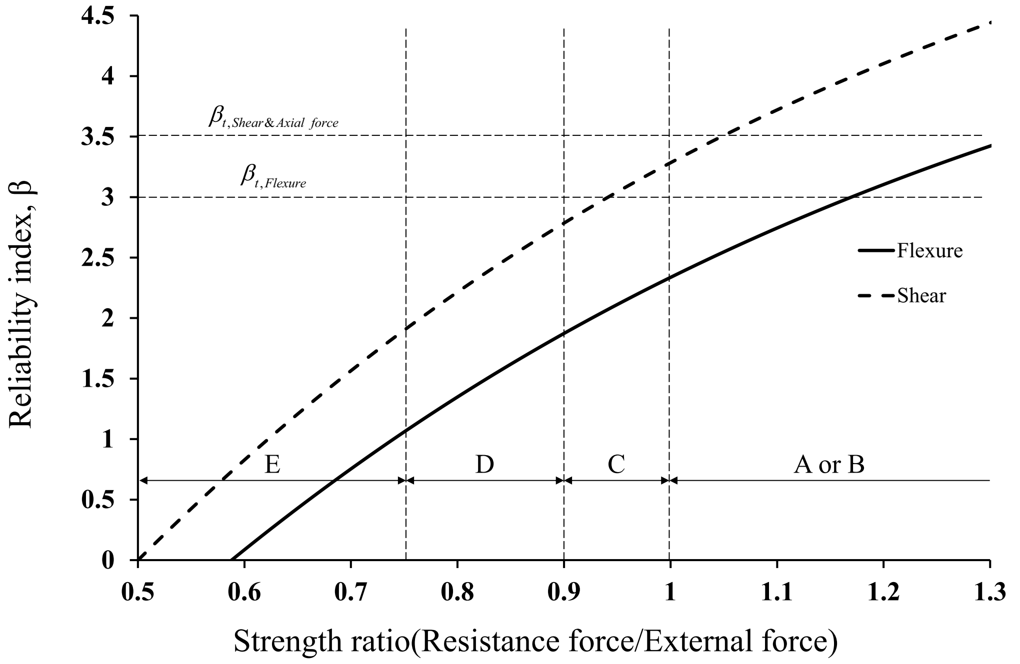
(a) Reliability index of slab calcuated by Eq. (6)



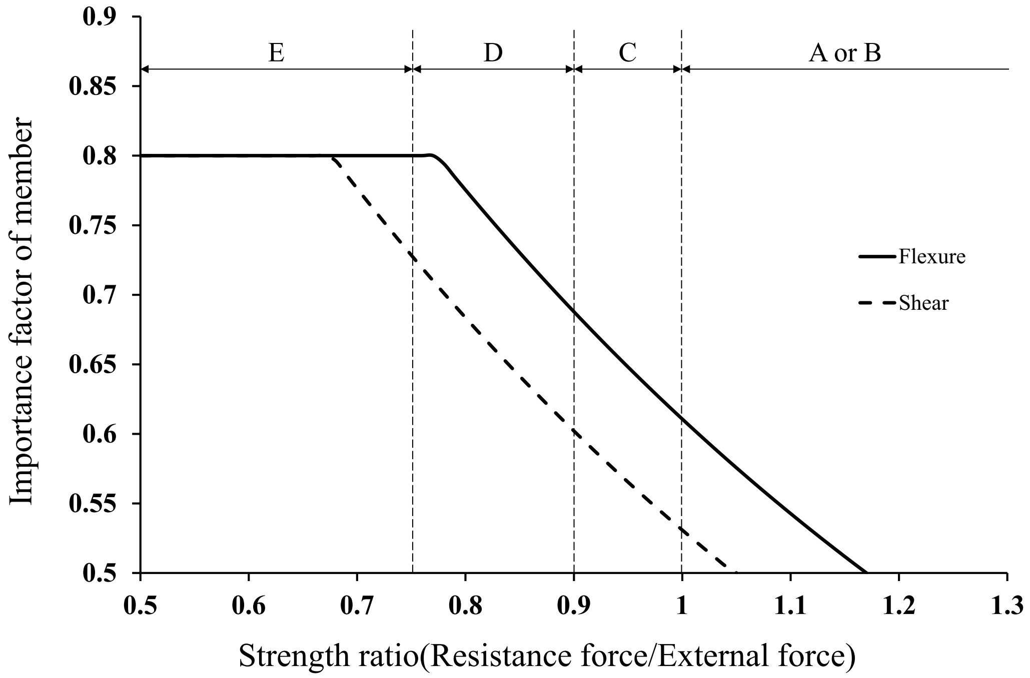
(b) Importance factor of slab calculated by Eq. (12)

Fig. 5 Relationship between reliability index and importance factor of slab

beams. The importance of the columns was maintained at 0.9, which was the same as the original value. The values of the strength ratio of the slab that met β_t were 1.06 for bending and 1.04 for shear. Those for the beams and girder were 1.17 for bending and 1.05 for shear. β_t could not be achieved when the strength ratio was 1.0 because the biases and standard deviations of the load and resistance were determined based on available statistics, which



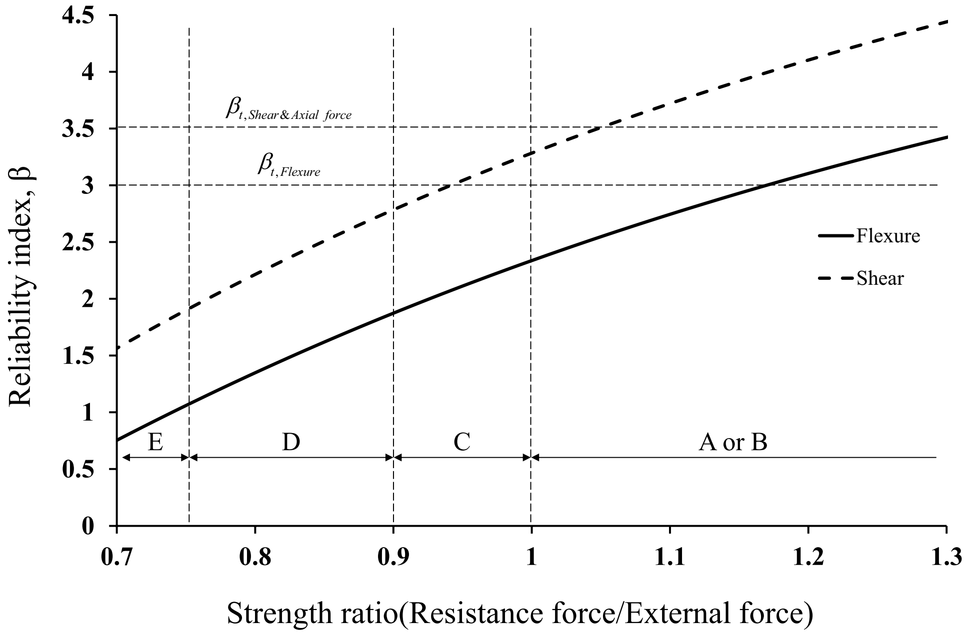
(a) Reliability index of beam calcuated by Eq. (6)



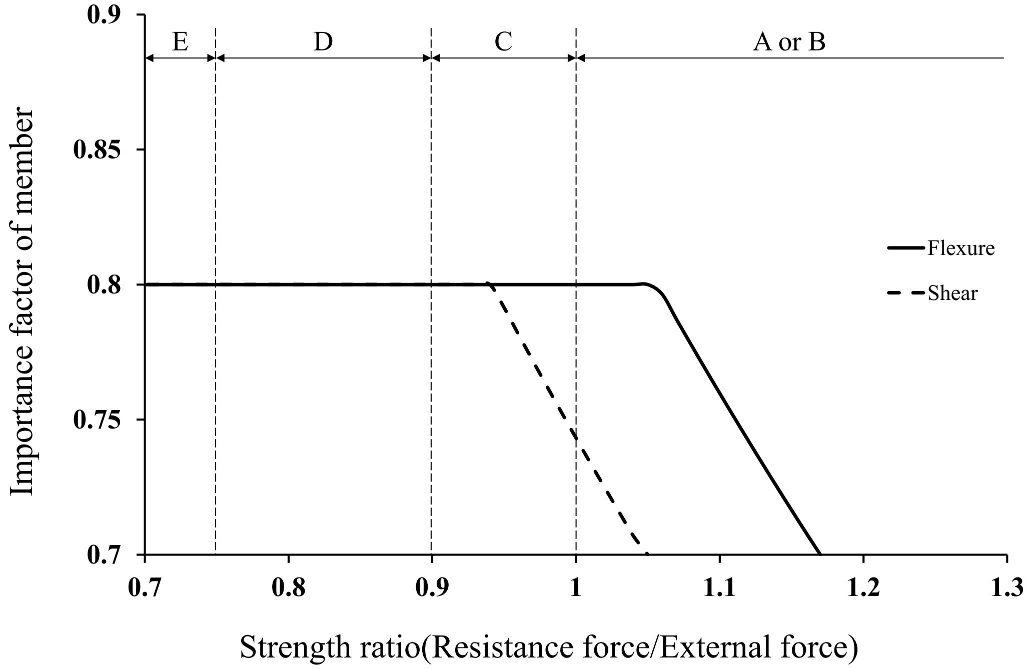
(b) Importance factor of beam calculated by Eq. (12)

Fig. 6 Relationship between reliability index and importance factor of beam

provided conservative inspection results. In Figs. 5, 6, and 7, the ultimate limit state load was determined based on the combination of dead and live loads; however, as shown in Table 7, the failure probability increased when the wind load, and horizontal and vertical earthquake-induced loads having large variations were considered.



(a) Reliability index of girder calcuated by Eq. (6)



(b) Importance factor of girder calculated by Eq. (12)

Fig. 7 Relationship between reliability index and importance factor of girder

For Case 1–1 in Table 7, where the combination of dead load and live load is considered, the member grades are A, A, A, and E for the column, girder, beam, and slab, respectively. Therefore, the strength ratios of each member are determined as 1.11, 1.11, 1.11, and 0.67. If the resistance strength of the column is assumed to be 100 (unit omitted), the dead load and live load are calculated as 45, respectively. The means and standard deviations of the resistance strength of the member and the applied load are required to calculate the reliability

Table 7 Comparison of results between KISTEC method and proposed method

Case	Member	Strength ratio	Member grade (score)	β	Ultimate limit state load	Evaluation grade (score)	
						KISTEC	Proposed method
1–1	Column	1.11	A(1)	3.69	$1.2D+1.6L$	B (3.40)	C (5.15)
	Girder	1.11	A(1)	4.30			
	Beam	1.11	A(1)	4.30			
	Slab	0.67	E(9)	0.94			
1–2	Column	1.11	A(1)	3.12	$1.2D+1.0W+1.0L$		C (5.62)
	Girder	1.11	A(1)	3.68			
	Beam	1.11	A(1)	3.68			
	Slab	0.67	E(9)	0.26			
1–3	Column	1.11	A(1)	3.16	$1.2D+1.0E+1.0L$		C (5.55)
	Girder	1.11	A(1)	3.71			
	Beam	1.11	A(1)	3.71			
	Slab	0.67	E(9)	0.37			
2–1	Column	1.11	A(1)	3.69	$1.2D+1.6L$	C (5.51)	D (6.90)
	Girder	1.11	A(1)	4.30			
	Beam	0.80	D(7)	2.79			
	Slab	0.67	E(9)	0.94			
2–2	Column	1.11	A(1)	3.12	$1.2D+1.0W+1.0L$		D (7.44)
	Girder	1.11	A(1)	3.68			
	Beam	0.80	D(7)	2.00			
	Slab	0.67	E(9)	0.26			
2–3	Column	1.11	A(1)	3.16	$1.2D+1.0E+1.0L$		D (7.38)
	Girder	1.11	A(1)	3.71			
	Beam	0.80	D(7)	2.06			
	Slab	0.67	E(9)	0.37			
3–1	Column	1.11	A(1)	3.69	$1.2D+1.6L$	B (3.61)	B (3.86)
	Girder	1.11	A(1)	4.30			
	Beam	0.91	C(5)	3.42			
	Slab	0.91	C(5)	2.21			
3–2	Column	1.11	A(1)	3.12	$1.2D+1.0W+1.0L$		C (4.17)
	Girder	1.11	A(1)	3.68			
	Beam	0.91	C(5)	2.69			
	Slab	0.91	C(5)	1.65			
3–3	Column	1.11	A(1)	3.16	$1.2D+1.0E+1.0L$		C (4.15)
	Girder	1.11	A(1)	3.71			
	Beam	0.91	C(5)	2.74			
	Slab	0.91	C(5)	1.72			
4–1	Column	1.11	A(1)	3.69	$1.2D+1.6L$	C (4.91)	C (5.70)
	Girder	1.11	A(1)	4.30			
	Beam	0.80	D(7)	2.79			
	Slab	0.80	D(7)	1.72			
4–2	Column	1.11	A(1)	3.12	$1.2D+1.0W+1.0L$		D (6.16)
	Girder	1.11	A(1)	3.68			
	Beam	0.80	D(7)	2.00			
	Slab	0.80	D(7)	1.11			
4–3	Column	1.11	A(1)	3.16	$1.2D+1.0E+1.0L$		D (6.12)
	Girder	1.11	A(1)	3.71			
	Beam	0.80	D(7)	2.06			
	Slab	0.80	D(7)	1.19			

index β, as shown in Eq. (10). According to the research of Szerszen and Nowak(2003), the means and standard deviations of the resistance strength of members and the applied load can be determined using statistical parameters (*bias* (λ) and *COV*) as shown in Tables 5 and 6.

Furthermore, in this study, the failure probabilities and reliabilities were applied to the safety inspection of the entire structure. Therefore, the floor-specific importance factor, ζ in Eq. (2) could be modified as follows by considering the member failure probability:

$$\zeta' = \zeta \times (1 + \alpha_{\max}) \leq 0.9, \tag{15}$$

where the modification factor for the floor-specific importance factor, $\alpha_{\max}$, is the importance correction factor of the member on the specific floor that has the highest failure probability.

3.3 Inspection Results Comparison for the KISTEC and Proposed Models

To compare the KISTEC model with the model proposed in this study, as shown in Table 7, sample cases having grade E slabs based on the KISTEC model were selected, and their inspection grades were recalculated based on the proposed method by varying the load combinations.

For all the sample cases, the forces were assumed as follows:

(i) D/(D + L) was set to 0.5.

(ii) Wind loads, and horizontal and vertical earthquake-induced forces were set to 0.5D.

The values of SR ($=\phi R_n/Q_u$) were determined based on Table 2. As grades A and B had the same SR value, grade B was considered the same as grade A. The SR values for grades A, C, D, and E were determined as 1.11, 0.91, 0.80, and 0.67, respectively.

In Cases 1–1, 2–1, and 3–1, where the grades of the columns, girders, and beams were A, and the grade of the slabs was E, the KISTEC method provided an overall grade of B or C, although the slab was in an unsafe state. However, when the proposed method was used, the effect of the slab with $\beta = 0.94$ was more appropriately reflected: the importance factor of the slab became approximately 1.7 times the original value, and the floor evaluation grade was lowered by one step to D. Moreover, when wind load, and horizontal and vertical earthquake-induced forces were considered, as in Cases 1–2 and 1–3, the floor evaluation grade was the same as that in Case 1–1, which was grade C; however, the evaluation score was increased by approximately 0.4–0.5, which is due to the larger uncertainties in wind load, and horizontal and vertical earthquake-induced forces. This trend was more clearly shown in Cases 4–2, 4–3, 5–2, and 5–3. Cases 4–1 and 5–1 provided the same grades for the KISTEC method and the proposed method, but Cases 4–2, 4–3, 5–2, and 5–3 with wind load, and horizontal and vertical earthquake-induced forces showed grades lowered by one step.

3.4 Evaluation of the Whole Structure

In this section, comparisons of the KISTEC method with the proposed method are provided through case studies of the inspection of floors and the entire structure. In Table 8, the inspection grades of floors for a total of 9 cases are provided, using both the KISTEC method and the proposed method. In Case 1, the strength ratios of the column, girder, beam, and slab are 1.39, 0.96, 1.42, and 1.41, respectively. Therefore, the member grades (scores) are determined as A(1), C(5), A(1), and A(1), respectively. The reliability indices are then calculated as 4.29, 3.07, 3.75, and 4.31, according to the procedure mentioned in Table 7. The reliability index of the girder is calculated as 3.07, which is lower than the target reliability index of 3.5. In the proposed method, the importance modification coefficient (α) of the girder is calculated as 0.12 according to Eq. (13), and the importance factor of the girder is recalculated as 0.79 (0.70 in the KISTEC method). According to Choquet integral using the scores of members and the modified importance factors in Case 1, the floor level of Case 1 is evaluated as C grade (score: 4.16). In Cases 1–5, the columns, beams, and slabs were evaluated as grade A, and girders were grade C. The SR values of the girder for these cases had values of 0.90–0.99. The KISTEC method evaluated the grade as B for all five cases, but the proposed method evaluated them using the modified importance factor, and provided updated grades. As shown in Fig. 8, the importance factor of each member type was modified according to the SR and the failure probability, and the effect of SR on floor safety was well reflected. Cases 6–9 in Table 8 show the results for the floors where the inspection grades of the slab were estimated as D or E, but their importance was relatively low. When the KISTEC method was used for these cases, although the grade of the slab was E, the floor grade was B, which was relatively high. However, this was corrected using the proposed method, and the failure probability of slabs was well reflected, as shown in Fig. 9.

Additionally, as shown in Table 9, further safety assessment was conducted for a 4-story structure, and the proposed method was compared with the KISTEC method. The example in Table 9 shows that the first-floor girder was assessed as grade E, and the grade of the overall structure became grade D with an evaluation score of 7.40. Girders are the second most important structural member type following columns, and girders at lower

Table 8 Evaluation results considering modified importance factor

Case	Member	Strength ratio	Member grade	Member score	Reliability Index, β	Importance correction factor, α	Previous importance factor	Modified importance factor	Evaluation result by KISTEC	Evaluation result by proposed method
1	Column	1.39	A	1	4.29	–	0.90	0.90	B (3.80)	C (4.16)
	Girder	0.96	C	5	3.07	0.12	0.70	0.79		
	Beam	1.42	A	1	3.75	–	0.50	0.50		
	Slab	1.41	A	1	4.31	–	0.30	0.30		
2	Column	1.39	A	1	4.29	–	0.90	0.90	B (3.80)	C (4.20)
	Girder	0.91	C	5	2.85	0.19	0.70	0.80		
	Beam	1.04	A	1	3.47	0.01	0.50	0.50		
	Slab	1.41	A	1	4.31	–	0.30	0.30		
3	Column	1.39	A	1	4.29	–	0.90	0.90	B (3.80)	C (4.04)
	Girder	0.95	C	5	3.19	0.08	0.70	0.76		
	Beam	1.04	A	1	3.47	0.01	0.50	0.50		
	Slab	1.41	A	1	4.31	–	0.30	0.30		
4	Column	1.40	A	1	4.32	–	0.90	0.90	B (3.80)	C (4.12)
	Girder	0.96	C	5	3.11	0.11	0.70	0.78		
	Beam	1.14	A	1	2.91	0.03	0.50	0.52		
	Slab	1.41	A	1	4.31	–	0.30	0.30		
5	Column	1.10	A	1	3.47	0.01	0.90	0.90	B (3.80)	B (3.96)
	Girder	0.99	C	5	3.28	0.06	0.70	0.74		
	Beam	1.23	A	1	3.20	–	0.50	0.50		
	Slab	1.32	A	1	4.00	–	0.30	0.30		
6	Column	1.72	A	1	4.92	–	0.90	0.90	B (3.40)	C (4.76)
	Girder	1.04	A	1	2.49	0.17	0.70	0.80		
	Beam	1.15	A	1	3.92	–	0.50	0.50		
	Slab	0.75	E	9	1.31	0.56	0.30	0.47		
7	Column	1.01	A	1	2.53	0.28	0.90	0.90	B (3.40)	C (5.32)
	Girder	1.04	A	1	3.47	0.01	0.70	0.71		
	Beam	1.01	A	1	3.33	0.05	0.50	0.52		
	Slab	0.65	E	9	0.64	0.79	0.30	0.54		
8	Column	1.72	A	1	4.92	–	0.90	0.90	B (3.79)	C (4.34)
	Girder	1.01	B	3	3.31	0.05	0.70	0.74		
	Beam	1.00	A	1	2.34	0.22	0.50	0.61		
	Slab	0.84	D	7	1.88	0.37	0.30	0.41		

Table 8 (continued)

Case	Member	Strength ratio	Member grade	Member score	Reliability Index, β	Importance correction factor, α	Previous importance factor	Modified importance factor	Evaluation result by KISTEC	Evaluation result by proposed method
9	Column	1.72	A	1	4.92	–	0.90	0.90	B (3.79)	C (4.25)
	Girder	1.10	B	3	3.72	–	0.70	0.70		
	Beam	1.04	A	1	3.47	0.01	0.50	0.50		
	Slab	0.85	D	7	1.96	0.35	0.30	0.40		

Table 9 Evaluation results for RC structures considering modified importance factor

Floor	Member	Member level	Floor level		Importance factor of floor (KISTEC)	Importance factor of floor (Proposed method)	Structure level	
			KISTEC	Proposed method			KISTEC	Proposed method
4th floor	Column	A	C (4.77)	C (5.32)	0.30	0.41	D (7.40)	E (8.14)
	Girder	C						
	Beam	A						
	Slab	D						
3rd floor	Column	A	B (2.80)	B (2.90)	0.50	0.59		
	Girder	B						
	Beam	B						
	Slab	B						
2nd floor	Column	B	B (2.98)	B (2.98)	0.70	0.83		
	Girder	B						
	Beam	A						
	Slab	B						
1st floor	Column	A	D (7.83)	E (8.61)	0.90	0.90		
	Girder	E						
	Beam	E						
	Slab	A						

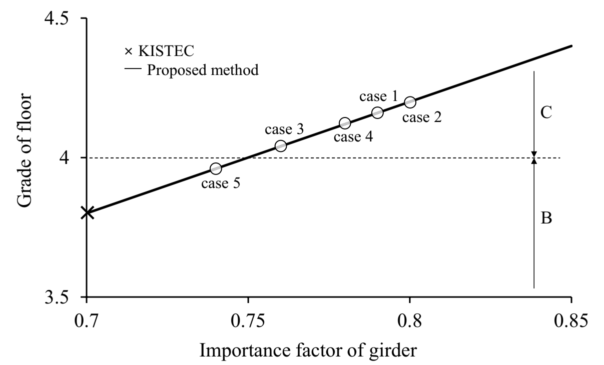


Fig. 8 Grade of floor according to the importance factor (Cases 1–5)

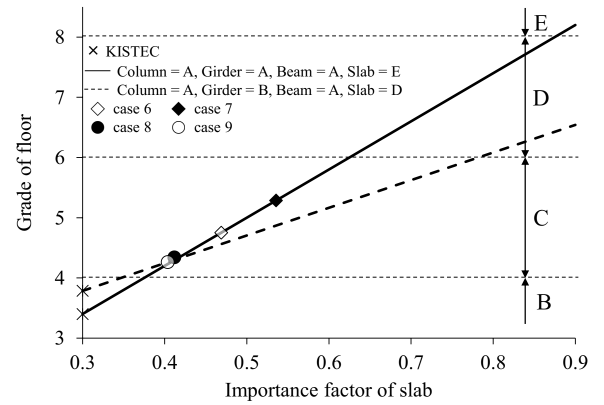


Fig. 9 Grade of floor according to the importance factor (Cases 6–9)

levels play an important role in supporting the whole structure. Using the proposed method, and considering the failure probability of the first-floor girders, a grade E was attained with an evaluation score of 8.14. The overall assessment using the proposed method showed conservative results, compared with the KISTEC method.

4 Summary and Conclusions

In this study, we proposed modified importance factors for deterioration inspection and grading, based on the structural reliability theory; and based on these factors, a safety inspection method for RC structures was proposed. The proposed method was also compared with the *Safety Inspection and Precise Safety Diagnosis: Detailed Guideline* provided by KISTEC, and the following conclusions were drawn:

(1) The importance factors for the structural member types provided in KISTEC were fixed values. The safety status of structural members with lower importance factors was not accurately reflected in the structural safety inspection results of the floor and entire structure.

(2) The structural reliability theory was adopted, and the reliability index (β) and failure probability (P_F) of each member were estimated. The ratio of β to

the target reliability index (β_t) was used to determine the modified importance factors.

(3) Using the proposed modified importance factors, even if the structural member had the same inspection grade, the importance of the member was modified differently according to its failure probability, and overall, conservative and reasonable inspection results were provided.

(4) Through the examples of floors and structures, the proposed method was compared with the KISTEC method. The proposed method showed that it considered the structural members having low importance more appropriately than the KISTEC method, in terms of the inspection of the floor or the whole structure.

Acknowledgements
Prof. Seong-Tae Yi would like to acknowledge that this work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (NRF-2021R1F1A1045693). Also, Prof. Kang Su Kim, the corresponding author, would like to thank that this research was supported by the 2022 Research Fund of the University of Seoul.

Author contributions
H-CC contributed to writing—original draft, and methodology. S-HL was involved in data curation. S-HC did investigation. S-TY performed formal analysis. W-HK performed validation. KSK was involved in supervision and writing—review & editing. All the authors read and approved the final manuscript.

Author's information
Hae-Chang Cho is the R&D manager in the technology center of Dream Structural Engineers Co Ltd. He received his B.S in architectural engineering from Konyang University and a M.S., Ph.D. in architectural engineering from University of Seoul. His research interest includes the remaining service life of structure. Sang-Hoon Lee is a Ph.D. candidate in the department of architectural engineering and smart city interdisciplinary major program of University of Seoul. He received his B.S. degrees in material science & engineering and architectural engineering and an M.S. degree in architectural engineering from University of Seoul. His research interest focuses on structural reliability and safety. Seung-Ho Choi is a postdoctoral researcher in the department of architectural engineering of University of Seoul. He received his B.S., M.S., and Ph.D. in architectural engineering from University of Seoul. His research interest includes the analysis of beam-column joints. Seong-Tae Yi is a professor in the department of civil and environmental engineering of Inha Technical College. He received his B.S. and M.S. in architectural engineering from Inha University and a Ph.D. in civil engineering from Korea Advanced Institute Science and Technology. His research interest includes the strength and size effect of concrete. Won-Hee Kang is a senior lecturer at Western Sydney University in the area of Structural Reliability. He obtained his B.S. in architectural engineering from Korea University and a M.S. and a Ph.D. in civil and environmental engineering from the University of Illinois at Urbana-Champaign. His research interest includes the systematic treatment of uncertainties. Kang Su Kim is a professor in the department of architectural engineering and smart city interdisciplinary major program of University of Seoul. He received his B.S. and M.S. in architectural engineering from Inha University and a Ph.D. in civil engineering from University of Illinois Urbana-Champaign. His research interest focuses on the structural analysis of prestressed concrete members.

Funding
National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (NRF-2021R1F1A1045693) for Seong-Tae Yi, and 2022 Research Fund of the University of Seoul for Kang Su Kim.

Availability of data and materials
All data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests
The authors declare no competing interests.

Author details
[1]Technology Center, Dream Structural Engineers, 25 Seongsuilro 4-Gil, Seongdong-Gu, Seoul 04871, South Korea. [2]Department of Architectural Engineering and Smart City Interdisciplinary Major Program, University of Seoul, 163 Siripdaero, Dongdaemun-Gu, Seoul 130-743, South Korea. [3]Department of Architectural Engineering, University of Seoul, 163 Siripdaero, Dongdaemun-Gu, Seoul 02504, South Korea. [4]Department of Civil and Environmental Engineering, Inha Technical College, 100 Inha-Ro, Michuhol-Gu, Incheon 22212, South Korea. [5]Centre for Infrastructure Engineering, Western Sydney University, Locked Bag 1797, Penrith South DC, NSW 2751, Australia.

Received: 10 June 2022 Accepted: 1 November 2022

References

ACI Committee 318. (2019). *Building code requirements for structural concrete and commentary (ACI 318–19)*. Farmington: American Concrete Institute.

Ang, A. H., & Tang, W. H. (1990). *Probability concepts in engineering planning and design*. Hoboken: Wiley.

Armen Der Kiureghian. (2022). *Structural and system reliability*. Cambridge University Press.

BCA. (2012). *Periodic Structural Insection of Existing Buildings*, Building and Construction Authority. Pp. 1–14

Ho, D. C. W., & Yiu, C. Y. (2013). *Professional Guide to Building Inspections*. Building Surveying Division, The Hong Kong Institute of Surveyors

Chetchotisak, P., Teerawong, J., Yindeesuk, S., & Song, J. (2014). New strut-and-tie-models for shear strength prediction and design of RC deep beams. *Computers and Concrete, 14*(1), 19–40.

Cho, H. C., Ju, H., Oh, J. Y., Lee, K. J., Hahm, K. W., & Kim, K. S. (2016). Estimation of concrete carbonation depth considering multiple influencing factors on the deterioration of durability for reinforced concrete structures. *Advances in Materials Science and Engineering, 2016*, 1–18.

Cho, H. C., Lee, D. H., Ju, H. J., Kim, K. S., Kim, K. H., & Monteiro, P. J. M. (2015). Remaining service life estimation of reinforced concrete buildings based on fuzzy approach. *Computers and Concrete, 15*(6), 879–902.

Cho, H. C., Lee, D. H., Ju, H. J., Park, H. C., Kim, H. Y., & Kim, K. S. (2017). Fire Damage assessment of reinforced concrete structures using fuzzy theory. *Applied Sciences., 7*(5), 518.

Cho, H. C., Park, M. K., Ju, H. J., Oh, J. Y., Oh, Y. H., & Kim, K. S. (2017b). Shear strength reduction factor of prestressed hollow-core slab units based on the reliability approach. *Advances in Materials Science and Engineering, 2017*, 1–11.

Choquet, G. (1954). Theory of capacities. *In Annales De L'institut Fourier, 5*, 131–295.

CPWD. (2002). *Handbook on repair and rehabilitation of RCC buildings*. Central Public Work Department. 498.

Ellingwood, B., Galambos, T. V., MacGregor, J. G., & Cornell, C. A. (1980). *Development of a probability-based load criterion for American national standard A58, building code requirements for minimum design loads in buildings and other structures*. Maryland: National Bureau of Standards.

EN 1992–1–1. (2004). *Eurocode 2: Design of Concrete Structures, Part 1–1: General Rules and Rules for Buildings*. European Committee for Standardization.

Frank, J. (2001). *Lebesgue integration on euclidean space*. Delhi: Jones & Bratlett.

Freudenthal, A. M. (1947). The Safety of structure. *ASCE. Transactions, 112*(1), 125–159.

Grabisch, M., Murofushi, T., & Sugeno, M. (2010). *Fuzzy measures and integrals*. Physica-Verlag.

JSCE. (2007). *Standard specifications for concrete structures*. Tokyo: Japan Society of Civil Engineers.

KCI. (2012). *Design Specifications for Concrete Structures*. Korea Concrete Institute.

Kim, Y. M., Kim, C. K., & Hong, G. H. (2007). Fuzzy set based crack diagnosis system for reinforced concrete structures. *Computers & Structures, 85*(23), 1828–1844.

Kim, Y. M., Kim, C. K., & Hong, S. G. (2006). Fuzzy based state assessment for reinforced concrete building structures. *Engineering Structures, 28*(9), 1286–1297.

Korea Infrastructure Safety and Technology Corporation (KISTEC). (2009). *Safety Inspection regulations, ministry of land*. Transport and Maritime Affairs

Koh, H. M., Lim, J. H., Kim, H. J., Yi, J. W., Park, W., & Song, J. (2017). Reliability based structural design framework against accidental loads – ship collision. *Structure and Infrastructure Engineering, 13*(1), 171–180.

Macgregor, J. G. (1983). Load and resistance factors for concrete design. *ACI Journal, 80*(4), 279–287.

Madsen, H. O., Krenk, S., & Lind, N. C. (1986). *Methods of structural safety*. Prentice Hall

Ministry of Construction and Transportation of Korea. (2008). *Safety for Infrastructure and maintenance plan*. notification No. 2008–318 of the Ministry of Construction and Transportation of Korea

Nielsen, J. S., & Sørensen, J. D. (2021). Risk-based derivation of target reliability levels for life extension of wind turbine structural components. *Wind Energy, 24*(9), 939–956.

Nowak, A. S., & Szerszen, M. M. (2003). Calibration of design code for buildings (ACI 318): Part 1-Statistical Models for Resistance. *ACI Structural Journal, 100*(3), 377–382.

PWD. (2013). *Guideline of building condition inspection for existing building*. Public Work Department

Szerszen, M. M., & Nowak, A. S. (2003). Calibration of design code for buildings (ACI 318): part 2-reliability analysis and resistance factors. *ACI Structural Journal, 100*(3), 383–391.

Zadeh, L. A. (1965). Fuzzy sets. *Information and Computation, 8*(3), 338–353.

Publisher's Note