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Determination of New Load and Resistance Factors for Reinforced Concrete Structural Members†

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ABSTRACT

In this study, a procedure for the determination of new load and resistance factors for reinforced concrete structural members is proposed in view of the fact that the design practice in Turkey has changed after the occurrence of major earthquakes. The implementation of the procedure is carried out for the shear failure mode of reinforced concrete beams subjected to dead and live load combination. First, the statistical parameters for the quantification of uncertainty involved in the design variables, modeling and loads are assessed based on the available data and knowledge. Then, the level of risk related with the current design practice is quantified in terms of the reliability index, β. Target reliability index β_T, is selected in view of the β values computed for the current design practice. By using the resulting target reliability index β_T, the load and resistance factors are computed based on the Advanced First Order Second Moment Method.

Keywords: *Reinforced concrete beams, load and resistance factors, uncertainty, earthquake load, reliability.*

1. INTRODUCTION

After realizing great many incompetencies and unconsciousness just after the big losses of life and properties due to major earthquakes in recent years in Turkey, public's attention to the earthquakes-resistant structures has increased, authorized institutions have started to take precautions against these disasters and many efforts have been made to raise technical staff. Consequently, the criteria of design and practise of structures in the country relatively has changed and some standards and regulations have been improved in order to make use of more qualified construction materials.

In the researches carried out after the earthquakes, much serious inefficiencies have been noticed in workmanship and construction materials being used [1-3]. Reinforced concrete structures have been found not to show the required earthquake performance and standards and regulations have been revised [4, 5]. In Turkey, conventional building methods have been given up and ready mix concrete in new constructions is started to be used to a great extent because of its advantages such as getting higher quality concrete, ease of production and its being more easily quality controlled by authorized institutions. Thus, compared with

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the 1990s, a higher concrete class is being utilized [6]. Moreover, the variabilities in targeted concrete classes are less than those produced in previous years [7].

It is revealed that there is a problem in quality of reinforcing steel as a result of surveys on damaged buildings and tests carried out on reinforcing steel samples taken from these buildings in earthquakes. It is a known fact that reinforcing steel corrodes especially in buildings being exposed to humidity throughout the time. For these reasons, some precautions have been taken to improve the quality of reinforcing steel. Some alterations have occurred from past to the present in some basic mechanical properties of reinforcing steel such as especially how much deviation of yield strength of reinforcing steel found at the end of the test will be indicated from anticipated yield strength in the relevant standards, and how much the ratio of tensile strength to yield strength found at the end of the tests should be tolerable. In addition to these, while S220 reinforcing steels were being used to a great extent in 1990s, today it is never being used and it is almost impossible to find it in markets [8].

In inspections carried out on constructions in previous years, many serious workmanship errors have been encountered and in some cases, inadequate materials have been found to be used as well, and building member dimensions are found to be manufactured smaller than those in the design. Due to increasing control and supervision process in Turkey, workmanship errors are being less than those in the past.

From past to the present, even if design and practice criteria of the constructions in Turkey as well as in the world change positively, some uncertainty will still remain in the structural materials, in modeling to be used in structural design and projects of structures. Besides, it is a widely known fact that major uncertainty exist in dead, live, snow, wind and earthquake loads and their effects on structures. Hence, load and resistance factors should be used in ultimate strength method and uncertainty and their effects on the structure should be solved by using probabilistic methods.

As it is summarized above, the necessity of revising load and resistance factors used in Turkey indicate itself as a must because of the reasons such as modifying of design and the practice criteria of the constructions to be built and the need of decreasing all the uncertainty sources with the new data and information. In the framework of these investigations, it is aimed here that new methods of identifying load and resistance factors for reinforced concrete structural members should be formulated. The practice of the design method is carried out on the beams subjected to shear. Furthermore, modeling of different design variables such as concrete, reinforcing steel, dead and live loads have been made. The modeling of design variables and computation method in the study will be valid for other reinforced concrete structural members and other failure modes.

2. STRUCTURAL RELIABILITY MODEL

Structural reliability is obtained by comparing the effects of load exposed throughout life span of the structure with its resistance capacity. When a failure mode such as flexural or shear is taken into consideration, resistance variables are represented by R and load variables are represented by S, system's p_s reliability is defined as possibility of

"p_s=P(R>S)". The possibility of risk of S having a bigger value than R (system's failure, in other words being inefficient) is defined as follows:

$$p_f=P(S>R)=1-p_s \quad (1)$$

In order to determine these reliability and risk values, it is a must to create a reliability modeling including all of the basic variables such as material properties, load effects, dimensions. In this study, while creating reliability model Advanced First Order Second Moment Method (AFOSM) [9] will be used. In carrying out this method, the limit state can be defined as being a case that cannot fulfill the created model's projected function. In a failure case, limit state function can be written as $g(\tilde{X})=g(X_i,...,X_n)$ and basic variables vector in the considered collapse case as $\tilde{X}=(X_i,...,X_n)$. A considered n-dimensional limit state function in space creates a collapse surface that divides the space of basic random variable into two regions such as a failure domain D_f and a reliable (safety) domain D_S. Failure domain includes all of $\tilde{X}$'s cases that will end in failure and likewise safety domain includes all of the cases of $\tilde{X}$ that will end in resistance. It will be appropriate to define failure domain by the Equation 2. In this equation, g function's positive values will indicate variables' safe sets (the safe region), g function's negative values will indicate variables' unsafe sets (the failure region). As the basic variables composing the limit state function have random values, the outcome of this function will also be a random variable.

$$g(\tilde{X}) = g(X_1,...,X_n) = 0 \quad (2)$$

In the limit state function mentioned above, the reliability index β is used as the safety measure. Reliability index β is the smallest distance between failure surface and origin [10].

3. UNCERTAINITY ANALYSIS

Uncertainty is generally analyzed under two major titles such as aleatory and epistemic. Aleatory uncertainty arises from the uncertainty in basic variability's own nature. Epistemic uncertainty, on the other hand, derives from models being applied, limited number of data and assumptions and predictions made in the design. Engineering foresight and experience based observations play an important role in epistemic variables' digitizing on an acceptable level and thus in decreasing them. One basic variable's real but unknown value to be gained by taking into consideration different uncertainty sources can be modeled by using the following equation [9].

$$X_i = N_i \hat{X}_i \quad (3)$$

Here: X_i is the real value of any basic variable, N_i is the random correction factor to be applied in order to take epistemic uncertainties into consideration, $\hat{X}_i$ is the model to predict X_i.

Epistemic uncertainty sources are shown by Δ_{X_i} and aleatory uncertainty are quantified by δ_{X_i}. The mean value of correction factor N_i is symbolized by $\overline{N}_i$ and X_i 's mean value is $\overline{X}$. Total uncertainty is calculated by combining aleatory uncertainty and epistemic uncertainty by the following formula [11].

$$\Omega_{X_i} = \sqrt{\delta_{X_i}^2 + \Delta_{X_i}^2} \tag{4}$$

Correction factor N_i is acquired by multiplying each correction factor proposed for every epistemic uncertainty source respectively. Mean correction factor $\overline{N}_i$ and total epistemic uncertainty Δ_{X_i} can be found by using the following formulas [11, 12].

$$\overline{N}_i = \overline{N}_{i1}\overline{N}_{i2},...,\overline{N}_{in} \tag{5}$$

$$\Delta_{X_i} = \sqrt{\Delta^2 X_{i1} + \Delta^2 X_{i2} +,...,+ \Delta^2 X_{in}} \tag{6}$$

4. RESISTANCE MODEL

The nominal resistance of reinforced concrete structural member proposed by standards and regulations will relatively be different from real resistance due to deviations of dimensions intended in the original design, variables in mechanical properties of materials and inefficiency of modeling being used in calculating structural component resistance. In this study, basic variables affecting the shear strength of reinforced concrete beams having rectangular cross-section will be analyzed and statistical parameters of these basic variables will be calculated which will be necessary in order to carry out a reliability analysis.

4.1. Concrete Compressive Strength

In order to specify statistical parameters of compressive strength of concrete being used in Turkey, the concrete compressive strength test results have been obtained from material laboratories operating in different cities of Turkey. The laboratories from which the data gained are construction material laboratories of official institutions such as universities, Turkish Chamber of Civil Engineering, General Directorate of State Hydraulic Works, Ministry of Environment and Urbanization or private institutions in cities of Ankara, Istanbul, Konya, Corlu, Trabzon, Erzurum, Kayseri, Samsun, Bursa, Izmir, Gaziantep, Denizli, Antalya and Malatya. Some statistical parameters are given in Table 1 according to concrete classes, which are acquired as a result of analyzing test reports arranged after the testing of 150 mm cube samples coming to these laboratories. In this table, $f_{ck,cyl}$ represents characteristic standard cylinder compressive strength of concrete and $f_{ck,cub}$ concrete's equivalent cube compressive strength. Coefficient of variation (COV) is defined as the ratio of standard deviation to mean value.

11085 numbers of 28 days and 6235 numbers of 7 days cube samples' test results have been analyzed for the purpose of calculating statistical parameters of concrete compressive strength, as it is seen in Table 1. Here, the ratio of the mean value of concrete compressive strength to the value given in concrete standards which is identified as "nominal" will be calculated. Thus, by taking sample numbers into consideration, weighted average nominal concrete compressive strength has been found. When all of the 28 day concrete samples are considered according to their sample numbers in accordance with their concrete class, the weighted average (mean) concrete compressive cube strength has been found to be μ=29.87 MPa, and for all 7 day samples has been found as μ=24.20 MPa. Based on these results, as a result of concrete's current design and applications, it can be said that concrete has gained 80 % of the resistance it would gain in 28 day just in 7 days. Besides, when all concrete classes are considered, the average of COV of 28 day samples has been found to be δ=0.105 and that of 7 day samples has been found to be 0.132.

By converting statistical parameters in Table 1, which have been obtained from cube sample test results, into standard cylinder compressive values, the mean compressive strength has been found to be μ_{fc}=24.87 MPa and COV of compressive strength to be δ_{fc}=0.105. It is to be noted that there are some changes between a construction's actual concrete strength value and the designed concrete strength targeted to be specified concrete class.

Table 1. Statistical parameters of 7 and 28 day compressive strength data according to concrete class for Turkey

Concrete class	**C14**		**C16**		**C18**		**C20**		**C25**		**C30**	
Concrete age	7 days	28 days	7 days	28 days	7 days	28 days	7 days	28 days	7 days	28 days	7 days	28 days
Number of samples	24	137	418	755	538	739	3091	5817	1701	2767	463	870
$f_{ck,cyl}$ ($f_{ck,cub}$) (MPa)	14(18)		16(20)		18(22)		20(25)		25(30)		30(37)	
Mean , μ (MPa)	14.32	20.04	20.26	25.11	18.69	25.82	23.04	28.46	26.85	32.48	32.63	40.07
Standard deviation, σ	2.28	2.87	3.12	3.62	2.86	3.10	3.04	2.96	3.46	3.25	3.26	3.17
COV	0.159	0.143	0.154	0.144	0.153	0.120	0.132	0.104	0.129	0.100	0.100	0.079

Moreover, some differences can be observed between compressive strength of concrete targeted in design of concrete class and those of samples taken from the same concrete. The main reasons of these differences are said to be due to concrete mixing ratios, quality of aggregate being used in making concrete, variables found in cement and admixtures, the variables in concrete mixing, transporting, placing, vibrating and curing processes, variables deriving from compression test's itself and similar inefficiencies. Moreover, the shapes of samples, sample dimensions, preparation, cure to be applied on them, the properties of caps made for cylinder samples and the number of samples in order to determine the compressive strength are the variabilities of samples itself [12, 13]. The differences and variables mentioned above can be stated as prediction uncertainty sources in concrete compressive strength. Firat and Yucemen [12] digitized this approximate prediction uncertainty as 0.14.

In a similar study, Komurcu and Yucemen [14] digitized the total uncertainty as 0.21 according to design and practice criteria in Turkey. Real et al. [15] have used three different values of the total uncertainty as 0.10, 0.15 and 0.20 respectively in their own study. Celik and Elingwood [16] used the value of total uncertainty as 0.18 for concrete compressive strength. Schlune et al. [17] used total uncertainty values of 0.16 and 0.11 for C25 and C 45 concrete classes, respectively. On the other hand, in our study, as a result of combining aleatory and epistemic uncertainty by using Equation 4, the total uncertainty has been found as $\Omega_{f_c} = \sqrt{0.105^2 + 0.14^2} = 0.18$. This result is in accordance with the values of the total uncertainty suggested in the literature.

When the uncertainty sources mentioned above are considered, the current concrete compressive strength (real) in a construction is anticipated to be 72% of the compressive test results of samples tested in laboratories [12,18]. Since the weighted average compressive strength obtained from samples has been found as 24.87MPa, the "real" compressive strength in a structure will be 0.72x24.87= 17.87 MPa. This value will be used as $\bar{f}_c$. Concrete nominal compressive strength also will be found as 21.55 (**14**x137+**16**x755+**18**x739+**20**x5817+**25**x2767+**30**x870)/11085) when considering the number of data for each concrete class in Table 1. In TS 500-2000 (Requirements for Design and Construction of Reinforced Concrete Structures) [19] it is indicated that γ_{mc}=1.5 will be taken for the cast-in place concretes but under circumstances in which quality control of concrete has not been properly done this coefficient will be taken as 1.7 with the designer's decision. In this study, material coefficient (partial factor) for concrete has been taken as γ_{mc}=1.5, and nominal compressive strength is acquired as $\frac{21.55}{1.5} = 14.37$. Here, this value will be indicated as "nominal" value and the one obtained as a result of statistical data analysis will be defined as "real" mean value. In this study, the ratio of mean value of compressive strength to nominal value will be used as $\frac{\bar{f}_c}{f_c} = \frac{17.87}{14.37} \cong 1.25$

4.2. Yield Strength of Reinforcing Steel

The data used in this study is obtained from samples brought to university laboratories or obtained from tests carried out for control purpose in iron and steel factories. The reports written after tensile tests have formed the database of this study and statistical parameters such as mean yield strength and COV are acquired at the end of this data analysis.19709 items of S420 reinforcing steel samples that have been subjected to tensile test in Colakoglu, Egecelik, Ekiciler, Habas, Ictas, Kroman and Yesilyurt iron and steel works have been analyzed separately according to their bar diameters. Statistical parameters of yield strength of reinforcing steel evaluated in factories having diameters from 8 mm to 26 mm are summarized in Table 2. Statistical parameters of 5693 items of S420 reinforcing steel samples subjected to tensile tests in laboratories of Istanbul Technical University, Middle East Technical University and Selcuk University are summarized in Table 3 according to their diameters respectively, and the factories in which these samples are produced are unknown.

Table 2. Statistical parameters belonging to yield strength of S420a reinforcing steel produced in different iron and steel factories

Iron and steel factory	**Factory I**	**Factory II**	**Factory III**	**Factory VI**	**Factory V**	**Factory VI**	**Factory VII**	**Overall**
Sample number	1073	1673	3024	2390	9619	1400	530	19709
Yield strength (MPa)	489.71	460.71	464.4	480.94	530.01	516.79	473.63	503.46
Standard deviation	25.46	16.12	16.72	22.60	18.02	--	22.73	19.13
COV	0.052	0.035	0.036	0.047	0.034	--	0.048	0.038

Table 3. Statistical parameters that belong to tensile tests of S420a reinforcing steel tested in different university laboratories

Diameter (mm)	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**Overall**
Sample number	644	817	945	750	859	438	739	452	5693
Yield strength (MPa)	477.36	500.02	504.52	481.90	493.26	492.28	516.27	505.81	497.96
Standard deviation	67.79	71.50	64.07	56.86	73.99	67.44	61.44	49.57	66.73
COV	0.142	0.143	0.127	0.118	0.150	0.137	0.119	0.098	0.134

The mean yield strength has been calculated as 502.23 MPa by evaluating production reports of iron and steel factories and sample test reports obtained from universities. Since the origin of the samples brought to the university laboratories are unknown, they reflect a great number of factory criteria together. For this reason, COV will be used in its simplest form as 0.038 for uncertainty analysis depending upon the production reports of iron and steel factories.

The basic uncertainty sources in yield strength of reinforcing steel can be considered as the variables in cross-sectional area, variables deriving from using the reinforcing steels obtained from different factories together in a construction, variables stemming from using the reinforcing steels acquired from the same factory that were produced in different times in a construction together, the strain effect during yielding of reinforcing steel while test is being carried out, load speed effect during tensile test and the effects of bar diameters. The variables and uncertainty mentioned above are defined as prediction uncertainty in yield strength of reinforcing steel. In the studies, if the uncertainty sources mentioned above are considered, the mean yield strength of reinforcing steel in a construction (real) becomes 90% less than mean yield strength that is obtained from samples subjected to tensile strength test and estimated uncertainty is calculated to be 0.08 [12,18]. Thus, mean yield strength of steel has been found as 0.9x 502.33= 452.10 MPa. Nominal yield strength is 365 MPa (420/1.15) as it is given in TS 500-2000. Consequently, the ratio of mean value of yield strength to the nominal value will be taken as 1.24 ($\bar{f}_y / f'_f$ =452.10/365).

In a similar study, Komurcu and Yucemen [14] digitized the total uncertainty as 0.14 according to the design and application criteria in Turkey. Real et al [15] accepted the values of 0.05 and 0.10 in their studies. Celik and Elingwood [16], on the other hand, used the value of 0.11 as the total uncertainty in yield strength. Schlune et al. [17] took the value of 0.054 as the total uncertainty in yield strength. In this study, after performing uncertainty analysis, the total uncertainty in yield strength of reinforcing steel will be found as $\Omega_{f_y} = \sqrt{(0.038^2 + 0.08^2)} \cong 0.09$ by using Equation 4.

4.3. Dimensions

The variables of structural members' dimensions affect structural members' weight, strength and strain. These variables are closely linked with activities of concreting and vibrating, workmanship mistakes, production techniques and the properties of the molds used. In order to determine the variables in dimensions of concrete beams 6043 measurements have been made in total. Measurements have been carried out in cities of Istanbul, Ankara, Konya, Adana, Malatya and Ordu to decrease the differences of design and application criteria in different regions. As a result of measurements, the rate of acquired mean value to nominal value has been found 0.998 for beam width b_w, 0.996 for beam height h and 1.00 for beam effective depth. Furthermore, aleatory uncertainty has been found as 4.5 % for beam width, 2.5 % for beam height and 2.4 % for beam effective depth. Prediction uncertainty (epistemic uncertainty) can be taken 3% for beam width and height and 7% for beam effective depth [18]. The total uncertainty has been foreseen as 5.4% for beam width, 4% for beam height and 7.4% for beam effective height by using Equation 4.

4.4. Shear Strength of Reinforced Concrete Beams

Reinforced concrete structural members are generally subjected to shear stress together with bending and normal stress. Structural members that are not designed to be resistant to shear stress usually fail in a brittle way. Therefore, while designing structural members, it is not desired that critical failure mode to be shear failure and structural member is required to reach ultimate strength capacity as a result of bending stresses. In TS 500-2000, a structural member's shear strength V_r, is acquired through combining shear reinforcement strength and concrete's strength against shear effect ($V_r=V_c+V_w$). The shear strength of concrete V_c, shear reinforcement strength V_w can be calculated by using the following formulas respectively:

$$V_c = 0.80(0.65 f_{ctd} b_w d \Psi) \tag{7}$$

$$V_w = \frac{A_{sw}}{s} f_{ywd} d \tag{8}$$

Here f_{ctd} is tensile axial strength of concrete, f_{ywd} is yield strength of shear reinforcement, A_{sw} is shear reinforcement total cross-sectional area and s is stirrup spacing. Ψ can be calculated by Equation 9 whether the beam is subjected to axial tension or axial compressive forces. In the equation, γ=0.07 is taken in the case of axial compression and γ=0.03 is taken in the case of axial tension. If axial tensile stress calculated based on concrete cross sectional area is smaller than 0.5 MPa γ can be taken as 0.

$$\Psi = 1 + \gamma \frac{N_d}{A_c} \tag{9}$$

It is very hard to anticipate shear strength of reinforced concrete members correctly since there are many uncertainty sources effecting shear strength [20]. In order to calculate the ratio of mean shear strength which is statistically calculated and described as "real" to nominal shear strength, a computer program has been written in MathCAD 12 in accordance with AFOSM approach. By using different shear reinforcement areas and different beam dimensions, different design cases are taken into consideration in this study. The ratio of statistically calculated mean shear strength to nominal shear strength $\overline{V}_r / V'_r$, is found through putting the mean values and nominal values of basic variables in their positions in Equation 10 and given in Table 4.

$$\frac{\overline{V}_r}{V'_r} = \frac{\dfrac{\overline{A}_{sw}}{\overline{s}} \bar{f}_{ywd} \bar{d} + 0,52 \bar{f}_{ctd} \bar{b}_w \overline{d\Psi}}{\dfrac{A'_{sw}}{s'} f'_{ywd} d' + 0,52 f'_{ctd} b'_w d' \Psi'} \tag{10}$$

Ellingwood et al. [21] take $\overline{V}_r / V'_r$ values as 1.09 for beams. Nowak and Szerszen [22] take this value in their study as 1.23. Somo and Hong [23] define experimentally found reel shear strength's rate to calculated shear strength as modeling mistake and acquired mean of modeling mistake as 1.239. As it is seen in Table 4, for all the cases considered $\overline{V}_r / V'_r$ value changes between 1.242 and 1.245 and its average can be taken as 1.24.

Standard deviation in shear strength σ_{V_r}, can be calculated by using Equation 11 as a consequence of regarding total uncertainty in basic variables such as concrete compressive strength, reinforcement yield strength, spacing of stirrups and beam dimensions.

$$\sigma_{V_r} = \sqrt{\left[\begin{array}{l}\left(\frac{\partial V_r}{\partial As}\right)^2 \sigma_{As}^2 + \left(\frac{\partial V_r}{\partial s}\right)^2 \sigma_s^2 + \left(\frac{\partial V_r}{\partial fyw}\right)^2 \sigma_{fyw}^2 + \left(\frac{\partial V_r}{\partial d}\right)^2 \sigma_d^2 \\ + \left(\frac{\partial V_r}{\partial fct}\right)^2 \sigma_{fct}^2 + \left(\frac{\partial V_r}{\partial bw}\right)^2 \sigma_{bw}^2 + \left(\frac{\partial V_r}{\partial \Psi}\right)^2 \sigma_{\Psi}^2\end{array}\right]} \quad (11)$$

For each design case, when the standard deviation calculated from Equation 11 is divided into the mean value calculated from Equation 10, the uncertainty of shear strength can be defined in terms of COV. As it can be seen in Table 4, the uncertainty of shear strength depending on COV change between 0.116 and 0.157 and its average is found as 0.14.

On the other hand, “real” shear strength of a beam will be different from nominal shear strength which is calculated according to nominal values and acceptances in standards and regulations. In order to take into account this effect Ellingwood et al. [21] and Nowak and Szerszen [22], used 0.115 and 0.10 values as epistemic uncertainty respectively in their studies. In this study, epistemic uncertainty of shear strength will also be taken as 0.10. In conclusion, the total uncertainty of shear strength has found as $\Omega_{V_r} = \sqrt{(0.14^2 + 0.10^2)} = 0.17$ by combining epistemic uncertainty resulting from modeling and average coefficient of variations calculated in this study shown in Table 4 by using Equation 4. Normal distribution has been adopted as probability distribution model [14, 18].

Table 4. The ratios of statistically calculated shear strength to nominal design shear strength and values of coefficients of variation in beam shear strength

b_w (mm)	h (mm)	d (mm)	A_{sw}(mm^2)	s (mm)	$\frac{\overline{V}_r}{V'_r}$	Ω_V
200	400	370	50	180	1.244	0.132
			78.5	180	1.243	0.122
			100	280	1.243	0.126
250	500	460	50	145	1.244	0.132
			100	145	1.243	0.119
			100	230	1.244	0.127
250	700	660	100	330	1.244	0.136
			100	400	1.244	0.138
			200	200	1.242	0.116

Table 4.Continued

bw (mm)	**h (mm)**	**d (mm)**	**A_{sw}(mm^2)**	**s (mm)**	$\dfrac{\overline{V}_r}{V'_r}$	**ΩV**
300	600	570	50	280	1.245	0.157
			78.5	280	1.245	0.144
			100	280	1.244	0.136
300	500	470	78.5	220	1.244	0.137
			100	280	1.244	0.136
			200	400	1.244	0.147
350	700	660	100	330	1.245	0.146
			78.5	320	1.246	0.157
			200	320	1.243	0.125
400	1000	960	78.5	200	1.245	0.142
			100	250	1.245	0.142
			200	350	1.243	0.132
800	300	270	78.5	100	1.245	0.142
			100	150	1.245	0.147
			200	200	1.244	0.135
Average value					**1.244**	**0.136**

5. LOAD MODEL

Different types of loads are incident on a structure. These loads can be separated as primary and secondary loads; dead load, live load, earthquake load, wind load and snow load can be considered as primary ones. Secondary loads can be exemplified such as heat alterations, eccentricity cases that have not been taken into consideration in design of structural members, the shrinkage of building materials and the foundation settlements. In this study, the case created by dead and live loads together are taken into consideration, which will act as an example for other loads and a set of load and resistance factors have been calculated. It is possible to calculate load and resistance factors belonging to other load conditions by using the method and modeling given here after making necessary statistical analysis. It is a must to make detailed and coherent analysis for local and environmental loads such as earthquake, wind and snow through collecting local data.

5.1. Dead Load

The weights of structural members like beam, column, shearwall, floor, roof covering, every kind of flooring and coverings compose dead load in a structure. Compared with the other loads, the uncertainty amount in dead loads is quite low. However, some uncertainty will occur stemming from mistakes and variables in dimensions of structural members, the differences between the real and anticipated weights of materials being used and the modeling.

In Table 5, the ratio of mean dead load obtained statistically to nominal value anticipated in standards and regulations and total uncertainty values of this load are summarized. As it can be understood from this table, the ratio of mean dead load to its nominal value $\overline{D}/D'$ is between 1.00 and 1.05 and the total uncertainty in this load changes between the space of 0.05 and 0.10. Many researchers indicate that the probability distribution of dead load is normal. In a study carried out in Turkey, Komurcu and Yucemen [12] take dead load distribution as normal. At the same time, in this study the ratio of mean value to nominal one and the uncertainty are given as 1.05 and 0.10, respectively. While specifying statistical parameters of dead load, researchers used very close values to each other. Also, the ratio of mean value to nominal one $\overline{D}/D'$ will be taken as 1.05 and the total uncertainty will be Ω_D, 0.10 in this study.

Table 5. The ratio of mean dead load to nominal given in different studies and the total uncertainty value in dead load [21]

Field Researches	$\overline{D}/D'$	$\mathbf{\Omega_D}$
Galambos and Ravindra(1973)	1.0	0.08
Allen, 1976	1.0	0.10
Ellingwood(1978)	1.0	0.10
Lind(1976)	1.05	0.09
Lindet al.(1978)	1.0	0.05
Ellingwood et al.(1980)	1.03	0.10

5.2. Live Load

Live loads generally indicate storage materials in the construction apart from dead loads, light division walls not carrying loads, crane, machine, equipments, humans, and furniture weights. Besides, this load includes gathering of people in the building encountered seldomly throughout a construction’s lifespan, collecting the furniture in a building for decoration and alteration purposes. Live loads may show different features in various categories like hospitals, hotels, shopping malls, factories, temples, houses and office areas. In some of these categories, human concentration in some fields composes main source of live load.

Many live load researches were conducted approximately 30 years ago and despite the time taken, presenting this load more scientifically has not been achieved due to data deficiency and inadequacies of statistical analysis in these studies. It is natural for live loads to differ in terms of countries, traditions in countries and regions and geographical areas in the same country. Besides, this difference amount is less important than those of especially snow, wind and earthquake loads. In a study carried out by Kumar [24], it is stated that general characteristics and variabilities of statistical analysis of live loads made in England, USA, Austria and India are very similar.

Live load examples that a construction will meet throughout its lifespan are very changeable and some cases may not be predicted while designing the construction. Moreover, live load may change randomly according to areas in the construction and time. Live load is generally modeled by dividing into two components. One of these components is "arbitrary point in time live load" L_{apt} showing load's any value in any time. These kinds of loads are those which are accepted to affect the construction constantly by taking different values throughout the time. The second live load component in modeling, on the other hand, is the maximum live load L, that the construction will meet throughout its lifespan. Maximum live load value, L can be calculated by adding arbitrary point in time live load value with the live load values that will occur in extraordinary cases like human collecting or furniture gathering.

5.2.1. Arbitrary Point in Time Live Load L_{apt}

Some live load researches have been conducted in various countries using statistical load models. Although many of these studies are made for the office buildings, some other live loads researches have also been made for residential buildings, retail establishments and other types of constructions. A summary of data obtained by load researches made in the field depending upon measurements and observations is given in Table 6. Among the differences of these researches, the number of measurements and observations, year differences between different field researches, data gathering method, time differences of observation and measuring times, the cultural values related to the socio-economic levels of the people using the relevant construction, the kind of equipments and devices and their usage span can be regarded.

By taking the studies given in Table 6 into consideration, the average arbitrary point in time live load to be used is taken as 0.55 kN/m^2. This value is the average of four live load field researches given in Table 6. Furthermore, average COV (aleatory uncertainty) is chosen as 0.78 considering the values given in Table 6.

When live load is considered, converting uniformly distributed load into load effect and the modeling presented in structural analysis can be evaluated as basic uncertainty sources. Epistemic uncertainty found after uniformly distributed load into load effect can be digitized as Δ_C=0.05 and epistemic uncertainty deriving from the modeling can be digitized as Δ_N=0.10 [21, 27]. Total epistemic uncertainty arising from these two basic uncertainty sources can be calculated from Equation 6 as $\Delta_L = \sqrt{0.10^2 + 0.05^2}$ =0.11. Consequently, when Equation 4 is used in order to combine aleatory and epistemic uncertainty, the total uncertainty in arbitrary point in time live load is found as $\Omega_L = \sqrt{0.11^2 + 0.78^2} = 0.79$.

Komurcu and Yucemen [14] and Elingwood et al. [21] have taken the total uncertainty in arbitrary point in time live load as Ω_{Lapt}, 0.60 in their studies. In this study, the average of 0.60 and 0.79 values found above will be taken as Ω_{Lapt}=0.70. In Turkish Standard TS 498-97 (Design loads for buildings) [28] the nominal live load, L', is given as 2 kN/m^2 for housing or terrace room and corridors, stores up to 50 m^2, hospital rooms and offices.

Accordingly, the ratio of mean arbitrary point in time live load to nominal one is calculated as $\frac{\overline{L}_{apt}}{L'} = \frac{0.55}{2} = 0.275$. Gamma probabilistic distribution is advised for arbitrary point in time live load [14, 21, 24].

Table 6. Field research results compiled for arbitrary point in time live load [25, 26]

Field research	**Room floor area (m^2)**	**Mean live load (kN/m^2)**	**Standard deviation (kN/m^2)**	**COV**
Mitchell and Woodgate (1971)	2.4	0.66	0.65	0.98
	5.2	0.64	0.53	0.83
	14.0	0.62	0.43	0.69
	31.2	0.61	0.34	0.56
	58	0.59	0.30	0.51
	111.3	0.58	0.26	0.45
	192.4	0.56	0.21	0.38
Culver (1975)	A≤4.7	0.83	0.82	0.99
	4.7<A≤9.3	0.63	0.60	0.95
	9.3<A≤27.9	0.44	0.31	0.70
	A>27.9	0.42	0.43	1.02
Choi (1992)	A≤5	0.50	0.66	1.32
	5<A≤10	0.62	0.64	1.03
	10<A≤20	0.55	0.47	0.85
	20<A≤40	0.45	0.53	1.18
	40<A≤80	0.43	0.45	1.05
	A>80	0.51	0.41	0.80
Kumar (2002)	A≤8	0.68	0.41	0.60
	8<A≤16	0.60	0.32	0.54
	16<A≤24	0.50	0.36	0.72
	24<A≤32	0.50	0.29	0.58
	32<A≤40	0.47	0.26	0.55
	40<A≤48	0.45	0.24	0.53
	48<A≤56	0.45	0.25	0.56
	64<A≤72	0.46	0.15	0.33
	72<A≤80	0.46	0.19	0.41
	A>80	0.31	0.20	0.65

5.2.2. Maximum Live Load (L)

Maximum live load, L used in structural designs consists of arbitrary point in time live load affecting structure during its lifespan and extraordinary load affecting it under extraordinary circumstances. Arbitrary point in time live load can be regarded as load arising as a result of normal daily activities in a structure. Crowding of people or stacking of furniture causes additional loads which act at a moment during the lifetime of building except for sustained load. This type of load can be defined as extraordinary live load.

Arbitrary point in time live load affecting the construction at any time is determined as a result of field researches. On the other hand, it is not possible to determine the value of maximum live load, which is expected to affect the construction at any time during its lifespan, since field researches are limited to a certain time. In addition to field researches, extraordinary load cases should be predicted. As maximum load's probabilistic distribution, Komurcu and Yucemen [14], Ellingwood et al [21] and Kumar [25] used Type 1 extreme value distribution in their studies. In this study, Type 1 extreme value distribution is used as well. Some results of studies on maximum live load for office buildings are given in Table 7. Although these results are obtained for office buildings, multi-layered residential and retail establishments also show similar features [21].

Aleatory uncertainty, δ_L, will be taken as 0.17 as the average of the values given in Table 7. In studies carried out by Elingwood et al. [21] and Komurcu [27], epistemic uncertainty is anticipated as Δ_C=0.05 while converting equivalent uniformly distributed load into load effect and epistemic uncertainty resulting from modeling is predicted as Δ_N=0.20. In this study, these values are taken. Total epistemic uncertainty caused from these two basic uncertainty sources are calculated from Equation 6 as $\Delta_L = \sqrt{0.05^2 + 0.20^2}$ =0.21. When Equation 4 is used in order to combine aleatory and epistemic uncertainty, the total uncertainty in maximum live load is found as $\Omega_L = \sqrt{0.21^2 + 0.17^2} = 0.27$.

Komurcu and Yucemen [14] and Nowak and Szerszen [29] suggest the ratio of maximum live load to nominal live load as $\overline{L}/L'$, 1.00. In this study, also, this ratio will be used as 1.00 in calculations.

Table 7. The ratios of mean maximum live load to nominal live load given in different studies and COV of maximum live load [21]

Studies	**Area**							
	18.58 m^2		**92.9 m^2**		**464.5 m^2**		**929 m^2**	
	$\overline{L}/L'$	δ_L	$\overline{L}/L'$	δ_L	$\overline{L}/L'$	δ_L	$\overline{L}/L'$	δ_L
McGuire and Cornell (1973)	1.38	0.14	-	0.13	-	0.15	-	0.15
Ellingwood and Culver (1977)	1.11	0.19	-	0.16	-	0.16	-	0.16
Chalk and Corotis (1979)	1.18	0.18	-	0.13	-	0.10	-	0.09
Sentler (1975)	-	0.26	-	0.18	-	0.14	-	0.12

6. SAFETY LEVEL IN CURRENT DESIGN PRACTICE

In this study, the case of the reliability of a structural member in its most general state is defined as the following:

The value of resistance multiplied by resistance factors	>	The effects of loading multiplied by load factors

In the limit case equation mentioned above, resistance factors are generally lower than 1.0 and load factors are generally higher than 1.0. The risk level in current design practice depending upon standards and regulations is determined at first while specifying factors of load and resistance. If this risk level is an acceptable value, load and resistance factors are calculated according to this current risk level. While determining risk levels according to AFOSM method, reliability index β is used as the reliability parameter. Reliability index β is a crucial reference source in determining target variability β_T to be used in specifying load and resistance factors. As β values indicating current case include deficiencies in standards and regulations, they should not be taken as the sole parameter in determining β_T values. In the current practice, while determining shear strength in beams, TS500-2000 has been taken into consideration and loads affecting beams have been taken from TS-498-97.

The relative frequency distribution values of the ratio of live load to dead load are given in Table 8 if the conditions in Turkey are taken into account [18].The value of reliability index β can be calculated for each case indicated in the table separately. The weighted average of these values, which will be gained from relative frequency distribution, will give expected value of $\overline{\beta}$.

Table 8. Relative frequency distribution of live load [18]

The ratio of live load to dead load, L'/D'	0.25	0.50	1.00	2.00	3.00
Relative frequency values for live load	0.10	0.45	0.35	0.10	0.00

Load combination equation for live and dead load suggested in TS 500-2000is given in the following:

$$F_d = 1.4G+1.6Q \tag{12}$$

Here F_d represents design load effect, G represents dead load and Q represents live load.

The reliability index β for shear strength of reinforced concrete beams that are under the effect of dead and live loads is calculated and given in Table 9 depending upon the load combination type proposed in TS 500-2000 and load effects given TS 498-97. In this table, β values have been found considering the values of design variables determined for four design cases. In computing R'/D' values, the safety criterion (R= 1.4D+1.6L) specified in TS 500 (2000) is used and relative frequency distribution values for L'/D' ratio are taken from Table 8.

Table 9. Reliability indices and design situations for the shear failure mode of reinforced concrete beams subjected to D+L combination

	$\frac{R'}{D'}$	$\frac{D'}{D'}$	$\frac{L'}{D'}$	β	Expected value of reliability index $\overline{\beta}$
Design Situations	1.8	1	0.25	2.36	2.41
	2.2	1	0.50	2.42	
	3.0	1	1.00	2.42	
	4.6	1	2.00	2.35	

As it can be seen in Table 9, the reliability index β for dead and live load combination change in a narrow range between 2.35 and 2.42 depending upon design cases (L'/D' ratios) and its expected value $\overline{\beta}$ is 2.41. In Figure 1, the expected value of reliability index and its distribution around expected value according to design cases are shown. These values reflect the risk levels of reinforced concrete beams in terms of available design and practice criteria when load effect and load combination type suggested in TS 498-97 and TS 500-2000 standards. It is necessary that specific level of risk should be targeted in determining new load and resistance factors to be suggested. Ellingwood et al. [21] indicated in their studies that expected value of reliability index of current risk level for shear strength of reinforced concrete beams, $\overline{\beta}$, change between 1.99-2.45 and suggest the value of target reliability index of β_T as 3.0. In a similar study, Nowak and Szerszen [29] calculate the $\overline{\beta}$ value indicating risk level of current case as 3.83; however as this value stays in a very safe place, they suggest the value of target reliability index β_T as 3.5 for reinforced concrete shear strength. In this study, $\overline{\beta}$ value is calculated as 2.41 ($P_f \cong 7.98 \times 10^{-3}$), yet, as this value is lower than other target reliability values used in literature, it is approved that β_T value should be taken as 3.0 ($P_f \cong 1.35 \times 10^{-3}$) in determining the new load and resistance factors to be suggested.

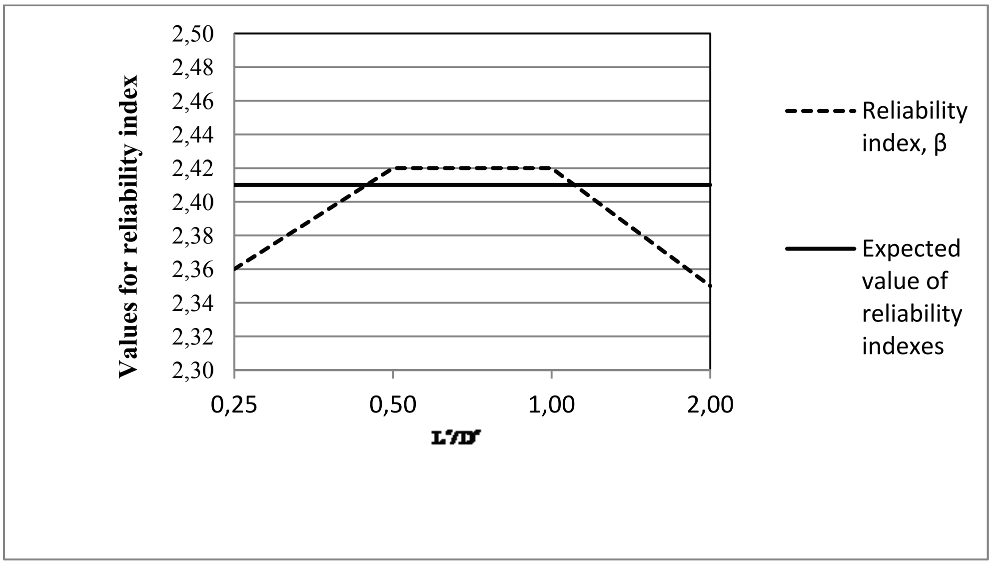

Figure 1. The variation of reliability index for D+L load combination

7. LOAD AND RESISTANCE FACTORS

The ratios of mean values to nominal values of basic variables such as compressive strength of reinforced concrete, yield strength of reinforcing steel and dimensions to be used in structural member modeling, and also the uncertainty in these basic variables can be quantified. By using these quantified values, the ratio of mean value to nominal value of a structural member in a failure mode considered and the total uncertainty in its modeling can be calculated. Moreover, the ratios of mean value to nominal values of load parameters in load combination and the uncertainty in these load parameters can also be calculated.

The current level of risk in current design and practice is firstly determined by using the ratios of mean values to nominal values mentioned above and COV reflecting the uncertainty. In this study, reliability index $\overline{\beta}$ that represents risk level of current state is calculated as 2.41. However, this value is increased due to reasons explained in previous section and the value of reliability index β_T value is taken as 3.0. A set of new load and resistance factors for reinforced concrete beams according to shear failure mode are calculated in terms of AFOSM method and given in Table 10.

As it can be seen in Table 10, resistance factor ϕ change between 0.63 and 0.776 depending on L'/D' ratios for dead and live load combination. The values of dead load factors undergo an alteration between the values of 1.071 and 1.119 and the values of live load factors change between 1.072 and 1.593. The distribution of load and resistance factors is shown in Figure 2.

Table 10. Load and Strength Coefficients Calculated for Shear Strength of Reinforced Concrete Beams

The ratio of live load to dead load L'/D'	Relative frequency values for live load	Resistance factors ϕ	Dead load factors γ_1	Live load factors γ_2
0.25	0.10	0.63	1.119	1.072
0.50	0.45	0.643	1.106	1.194
1.00	0.35	0.684	1.088	1.404
2.00	0.10	0.776	1.071	1.593

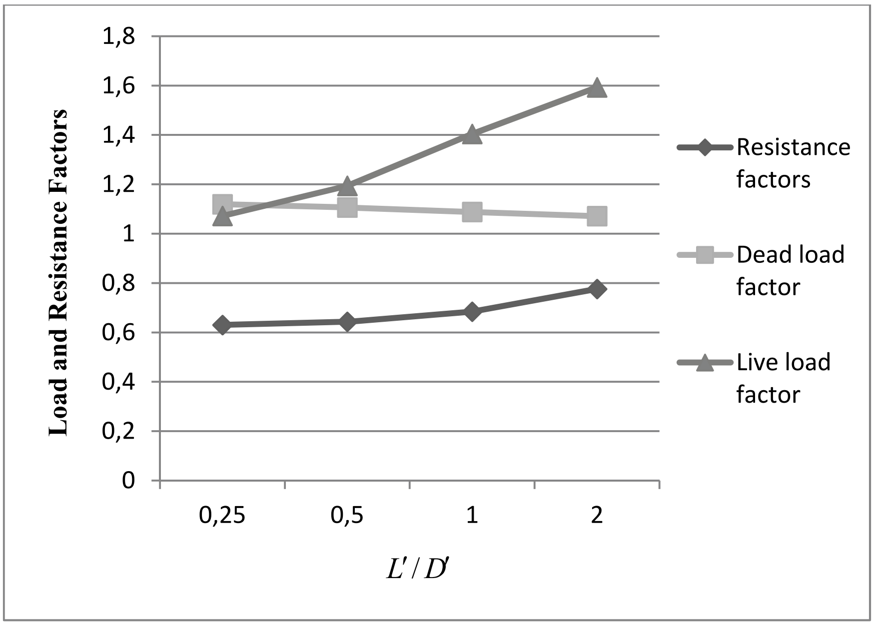

Figure 2. The variation of load and resistance factors

As it is seen in Figure 2, as the ratio of live load to dead load increases, the live load factor also increases. Although dead load factor doesn't show a great deviation from 1.1 value, it will be taken as 1.2 in this study. In the case of using one single live load factor as in standards and regulations, there will be some deviations from targeted reliability index of β_T. This situation will require the solution of an optimization problem minimizing the deviations from β_T value. Consequently, the new load and resistance factors obtained in this way are defined as optimal load and resistance factors and given in Equation 13.

$$0.80R=1.20D+1.70L \tag{13}$$

As mentioned before, it is possible to identify the valid risk level by using the ratios of mean value to nominal value for each design variable taking current design and practice criteria into consideration. In this study, it is stated that reliability index that represents risk level of current situation changes between 2.36 and 2.42 and its mean is $\overline{\beta}=2.41$. The new load and resistance factors for shear strength of reinforced concrete beams are calculated and suggested in Equation 13 together with slight changes, by taking target reliability index β_T value as 3.0. The risk level calculated according to these load and resistance factors is required to be close to $\beta=3.0$. The values of reliability index β, which are calculated by taking the new load and resistance factors suggested in Equation 13, change between the values of 2.83 and 3.06 and its mean becomes 3.0. This reliability index value indicates that the new load and resistance factors provide the required risk level.

8. RESULTS

In this study, a probabilistic method directed to determine new load and resistance factors for reinforced concrete structural members are presented. This method is applied to beams in shear failure mode for dead and live load combination. First, the values of statistical parameters of basic design variables used in modeling of beam shear strength are found depending on the obtained data. The statistical parameters of shear strength are calculated by using these statistical parameters. Then, dead and live loads are examined in detail and the uncertainty in these loads is quantified. By using all these values, the load and resistance factors are calculated according to AFOSM method depending on targeted reliability level. The results obtained are given in the following respectively:

The ratios of statistically calculated mean shear strength to nominal shear strength and the uncertainty value in shear strength of beams are calculated for different design cases by using a MathCAD 12 program prepared for this study. For all the cases considered, the mean value of $\overline{V}_r / V'_r$ is found as 1.24 and the total uncertainty value Ω_{V_r} in beam shear strength is found to be 0.17.

In this study, the ratio of mean dead load to nominal value $\overline{D}/D'$ is proposed as 1.05 and the total uncertainty in dead load Ω_D is proposed as 0.10. The ratio of mean arbitrary point in time live load to nominal one is calculated as 0.275. The total uncertainty in arbitrary point in time live load is found as 0.79. The ratio of mean maximum live load to nominal live load is taken as 1.00 and the total uncertainty in maximum live load is calculated as 0.27.

The reliability index β for the combination of dead and live load (R=1.4G+1.6Q) for a reinforced concrete beam according to current practice and design criteria changes between a narrow margin between 2.36 and 2.42 depending on design cases (L' / D' ratios) and the expected value of reliability index $\overline{\beta}$ is calculated as 2.41. The value of target reliability index β_T for new load and resistance factors is taken as 3.0. As a consequent, new load and resistance factors are calculated according to AFOSM method and following design criteria is suggested.

$0.80R > 1.20D+1.70L$

There are significant changes between load and resistance factors obtained as a result of this study and existing load and resistance factors. Although it is a known fact that the magnitude of load factors is directly proportional to uncertainty in loads, the usage of the value of 1.40 for dead load having comparatively less uncertainty is an approach staying in the safe side with respect to current design and practice criteria.

Here, the statistical parameters of ribbed reinforcing steel and concrete depending on a very broad statistical analysis can be used in determining the reliability of other reinforced concrete structural members in different failure modes. While carrying out reliability analysis of structural members like column and shear wall, the statistical parameters of other design variables used in modeling can also be obtained by using the proposed method in this study.

The statistical analysis of environmental loads such as snow, wind, earthquake that show alterations according to location should be performed based on a broad data source. Besides, the statistical parameters of dead and live load proposed in this study can be used in other studies as well.

For steel, masonry and other reinforced concrete structural members, the new load and resistance factors that could be used in the recent design and practice criteria can be calculated by making use of the method adopted here.

Symbols

A_c Cross sectional area of structural member

A_{sw} Cross sectional area of stirrups

b_w Beam width

D Dead load effect

D_f Failure domain

D_s Safety domain

d Depth of beam

$f_{ck,cub}$ Equivalent concrete compressive cube strength

$f_{ck,cyl}$ Standard concrete compressive cylinder strength

f_{ctd} Tensile axial strength of concrete

f_y Yield strength of reinforcing steel

f_{ywd} Yield strength of shear reinforcement)

L Live load

L_{apt} Arbitrary point in time live load

N Random correction factor

N_d Axial load

P_f	Probability of failure
P_s	Survival probability (reliability)
R	Generalized resistance
s	Spacing of stirrups
V_r	Shear strength
V_c	Shear resistance of concrete
V_w	Resistance of shear reinforcement
X	Basic random variable
$\overline{X}$	Mean value of X
X'	Nominal value of X
β	Reliability index
β_T	Target reliability index
γ	Load factor
γ_{mc}	Material factor for concrete
γ_{ms}	Material factor for reinforcing steel
Δ	Epistemic (prediction) uncertainty
δ	Aleatory uncertainty
μ	Mean value
σ	Standard deviation
Ω	Total uncertainty
ϕ	Resistance factor

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