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Reliability Construction of Multi-story Reinforced Concrete Buildings

Toshihiko Yamamoto
Professor, Department of Architecture
Daido Institute of Technology, Nagoya, Aichi, Japan

Abstract

This paper explains a reliability construction method to prevent structural damage such as cracking, excessive deflection and yielding of structural members during the construction of reinforced concrete buildings. The structural damage remains after construction and affects the building's lifetime serviceability. An improved nonlinear analysis model of construction loads on the supporting floors of multi-story reinforced concrete buildings was presented and Monte Carlo simulations were performed to examine the variation of the construction loads for the reliability construction. The results indicate that the construction loads are inevitably heavy and the creep deformation is not negligible. The coefficient of variation due to the variation of concrete strength and Young's modulus and shore rigidity was less than 10% for the construction loads and about 20% for the creep deformation during construction. The results of the nonlinear analysis and Monte Carlo simulations are compared with field measurements.

Keywords

Reliability construction, Multi-story concrete building, Construction load, Cracking, Deflection

1. Introduction

In the current formwork for multi-story reinforced concrete buildings, a freshly placed floor is shored by several of the previously cast floors. Many field and analytical researches (Chen and Mosallam, 1991) on the construction loads on supporting floors have been performed in recent decades with results indicating that the construction loads may exceed the load-carrying capacity of the structures before reaching their specific concrete strength. Although in the reliability-based construction method it is necessary to consider both the magnitude and variation of the construction loads, the previous researches were mainly focused on the magnitude. Besides, the previous analytical models of the construction loads are insufficient to represent the nonlinear behavior and thermal effect of the concrete columns. This paper presents an improved nonlinear analysis model of the construction loads reflecting the vertical thermal deformation of the columns and the shrinkage of formwork. Using this model, Monte Carlo simulations were performed to evaluate the variation of the construction loads under several affecting factors.

2. Nonlinear Aanalysis Model of the Construction Loads

The structural model for the nonlinear analysis of the construction loads is composed of slabs, beams and columns as shown in Fig. 1.

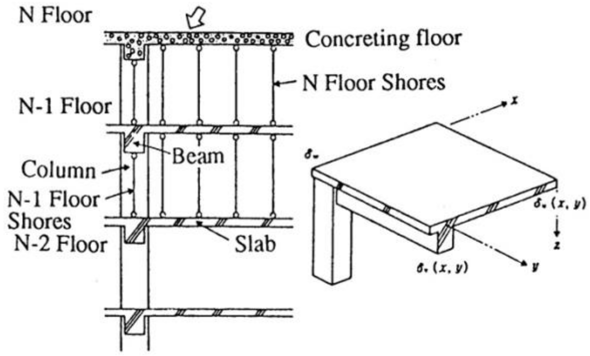

Figure 1: Structural Model

2.1 Time-dependent Strains of Concrete

The time-dependent concrete strains affecting construction loads are written as:

□ (*t*) =□□□□□□(*t*) +□□□c (*t*) ; for beams and slabs (1)

□ (*t*) =□□□□□(*t*) +□□□c (*t*)+□□ *T* (*t*) ; for columns (2)

where □□□□ and □□c are the elastic and creep strains, respectively; □□*T* is the thermal strain.

2.2 Time-dependent Deformation of Slabs, Beams and Columns

Since the deformed forms of slabs and beams after being subjected to construction loads are almost similar to the deformed forms under self-dead loads, the deformation of the i_{th} floor slab and beam can be expressed as a time-dependent function in the XY plane:

□□*u,i*□(*x*,*y*,*t*)=□□□*so*□(*x*,*y*)･*u*□*i*□(*t*) (3)

□□*v,i*□(*x*,*y*,*t*)=□□□*bo*□(*x*,*y*)･*v*□*i*□(*t*) (4)

where □□*so*□(*x*,*y*) and □□*bo*□(*x*,*y*) denote the slab and beam deformation by self-dead loads, respectively; *u*□*i*□and *v*□*i*□ are deformation parameters.

The deformation of the i_{th} floor column can also be expressed as:

□□*w,i*□(*t*)=□□ *co*･*w*□*i*□(*t*) (5)

where □*co* is the column axial deformation by the floor dead load; *w*□*i*□ is a deformation parameter corresponding to the load and load-independent thermal effect. The deformation parameters of the slab, beam and column are obtained from adding the time *t*' for elastic deformation, duration *t*-*t*' for creep, and stress-independent thermal effects (for columns only) as:

$$u_i(t) = E_{c28}\int_0^t \Phi_u(t,t')du_i^{el}(t) \quad (6)$$

$$v_i(t) = E_{c28}\int_0^t \Phi_v(t,t')dv_i^{el}(t) \quad (7)$$

$$w_i(t) = E_{c28}\int_0^t \Phi_w(t,t')dw_i^{el}(t) + w_i^T(t) \quad (8)$$

where *t* and *t*' are the time from casting of concrete and time at loading, respectively; E_{c28} is Young's modulus for concrete at 28 days; □*u* (*t*,*t*'), □*v* (*t*,*t*') and □*w* (*t*,*t*') are the creep functions of the slab, beam and column, respectively;□□ (*t*,*t*') =□□□□*t*,*t*'□□□*co* = □□E_c + □□□*t*,*t*'□□E_{c28} □CEB-FIP□□□□□□□; □□□*t*,*t*'□□is the total elastic and creep strain for the duration of *t*-*t*'; □*co* is the stress at loading; □□□*t*,*t*'□□is the creep coefficient; *du*iel□(*t*'), *dv*iel□(*t*') and *dw*iel□(*t*') are the elastic contributions of each deformation parameter; *w*i□T□(*t*) is the stress-independent contribution, which includes the thermal expansion due to hydration and the differential deformations between the columns and shores due to ambient temperature changes and the drying shrinkage of formwork. These differential deformations are compared to the column deformation.

2.3 Shore Load and Equilibrium of Each Floor Load

The shores are first subjected to a dead load, which includes the formwork at concreting, and then the shore loads change due to the change in the differential deformations of the structural members. It is assumed that the shores are installed close enough to transmit loads. Using the assumption that the deformed forms of the slabs and beams after being subjected to construction loads are almost similar to the same forms under self-dead loads, the shore loads on the i_{th} floor slab and beam can be expressed as follows:

$P_{\square i \square}(t) = W_{so} \cdot p_{\square i \square}(t)$; total slab shore load (9)

$Q_{\square i \square}(t) = W_{bo} \cdot q_{\square i \square}(t)$; total beam shore load (10)

where W_{so} and W_{bo} are the dead loads of the slab and beam, respectively; $p_{\square i \square}(t)$ and $q_{\square i \square}(t)$ are shore load parameters which depend on the shore load distribution in the XY plane.

The equilibrium of each floor load is described as follows:

$W_{s,i}(t) = W_{so} + P_{\square i+1 \square}(t) - P_{\square i \square}(t)$ (11)

$W_{b,i}(t) = W_{s,i}(t) + W_{bo} + Q_{\square i+1 \square}(t) - Q_{\square i \square}(t)$ (12)

$W_{c,i}(t) = W_{b,i}(t) + W_{co} + W_{c,i+1}(t) = (N-i+1)W_o - P_{\square i \square}(t) - Q_{\square i \square}(t)$ (13)

where W_{co} is the dead load of the column; W_o is the dead load of the floor (slab, beam and column).

The construction loads at any time can be calculated through iterative and step-by-step procedures.

3. Properties of Concrete During Construction

According to the report (Takahashi, 1985), the average of 28 days strength of 24,000 specimens by field water curing varies from 1.08 to 1.40 times as large the design nominal strength with the coefficient of variation of 0.10 to 0.14. The variation of actual concrete strength in structures are supposed to be larger than that of the specimens.

To evaluate the relation between concrete strength and Young's modulus at early ages the laboratory test data (Takada et al, 1981) are statistically analysed. The relation is supposed to be expressed as follows:

$$a = \frac{f_c^{\frac{1}{3}}}{E_c} \quad (14)$$

where f_c is the compressive strength of concrete; E_c is Young's modulus of concrete; a is a coefficient of deformation.

The rerelations between the coefficient of deformation and the concrete strength of the specimens cured in water and in air are shown in Fig. 2. The coefficient of deformation a is almost constant to the developing strength of concrete with the coefficient of variation of 0.15 to 0.18 for the specimens cured in water and in air, respectively.

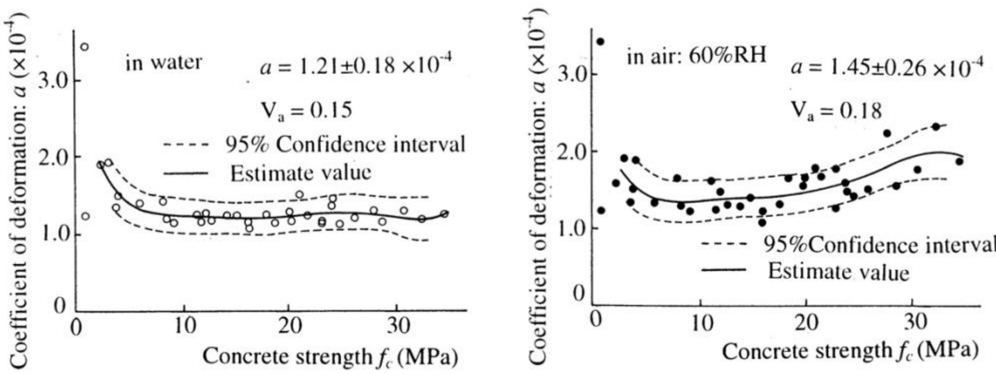

Figure 2: Relation between Coefficient *a* and Concrete Strength

Reliability of the method to evaluate reliable flexural strengths of structural members is examined on the laboratory test data (Takada et al, 1981). The relation is supposed to be expressed as follows:

$$b = \frac{f_b}{\sqrt{f_c}} \tag{15}$$

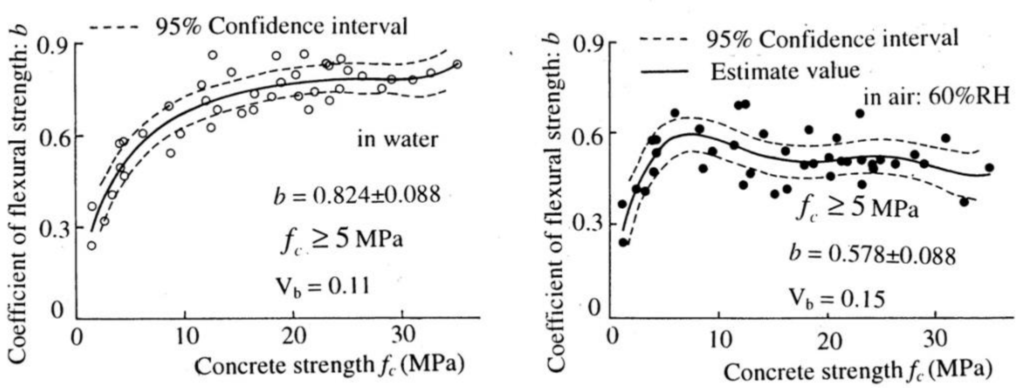

Figure 3: Relation between Coefficient *b* and Concrete Strength

where f_b is the flexural strength of concrete; *b* is a coefficient of flexural strength.

The rerelations between the coefficient of flexural strength *b* and the concrete strength are shown in Fig. 3. The coefficient of flexural strength *b* is roughly constant to the concrete strength above 5 MPa with the coefficient of variation of 0.11 to 0.15 for the specimens cured in water and in air, respectively.

4. Monte Carlo Simulations

Monte Carlo simulations were performed on a 10-story reinforced concrete building to evaluate the effect of rigid ground floor on the construction load distribution. The effect of the variation of concrete strength, Young's modulus, and shore rigidity on the construction loads were examined using the above mentioned nonlinear analysis model. The example building has 6-m spans, a 1/35 slab thickness-span ratio, 1/10 beam depth-span ratio, 0.2 slab-beam rigidity ratio and 3.0-m floor height. The rigidity of the slab shore is half the rigidity of the slab, and the rigidity of the beam shore is twice that of the slab shore. The floor at concreting is supported by the two floors below. The construction cycle is two weeks for one floor and the removal time of the shores is intermediate between concreting. The calculation starts at infinite rigid ground level and stops at the 10th floor with 1/4-day calculation steps. Each step is iterated until the convergence (less than 1/1000 error) is reached. The sample size of each floor is 500. The properties of concrete are obtained from CEB-FIP 1978 which is the most convenient for this purpose. The coefficient of variations of the three factors are supposed to be 0.15 from the properties of concrete during construction and the measured shore data.

4.1 Response of the Construction Loads and Deflection

The responses of the construction loads to the variation of concrete strength, Young's modulus, and shore rigidity are shown in Table 1. Although the responses of the construction loads to the three factors are not high, that of the deflection is amplified by the variation of the deformation coefficient *a*. The effect of the variation of shore rigidity is quite small.

Table 1: Response of the Construction Loads and Deflection

Factor V=0.15	Member	Sample Size	Response: Coefficient of Variation (%)		
			Removal	Maximum	Deflection(at 91 days)
Concrete Strength	Beam	500	0.68	1.11	6.52
	Slab	500	0.82	1.28	5.86
Deformation cefficient: *a*	Beam	500	2.05	3.44	19.9
	Slab	500	2.48	3.70	17.8
Shore Rigidity	Beam	500	1.34	0.14	0.31
	Slab	500	1.18	0.00	0.53

3.2 Realization of the Construction Loads

To simulate acutual conditions in construction, the variations of concrete strength, Young's modulus and shore rigidity are independently generated in the calculations. Figure 4 shows the construction load variations imposed on the 8_{th} floor slab calculated by Monte Carlo simulations. The variation of the construction loads becomes larger at concreting compared with the variation at shore removal. The coefficient of variation is 4% for the maximum construction load and less than that for the contributing variables.

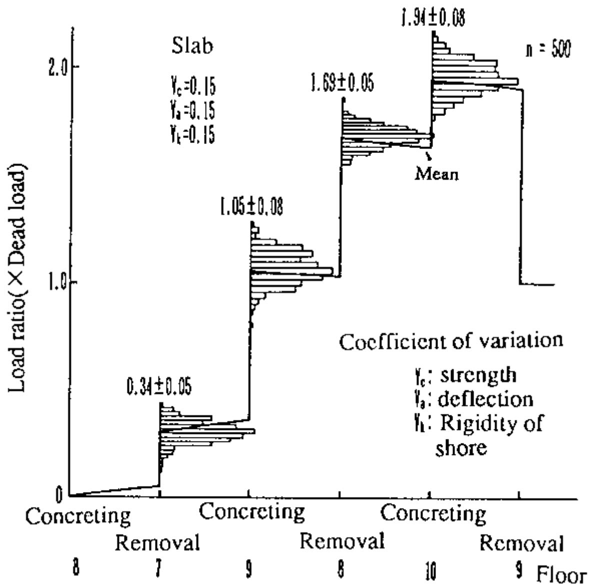

Figure 4: Realization of Construction Loads by Monte Carlo Simulations

4.3 Comparison to Field Measurements

Figure 5 shows typical field measurement data (Yamamoto et al, 1981) of the shore loads of the slabs and beams. In general, the shore loads tend to decrease during the first few days due to the thermal expansion of the columns as the slabs and beams become self-supporting due to increasing concrete strength. Then the shore loads increase with the shrinkage of columns due to the decrease in temperature. However the behavior of the shore loads between the slabs and beams is somewhat different. To simulate these behaviors, the calculations were performed by adding the following properties and variables: maximum column temperature rise of 10°C at one day after concreting; 0.5% drying shrinkage of the wood part (1/30) of the shores with a 15% coefficient of variation; removal of the shores at 4 days after concreting. Figure 6 shows the calculated results of the slab and beam shore loads; these results represent well the properties of the field measurement data. Table 2 shows the results of the Monte Carlo simulations. The construction load-dead load ratios of the slab and beam are 1.68 and 1.70 at removal and 1.81 and 1.94 at the maximum, respectively. The coefficient of variation was less than 10% for the construction loads and about 20% for the creep deflections during construction. The field measurement data (Yamamoto et al, 1982) are shown in Table 2 and show wide variations due to different construction process.

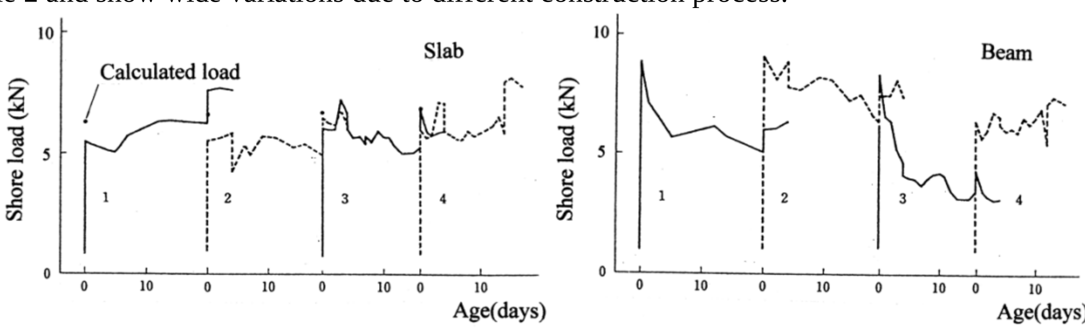

Figure 5: Field Measurements of Construction Loads

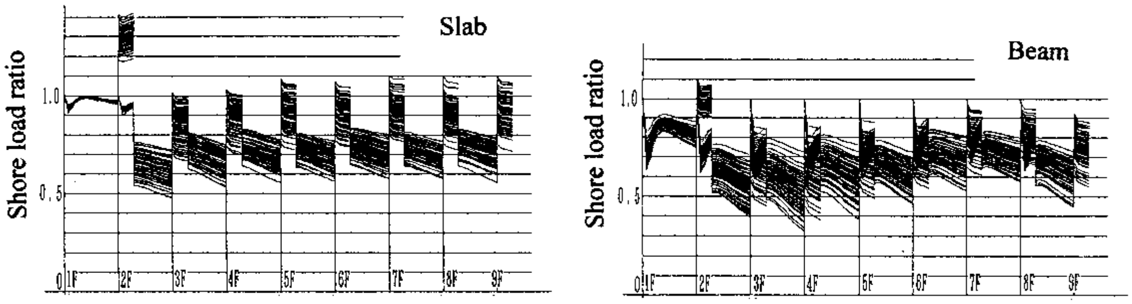

Figure 6: Realization of Construction Loads

Table 2: Results of Monte Carlo Simulations

		Sample Size	Construction Load Ratio (×Dead Load)					
			Removal		Maximum		Deflection (at 91 days)	
			Mean	C.V.(%)	Mean	C.V.(%)	Mean	C.V.(%)
No Variation	Beam	1	1.68	-	1.80	-	3.31	-
	Slab	1	1.71	-	1.95	-	3.48	-
1st Floor	Beam	500	1.62	3.70	1.74	4.71	2.81	19.1
	Slab	500	1.60	3.50	1.86	4.58	2.89	18.1
8th Floor	Beam	500	1.67	3.37	1.80	4.77	3.32	19.4
	Slab	500	1.71	2.81	1.95	4.16	3.50	17.3
1-8th floors	Beam	4000	1.68	4.05	1.81	5.51	3.22	19.6
	Slab	4000	1.70	3.60	1.94	4.48	3.43	18.9
Field measurement *n=15	Beam	25	1.69	9.47	1.74	11.5		
	Slab	25	1.64	7.32	1.83	13.7	3.17*	32.0*

4. Probability of Flexural Cracking

The distributions of the concrete flexural strength $f\,(B)$ and the concrete stress due to construction loads $f\,(W)$ are supposed to be the normal distributions $N_b\,(\overline{B}, \overline{B}^2 \cdot V_b^2)$ and $N_w\,(\overline{W}, \overline{W}^2 \cdot V_w^2)$, respectively. The distribution of the difference between the concrete flexural strength and the concrete stress due to construction load $f\,(B\text{-}W)$ can be expressed as follows:

$$f(B-W) = \frac{1}{\sqrt{\overline{B}^2 \cdot V_b^2 + \overline{W}^2 \cdot V_w^2} \cdot \sqrt{2\pi}} \times e^{-\frac{1}{2}\left\{\frac{B-W-(\overline{B}-\overline{W})}{\sqrt{\overline{B}^2 \cdot V_b^2 + \overline{W}^2 \cdot V_w^2}}\right\}^2} \qquad (14)$$

The probability of cracking due to the construction loads can be expressed as:

$$P = \int_{-\infty}^{0} f(B-W) \cdot d(b-W) \qquad (15)$$

If the coefficients of variation of the concrete flexural strength and concrete stress due to the construction loads are supposed to be 15% and 10%, respectively, when the ratio of the concrete flexural strength to concrete stress due to construction loads is 1.2, the probability of cracking is calculated to be 15%. To prevent the yielding of structural members, the same procedure can be used. Because yielding seriously affects structures, a higher strength-stress ratio and lower probability are desirable.

5. Conclusions

From the analysis of construction loads and Monte Carlo simulations the following conclusions have been derived:

1) The proposed nonlinear analysis model of the construction loads on supporting floors of multi-story reinforced concrete buildings can be adapted to various construction practices.
2) The construction loads are inevitably heavy and the creep deformation is not negligible.
3) The coefficient of variations due to the variation of concrete properties and shore rigidity are less than 10% for construction loads and about 20% for creep deflections during construction, respectively.
4) From the nonlinear analysis of construction loads and Monte Carlo simulations, a construction method of multi-story reinforced concrete buildings based on the reliability concept is proposed.

6. References

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