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STRENGTH AND SAFETY OF SLAB-WALL JOINTS OF REINFORCED CONCRETE BUILDINGS UNDER GRAVITY AND LATERAL LOADS

Alg. Kudzys

1. Introduction

This article considers structural safety of ordinary slab-wall joints in cast-in-situ reinforced concrete buildings with thin-walled and thin-slabed bearing members. These members are under action effects caused by gravity and lateral (wind or seismic) loads. Bending moments of alternating sign need double reinforcement for slabs and walls. The joints designed on the basis of strength without considering special ductility requirements by analogy with beam-column joints [1].

An influence of out-plane lateral forces on slab-wall joints is not yet sufficiently investigated. It is known that an endurance of slab-wall joints, i.e. their long-term safety and durability under reiterated episodic lateral loads of great intensity is closely connected with strength of joint core. Joint safety analysis can be based on the assumption that its core is a free concrete member with compressive, tensile and shear forces acting on its critical section adjacent to the slab and wall members with double reinforcement.

If bending moment reversals can cause stress reversals in the slab and wall longitudinal reinforcement and for composite (precast and cast-in-situ) floor slabs, the critical section of slabs concurs with a face of the confined wall core, i. e. the design depth of the wall is h'_w (Fig. 1).

Research results [2, 3] have shown that a loss of bearing resistance of slab-wall joints subjected to large out-plane lateral loading may occur due to brittle failure under compression of concrete diagonal strut of a joint core. It leads to a loss of overall stability of bearing structures. Therefore, a core belongs to high-reliability member of slab-wall joints, which structural safety must be checked in design procedures.

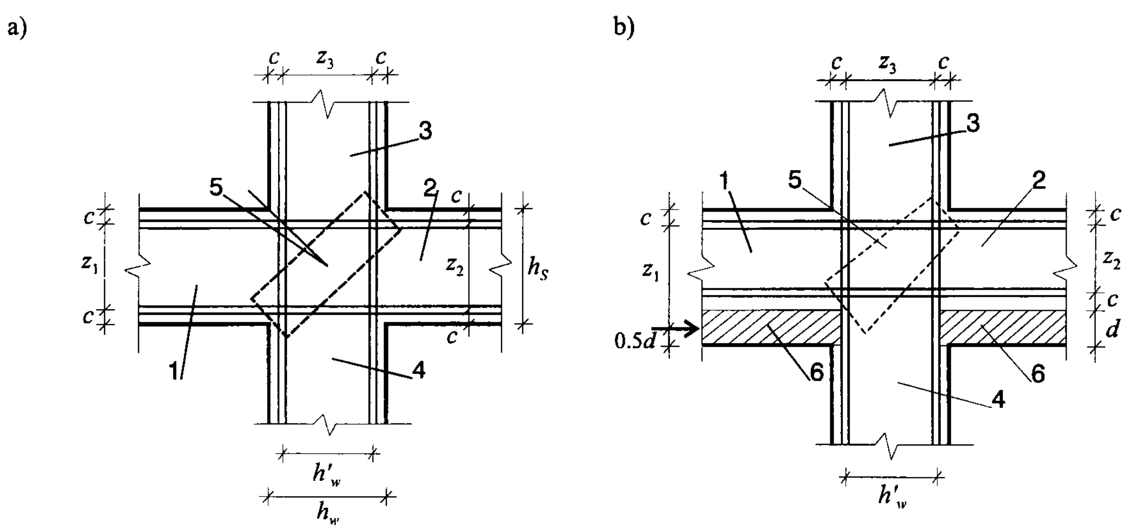

Fig. 1. Elevation of slab-wall joints with floor slabs cast on split moulds (a) and precast reinforced concrete slabs (b): 1 and 2 - floor slabs; 3 and 4 - wall members; 5 - joint core; 6 - precast slabs

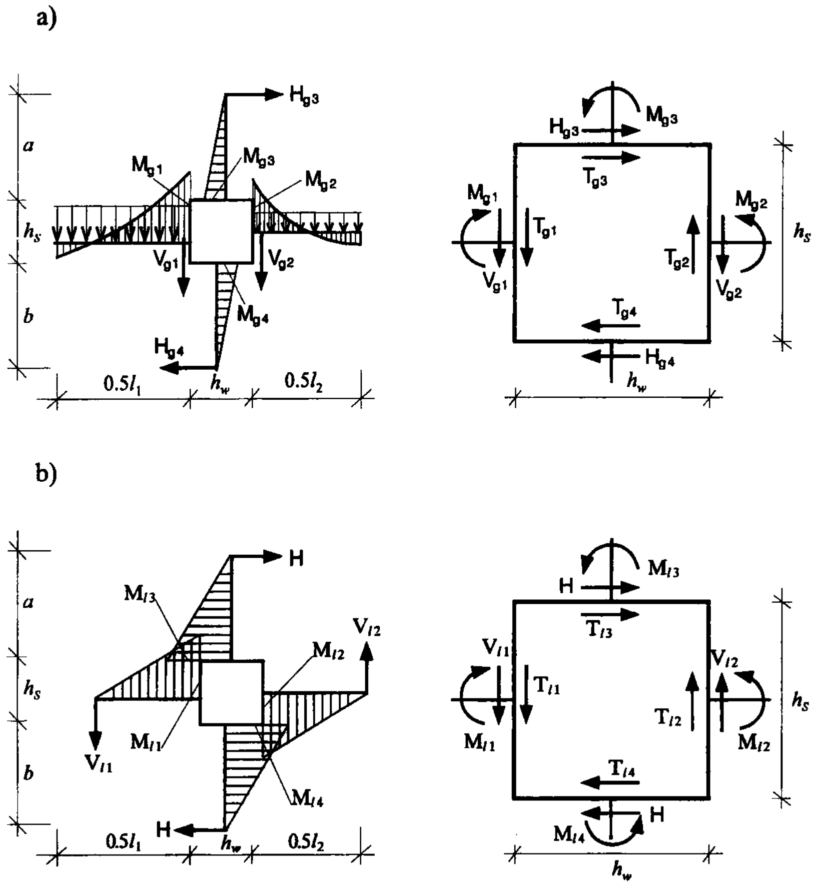

Fig. 2. Acting bending moments and shear forces in slabs, walls and their joint core caused by gravity (a) and lateral (b) loads

2. Joint core shear forces

From Fig. 2 the action of bending moments and shear forces on a core of slab-wall joints is evident. The moments and forces required to keep the slab-wall joints in equilibrium and their numerical values are calculated by the following equations:

$$M_{g1} = \beta_M p_1 l_1^2; M_{g2} = \beta_M p_2 l_2^2; \quad (1)$$

$$M_{g3} = \frac{b\beta_M}{a+b}\left(p_1 l_1^2 - p_2 l_2^2\right);$$

$$M_{g4} = \frac{a\beta_M}{a+b}\left(p_1 l_1^2 - p_2 l_2^2\right); \quad (2)$$

$$V_{g1} = \beta_Q p_1 l_1; V_{g2} = \beta_Q p_2 l_2; \quad (3)$$

$$H_{g3} = \frac{b\beta_M}{a(a+b)}\left(p_1 l_1^2 - p_2 l_2^2\right);$$

$$H_{g4} = \frac{a\beta_M}{b(a+b)}\left(p_1 l_1^2 - p_2 l_2^2\right); \quad (4)$$

$$M_{l1} = Hl_2(a+b)/(l_1+l_2);$$

$$M_{l2} = Hl_1(a+b)/(l_1+l_2); \quad (5)$$

$$M_{l3} = Ha; M_{l4} = Hb; \quad (6)$$

$$V_{l1} = H\frac{2l_2(a+b)}{l_1(l_1+l_2)};$$

$$V_{l2} = H\frac{2l_1(a+b)}{l_2(l_1+l_2)}; \quad (7)$$

$$V_{w3} = V_{w4} = H. \quad (8)$$

Here the coefficients β_M and β_Q evaluate the geometry of slabs and redistribution of gravity actions effects due to concrete creep and settlement of foundation; H is the joint horizontal action effect caused by lateral loads.

The statistical estimates (means and variances) of probability distribution of the shear forces of joint core caused by gravity and lateral loads (Fig. 2) are calculated by formulae:

$$T_{g1m} = \left(M_{g1m} - M_{g2m}\right) / h_{wm} + V_{g1m}; \qquad (9)$$

$$s^2 T_{g1} = \frac{1}{h_w^2}\left(s^2 M_{g1} + s^2 M_{g2}\right) + \frac{s^2 h_w}{h_w^4}\left(M_{g1}^2 + M_{g2}^2\right) + s^2 V_{g1}; \qquad (10)$$

$$T_{g2m} = \left(M_{g1m} - M_{g2m}\right) / h_{wm} + V_{g2m}; \qquad (11)$$

$$s^2 T_{g2} = \frac{1}{h_w^2}\left(s^2 M_{g1} + s^2 M_{g2}\right) + \frac{s^2 h_w}{h_w^4}\left(M_{g1}^2 + M_{g2}^2\right) + s^2 V_{g2}; \qquad (12)$$

$$T_{g3m} = \left(M_{g3m} + M_{g4m}\right) / h_{sm} + H_{g3m}; \qquad (13)$$

$$s^2 T_{g3} = \frac{1}{h_s^2}\left(s^2 M_{g3} + s^2 M_{g4}\right) + \frac{s^2 h_s}{h_s^4}\left(M_{g3}^2 + M_{g4}^2\right) + s^2 H_{g3}; \qquad (14)$$

$$T_{g4m} = \left(M_{g3m} + M_{g4m}\right) / h_{sm} + H_{g4m}; \qquad (15)$$

$$s^2 T_{g4} = \frac{1}{h_s^2}\left(s^2 M_{g3} + s^2 M_{g4}\right) + \frac{s^2 h_s}{h_s^4}\left(M_{g3}^2 + M_{g4}^2\right) + s^2 H_{g4}; \qquad (16)$$

$$T_{l1m} = \left(M_{l1m} + M_{l2m}\right) / h_{wm} + V_{l1m}; \qquad (17)$$

$$s^2 T_{l1} = \frac{1}{h_w^2}\left(s^2 M_{l1} + s^2 M_{l2}\right) + \frac{s^2 h_w}{h_w^4}\left(M_{l1}^2 + M_{l2}^2\right) + s^2 V_{l1}; \qquad (18)$$

$$T_{l2m} = \left(M_{l1m} + M_{l2m}\right) / h_{wm} + V_{l2m}; \qquad (19)$$

$$s^2 T_{l2} = \frac{1}{h_w^2}\left(s^2 M_{l1} + s^2 M_{l2}\right) + \frac{s^2 h_w}{h_w^4}\left(M_{l1}^2 + M_{l2}^2\right) + s^2 V_{l2}; \qquad (20)$$

$$T_{l3m} = T_{l4m} = \left(M_{l3m} + M_{l4m}\right) / h_{sm} + H_m; \qquad (21)$$

$$s^2 T_{l3} = s^2 T_{l4} = \frac{1}{h_s^2}\left(s^2 M_{l3} + s^2 M_{l4}\right) + \frac{s^2 h_s}{h_s^4}\left(M_{l3}^2 + M_{l4}^2\right) + s^2 H. \qquad (22)$$

According to data [4, 5], for cast-in-situ slab and walls the design variances of probability distribution of geometrical dimensions can be accepted as follows:

$s^2h_s = s^2h_w = 1$ cm in height of member cross-section;

$s^2c = 0.25$ cm^2 in thickness of concrete conditional cover;

$s^2d = 0.25$ cm^2 in thickness of precast thin slabs used instead of split moulds.

3. Joint core compression forces

Compression forces of joint core are caused by wall axial forces and bending moment acting on its vertical and horizontal estimates of compression forces depend both on probability distribution of these action effects and arms of inner couples (Fig. 3).

The means and variances of the arms of inner couples are:

$$z_{1m} = z_{2m} = h_{sm} - 2c_m;\ s^2z_1 = s^2z_2 = s^2h_s + 4s^2c; \qquad (23)$$

for pure cast-in-situ floor slabs, and

$$z_{1m} = h_{sm} - c_m - 0.5d_m;\ s^2z_1 = s^2h_s + s^2c + 0.25s^2d; \qquad (24)$$

$$z_{2m} = h_{sm} - 2c_m - d_m;\ s^2z_2 = s^2h_s + 4s^2c + s^2d \qquad (25)$$

for composite floor slabs.

The statistical estimates for wall members are:

$$z_{3m} = 0.5h_{wm} - c_m + M_{3m} / N_{g3m}; \qquad (26)$$

$$s^2 z_3 = 0.25 s^2 h_w + s^2 c + s^2 M_3 / N_{g3m}^2 + \left(M_{3m} / N_{g3m}^2\right)^2 s^2 N_{g3}; \qquad (27)$$

$$z_{4m} = 0.5h_{wm} - c_m + M_{4m} / N_{g4m}; \qquad (28)$$

$$s^2 z_4 = 0.25 s^2 h_w + s^2 c + s^2 M_4 / N_{g4m}^2 + \left(M_{4m} / N_{g4m}^2\right)^2 s^2 N_{g4}; \qquad (29)$$

where $M_3 = M_{g3} = M_{l3}$ and $M_4 = M_{g4} + M_{l4}$ are the sums of bending moments, and N_{g3} and N_{g4} are the acting axial forces in upper and lower wall members, respectively. The axial forces in slab and wall members caused by lateral forces can be neglected due to their small values.

The joint core compression forces D_i (Fig. 3) consist of two components D_{gi} and D_{li} caused by gravity and lateral loads, respectively. The means and variances of

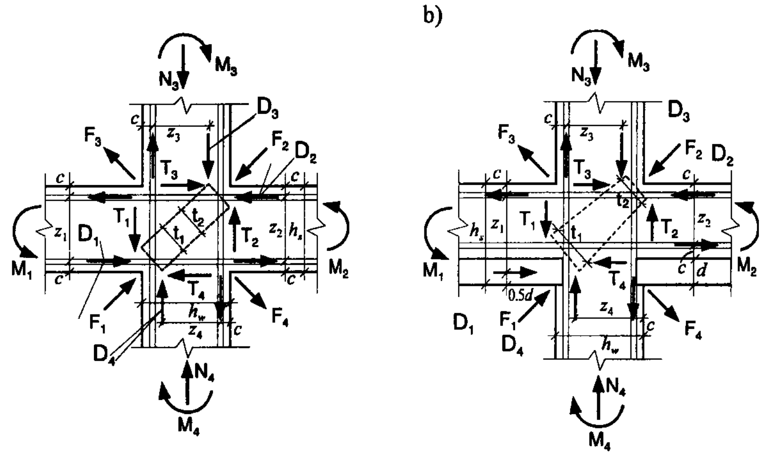

Fig. 3. Inner forces in joint core of slab-wall connections with pure cast-in-situ (a) and composite (b) floor slabs

probability distribution of these components are calculated by following formulae :

$$D_{g1m} = M_{g1m} / z_{1m}; \quad (30)$$

$$s^2 D_{g1} = s^2 M_{g1} / z_{1m}^2 + s^2 z_1 M_{g1m}^2 / z_{1m}^4; \quad (31)$$

$$D_{g2m} = M_{g2m} / z_{2m}; \quad (32)$$

$$s^2 D_{g2} = s^2 M_{g2} / z_{2m}^2 + s^2 z_2 M_{g2m}^2 / z_{2m}^4; \quad (33)$$

$$D_{g3m} = \left[M_{g3m} + N_{g3m}(0.5h_{wm} - c_m) \right] / z_{3m}; \quad (34)$$

$$s^2 D_{g3} = \sum_{i=1}^{5} \left(\frac{\partial D_{g3}}{\partial \xi_i} \right)_m^2 s^2 \xi_i; \xi_i = M_{g3}; N_{g3}; h_w; c; z_3; \quad (35)$$

$$D_{g4m} = \left[M_{g4m} + N_{g4m}(0.5h_{wm} - c_m) \right] / z_{4m}; \quad (36)$$

$$s^2 D_{g4} = \sum_{i=1}^{5} \left(\frac{\partial D_{g4}}{\partial \xi_i} \right)_m^2 s^2 \xi_i; \xi_i = M_{g4}; N_{g4}; h_w; c; z_4; \quad (37)$$

$$D_{l1m} = M_{l1m} / z_{1m}; \quad (38)$$

$$s^2 D_{l1} = s^2 M_{l1} / z_{1m}^2 + s^2 z_1 M_{l1m}^2 / z_{1m}^4; \quad (39)$$

$$D_{l2m} = M_{l2m} / z_{2m}; \quad (40)$$

$$s^2 D_{l2} = s^2 M_{l2} / z_{2m}^2 + s^2 z_2 M_{l2m}^2 / z_{2m}^4; \quad (41)$$

$$D_{l3m} = M_{l3m} / z_{3m}; \quad (42)$$

$$s^2 D_{l3} = s^2 M_{l3} / z_{3m}^2 + s^2 z_3 M_{l3m}^2 / z_{3m}^4; \quad (43)$$

$$D_{l4m} = M_{l4m} / z_{4m}; \quad (44)$$

$$s^2 D_{l4} = s^2 M_{l4} / z_{4m}^2 + s^2 z_4 M_{l4m}^2 / z_{4m}^4 .. \quad (45)$$

4. Diagonal strut forces

The diagonal cracks in a joint core are caused by tensile force resultants F_3 and F_4 (Fig. 3). Concrete member between diagonal cracks in the core centre becomes a conditional compression strut. An analysis of structural safety of concrete joint core can be based on the failure mechanism of this strut, which compressive forces F_1 and F_2 are caused by gravity and lateral loads [6].

If the resultant forces F_{g1} and F_{g2} are caused by gravity loads, their means of probability distribution can be expressed by the equations :

$$F_{g1m} = \left[(2D_{g1m} + T_{g4m})^2 + (2D_{g4m} + T_{g1m})^2 \right]^{1/2}; \quad (46)$$

$$F_{g2m} = \left[(2D_{g2m} + T_{g3m})^2 + (2D_{g3m} + T_{g2m})^2 \right]^{1/2}. \quad (47)$$

For revealing statistical estimates of probability distribution of compressive forces F_{l1} and F_{l2} caused by lateral loads, the following equations are used :

$$F_{w1m} = \left[(2D_{l1m} + T_{l4m})^2 + (2D_{l4m} + T_{l1m})^2 \right]^{1/2}; \quad (48)$$

$$F_{w2m} = \left[(2D_{l2m} + T_{l3m})^2 + (2D_{l3m} + T_{l2m})^2 \right]^{1/2}. \quad (49)$$

In both loading cases, the variances of resultant forces can be calculated by the equation :

$$s^2F = \sum_{i=1}^{4}\left(\frac{\partial F}{\partial \xi_i}\right)_m^2 s^2\xi_i + \sum_i\sum_j\left(\frac{\partial F_g}{\partial \xi_i}\right)_m\left(\frac{\partial F_g}{\partial \xi_j}\right)_m \operatorname{cov}(\xi_i;\xi_j). \qquad (50)$$

Here $s^2\xi_i$ denotes the variance of probability distribution of random vector ξ_i representing the compressive force D_i or shear force T_i ;

$\operatorname{cov}(\xi_i;\xi_j) = \left(\frac{\partial \xi_i}{\partial \eta}\frac{\partial \xi_j}{\nabla \eta}\right)_m s^2\eta$ is the cross covariance of two random vectors ξ_i and ξ_j, where η is the random argument representing gravity or lateral loads.

5. Diagonal strut resistance

The compression resistance of concrete strut of joint core is closely connected with statistical estimates of the strut thickness t and its concrete resistance f_c.

On the basis of research data [5], the distance between diagonal concrete and just the same the thickness of the conditional diagonal strut is

$$t = 0.4\left(z_s^2 + z_w^2\right)^{1/2}; \qquad (51)$$

where z_s and z_w are the arms of inner couple of slab and wall members, respectively.

Therefore, the means and variances of probability distribution of thickness t_1 and t_2 are :

$$t_{1m} = 0.4\left(z_{1m}^2 + z_{4m}^2\right)^{1/2}; \qquad (52)$$

$$s^2t_1 = 0.16\left(z_{1m}^2 s^2z_1 + z_{4m}^2 s^2z_4\right)/\left(z_{1m}^2 + z_{4m}^2\right); \qquad (53)$$

$$t_{2m} = 0.4\left(z_{2m}^2 + z_{3m}^2\right)^{1/2}; \qquad (54)$$

$$s^2t_2 = 0.16\left(z_{2m}^2 s^2z_2 + z_{3m}^2 s^2z_3\right)/\left(z_{2m}^2 + z_{3m}^2\right); \qquad (55)$$

where z_{im} and s^2z_i are estimates by (23)...(28).

According to reference [4], the coefficient of variation of the concrete compression strength δf_c depends not only on concrete type and strength but also on concrete mix consistency and quality, its production and casting process culture. For cast-in-situ normal concrete the coefficient δf_c = 6...20 %. In the case of average quality of erection culture of reinforced concrete structures the design coefficient $\delta f_c \approx 13\%$.

The slab-wall connections of reinforced concrete structures subjected to intensive impact loads may be analyzed taking into account an increase in strength of materials. However, here one should not forget the increase in variance of probability distribution that may be increased considerably. It practically allows to consider the usual estimates of joint core mechanical parameters.

The estimates of probability distribution of the compression resistance of diagonal structure:

$$R_{1m} = bt_{1m}f_{cm}; \qquad (56)$$

$$s^2R_1 = \left(bt_{1m}\right)^2 s^2f_c + \left(bf_{cm}\right)^2 s^2t_1; \qquad (57)$$

$$R_{2m} = bt_{2m}f_{cm}; \qquad (58)$$

$$s^2R_2 = \left(bt_{2m}\right)^2 s^2f_c + \left(bf_{cm}\right)^2 s^2t_2, \qquad (59)$$

where b is the design width of the slab and wall members; f_{cm} and s^2f_c are estimates of concrete compression strength.

6. Structural safety index

The effect of random in nature lateral loads on probabilistic reliability of structures is analyzed using statistics of the extreme distribution law of type I or II [7, 8]. However, the effect of maximum stochastically independent lateral loads can be modelled by discrete non-homogenous Poisson process. In this case the method of limit random effects leads to simplification of analysis procedure and structural safety assessment of slab-wall joints [7]. This method excludes any estimation of structural failure due to human errors.

The efficiency of slab-wall joint core at the cut k of non-stationary stochastic sequence can be expressed by the random process performance function

$$Z_k = R_k - F_{gk} - F_{lk} = F_{\lim,k} - F_{lk}, \qquad (60)$$

where R_k is the strut compression resistance; F_{gk} and F_{lk} are the resultant forces caused by gravity and lateral loads, respectively; $F_{\lim,k} = R_k - F_k$ is the limit action effect that is caused by episodic lateral force in limit state of joint core (Fig. 4).

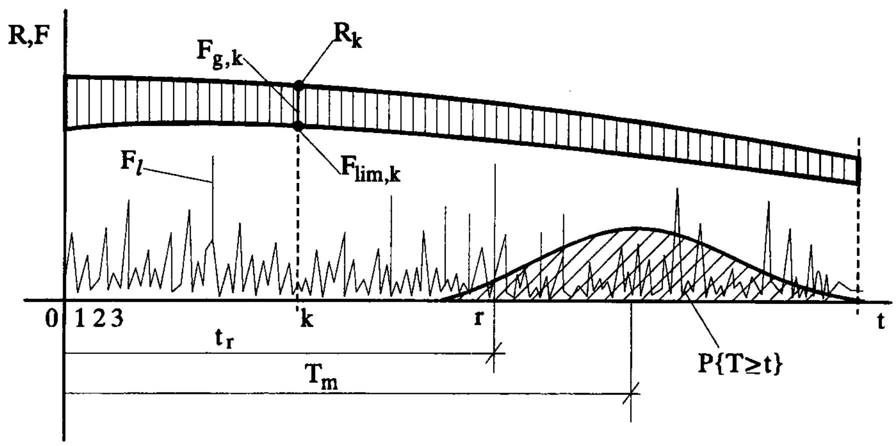

Fig. 4. Dynamic model for the estimation of structural safety of a member by method of random limit action effects

The resistance R_k evaluates a gradual decrease in compression strength of strut member due to its instantaneous overloading, stress reversals and concrete cracking. The resistance R_k is a fixed random function, because its numerical value is random only at the beginning of a stochastic sequence, while in other cuts this value changes in accordance with a determinate law.

The percentage coefficient of variation is 5 % for dead loads and 10...30 % for long duration and variable in time loads [7]. The normal law is applicable to action effects F_{gk} caused by these loads and concrete resistance R_k. Therefore, the probabilistic distribution law of one-model limit action effect $F_{lim,k} = R_k - F_{gk}$ is close to the normal one and its value may be expressed by the formula:

$$F_{\lim,k} = R_{mk} - F_{gmk} - \beta_1\left(s^2 R_k + s^2 F_{gk}\right)^{1/2}. \quad (61)$$

Here R_{mk}, s^2R_k and F_{gmk}, s^2F_{gk} are the estimates of probability distribution of strut resistance and compressive force; $\beta_l \approx 0.95$ is the relative deviation of vector R_k and F_{gk} values from their means.

The law of distribution density of probability of extreme lateral loads, for instance, annual extreme wind values, are close to Gumbell [7] and Fisher - Tippet one with the coefficient of variation equal to 30...45 % [9, 10].

According to the method of limit random effects [7], an analysis sequence consists of r stochastically independent cuts, where r is the reiteration number of an episodic peal load.

The analysis of long-term safety of slab-wall joint cores may be based on the compound Poisson - Gumbell distribution law. The long-term safety index is

$$\mathbf{P}\{T \geq t\} = \exp\left[-\sum_{k=1}^{r} \exp\left(\frac{a - F_{\lim,k}}{b}\right)\right]. \quad (62)$$

Here a and b are the parameters of the extreme distribution of an episodic action effect. The parameters $b = (s^2F_{lk}/1.645)^{1/2}$ and $a = F_{lm,k} - 0.5776b$, where $F_{lm,k}$ and s^2F_{lk} are the mean and variance of extreme action effect caused by lateral load. Therefore, the equation (62) can be written in the form:

$$\mathbf{P}\{T \geq t\} = \exp\left[-\sum_{k=1}^{r} \exp\left(\frac{F_{lm,k} - F_{\lim,k}}{0.78sF_{lk}} - 0.5776\right)\right], \quad (63)$$

where $r = t_r$ in years; sF_{lk} is the standard of probability distribution of the action effect F_{lk}.

If the member resistance doesn't change in course of time, the analysis of its structural safety is simplified, because the long-term safety index is

$$\mathbf{P}\{T \geq t\} = \exp\left[-r \exp\left(\frac{F_{lm} - F_{\lim}}{0.78sF_l} - 0.5776\right)\right]. \quad (64)$$

7. Conclusions

The proposed simple method of limit random action effects allows to estimate the long-term structural safety of joint core of cast-in-situ reinforced concrete slab and wall connections subjected to gravity and episodic out-plane lateral loads. This method evaluates the decrease of joint core resistance due to its random instantaneous overloading, stress reversals and by concrete strut cracking.

The structural safety indices belong to the main parameters characterizing reliability and cost of frameless reinforced concrete buildings subjected to large lateral loading.

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GELŽBETONINIŲ PASTATŲ, KURIUOS VEIKIA VERTIKALIOSIOS IR HORIZONTALIOSIOS APKROVOS, STIPRUMAS IR PATIKIMUMAS

Alg. Kudzys

S a n t r a u k a

Straipsnyje nagrinėjamas vertikaliomis ir atsitiktinėmis ar epizodinėmis horizontaliomis apkrovomis veikiamų gelžbetoninių sienų ir perdangos plokščių sandūrų įtempimų būvis ir tikimybinis saugis. Analizuojamas monolitinio ir surenkamojo-monolitinio mazgo darbas įvertinant gniuždomos betoninės prizmės būklę susiformavus įstrižiems plyšiams. Išskiriamos sienų ir plokščių sandūros mazge veikiančios gniuždomosios jėgos, sukeltos atskirai vertikalių ir horizontalių poveikių. Pateikiami mazgo ir jame susiformavusios įstrižos betoninės prizmės įrąžų statistiniai parametrai, įvertinant medžiagų fizinių-mechaninių savybių ir apkrovų variacijas. Nagrinėjamas ryšys tarp betoninės prizmės pločio ir mazge veikiančių vidaus jėgų peties kitimo.

Betoninio mazgo saugio indekso reikšmės skaičiavimui siūlomas ribinių atsitiktinių įrąžų metodas. Šis metodas leidžia įvertinti daugiaaukščio pastato sandūros mazgo stiprumo sumažėjimą dėl atsitiktinių nuolatinių perkrovimų, įrąžų krypties kitimo bei betono supleišėjimo. Struktūrinio saugio indeksas pateikiamas kaip vienas iš pagrindinių parametrų, apibūdinančių gelžbetoninių pastatų, veikiamų didelėmis horizontaliomis apkrovomis, patikimumą ir kainą.