Determination of efforts from temperature and humidity exposure in walls

Elena Korol, Yuliya Kustikova, Vu Dinh Tho and Valerii Antoniadi
Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, Russia
E-mail: AntoniadyVD@mgsu.ru

Abstract. The construction of large-panel buildings has more than half a century of history, during which space-planning and design solutions have been improved, methods of calculation have been developed and the regulatory and technical base has been updated. For this period, accurate and approximate calculation methods, both of individual structural elements and the structural systems of buildings on the whole, have been harmonised and verified, the technologies and techniques of automated calculation methods and software systems for their implementation have been developed. One of the features of the life cycle of the housing stock of large-panel buildings is that over the long period of their operation, the regulatory and technical base on which they were designed periodically underwent changes. In terms of ensuring constructive safety from the effect of power loads on buildings, a system of fixed coefficients of working conditions supports the continuity of development of design standards. The affection of temperature and humidity exposure is determined according to the requirements for the temperature difference between the outer and inner surfaces of the outer walls. Based on the accumulated experimental data for the past years between the design period and the current period of operation, the numerical standard values of the heat transfer coefficients of the inner and outer surfaces of the enclosing structures have changed in relation to the previous standards by which these structures were designed. This necessitates a re-evaluation of efforts caused by temperature and humidity exposure in order to make a decision on the need to strengthen structures.

1. Introduction
When calculating the external and internal walls of large-panel buildings taking into account their joint work, it is necessary to take into account the possible redistribution of vertical loads due to unequal shrinkage deformations due to changes in the humidity of the mating walls and uneven temperature deformations arising from changes in the outdoor temperature [1].

The initial data for calculating the temperature effects are determined in accordance with the current regulatory and technical documents, when the humidity effects are based on the generalised results of experimental and theoretical studies [3,4,5].

Forces from temperature and humidity effects are determined on the basis of the design scheme in the form of a plate system connected by pliable bonds [7-8].

When calculating, it is necessary to take into account: local bending of panels within the height of the floor due to the eccentric transmission of vertical loads and temperature differences along the wall thickness; uneven longitudinal deformations of the median wall surface during redistribution of
vertical loads between them; one-sided nature of the connections between wall panels at their horizontal joints; the effect of creep deformations and the possible formation of cracks in panels and joints, leading to less effort from forced influences. [9-16]

The forces caused by temperature and humidity exposure can be approximately determined by the method described above. Calculation based on this method leads to some completion of efforts from temperature and humidity effects. If accounting of additional impacts leads to the necessity of structural reinforcement, it is recommended to use more accurate calculation methods. [17-22]

For approximate determination of forces because of unequal temperature and humidity wall deformations, a design scheme is used in the form of a compound rod of two strips connected by compliant and absolutely rigid transverse bonds. The first strip is the partition of the outer wall, and the second is the partition of the inner wall [22-25].

The calculation is performed for the operational period. When calculating the shrinkage, the difference in the relative shrinkage deformations of the mating walls arising after the end of their installation is taken into account. When calculating the temperature effects, the winter and summer operating conditions of the building are considered.

2. Materials and methods

The calculated difference in the relative longitudinal deformations of the outer and inner walls, causing their mutual shift, due to the unequal temperature of the walls, is determined by the formula:

\[ e^t = \alpha_{bc}(t_{int,w} - t_{int,cw} + \frac{t_{int,cw} - t_{ext,extw}}{h_H} \cdot \frac{Y_{ctA} + Y_{clA}}{1+A}) \]  

where

- \( t_{int,w} \) - average temperature of the inner wall;
- \( t_{int,cw} \) - temperature of the inner surface of the outer wall;
- \( t_{ext,extw} \) - temperature of the outer surface of the outer wall;
- \( h_H \) - average temperature of the inner wall;
- \( Y_{ct} \) - the distance from the geometric center of the horizontal section of the partition to one of the faces of the wall; for external walls distance reports from the inner face, for internal walls - from the face that adjoins the largest of the supporting areas;
- \( Y_{cl} \) - the distance from the center of rigidity of the supporting platform to the face of the wall from which the distance YCT is measured;
- \( A \) - is an immeasurable parameter;
- \( \alpha_{bc(H)} \) - coefficient of linear temperature deformations of the inner (outer) wall.

Calculation of forced deformations is performed accounting the possible disclosure of horizontal joints between the panels and the “hovering” of one of the wall panels (for example, the outer) on the panels of the other. If the calculated difference in the forced deformations is \( \Delta > 0 \), then the horizontal joints of the outer wall panels can open; if \( \Delta < 0 \), then the horizontal joints of the panels of the inner wall can be revealed.

In the calculation, accounting the disclosure of horizontal joints, it is assumed that the bonds in the horizontal joints are switched off concisely, starting from the panels of the upper floor. The calculation is carried out according to the types corresponding to the "hovering" of the next floor.

For the stage number \( l (1 \leq l \leq n) \), which corresponds to the disclosure of the horizontal joints of one of the wall panels at the level of overlap \( (n - 1 + 1) \) above the floor, a composite system with the height of the floors is considered. The calculation is performed in the following sequence.

Step 1. The calculated difference of forced deformations is determined, causing the disclosure of the horizontal joint between the panels of one of the walls at the level of overlap between floors \( (n - 1) \) and \( (n - 1 + 1) \).

\[ \Delta_l = \frac{\gamma_1 n^{(l-1)} c_{h,n-1}}{c_{h1} n^{(l-1)} c_{h1} (n-1) + c_{h1} (n-1+1)} \]  

2
where \( Y = \frac{1}{E_1 a_{11} F_1} + \frac{1}{E_2 a_{22} F_2} \) (3)

- \( F_1^{(l)} \) - the estimated area of the first (second) strip, calculated according to the condition that the strip length should not exceed 0.2 of the height of the composite system in step \( l \);
- \( N_{n-1}^{(l-1)} \) - the longitudinal force at the horizontal joint of the floor panels \((n-l)\) and \((n-l+1)\) the outer wall (if \( \Delta > 0 \)) or the inner wall (if \( \Delta < 0 \)), calculated for the stage \((l-1)\);
- \( \mu_l = \frac{H}{h} \sqrt{\beta_l} \) (4)

Step 2. If the condition is met
\[
\Delta < \sum_{f=1}^{l} \Delta_f,
\]
then the calculated difference of forced deformation for the \( l \)-th stage instead of formula (2) is determined by the formula:
\[
\Delta_l = \Delta - \sum_{f=1}^{l-1} \Delta_f,
\]
(6)

If the condition (6) is met, stage \( l \) is final.

Step 3. The longitudinal forces \( N_{H1}^{(l)} \), \( N_{si}^{(l)} \), are calculated in the horizontal joints of the panels of the external and internal walls \((0 \leq i \leq n-1)\):

\[
\begin{cases}
N_{H1}^{(l-1)} - T_{i}^{(l)} = N_{H1}^{(l)} \\
N_{si}^{(l-1)} + T_{i}^{(l)} = N_{si}^{(l)}
\end{cases}
\]
(7)

where \( T_{i}^{(l)} \) - the longitudinal force redistributed between the walls in the level of overlap above the i-th floor at stage \( l \);

\[
T_{i}^{(l)} = \frac{\Delta_i}{\gamma_i} \left[ 1 - \frac{c_i h_{\mu i}}{c_i h_{\mu i (n-1+l)}} \right]
\]
(8)

At the first stage \((l=1)\), the longitudinal forces \( N_{H1}^{(0)} \) and \( N_{si}^{(0)} \) are determined from the calculation of the walls for vertical loads.

If condition (6) is not met at stage \( l \), then this means that all horizontal joints \( l \) of the upper floors are open. In this case it is necessary to perform calculation for the next step \((l+1)\).

3. Research results
The calculation of the climatic temperature effects and the difference in shrinkage of the walls is made for the operational period, when the temperature difference between the external and internal air is the largest.

The temperature distribution is determined by the thickness of the outer wall. The temperatures on the outer and inner surfaces of the wall are taken according to the requirements of regulatory documents and the generalised results of experimental studies:

\[
t_{HLCT} = t_h - (t_h - t_H) \frac{R_h}{R_0};
\]

\[
t_{RLCT} = t_h - (t_h - t_H) \frac{R_h}{R_0};
\]

\[
R_h = \frac{1}{a_h}; R_H = \frac{1}{a_H};
\]

\[
R_0 = R_h + R_H + \frac{h}{\lambda};
\]

where \( t_h = -29^\circ \); 
\( t_h \) - standard temperature of internal air.
In the above formulas the following designations are accepted:

\[ \alpha_1 \] — heat transfer coefficient of the inner surface of the enclosing construction; \( \alpha_1 = 8.7 \frac{\text{Kcal}}{\text{m}^2\cdot\text{C}}; \)

\[ \alpha_2 \] — heat transfer coefficient of the outer surface of the enclosing construction; \( \alpha_2 = 23 \frac{\text{Kcal}}{\text{m}^2\cdot\text{C}}; \)

\( h \) - wall thickness; \( h=0.35 \text{ m}; \)

\( \lambda \) - the coefficient of thermal conductivity of the material, depending on the volumetric weight in the dry state of the wall material and the operating conditions of the fence.

The area for which the calculation is carried out refers to the dry zone. This implies that the humidity mode of the room is normal (relative humidity of the air is 50-60%). Then the thermal conductivity coefficient for expanded clay concrete at \( \gamma_0 = 1200 \text{ kg/m}^3=12 \text{ kH/m}^3 \), \( \lambda =0.35 \frac{\text{Kcal}}{\text{m}^2\cdot\text{C}}; \)

Then \( R_0 = \frac{1}{8.7} = 0.115 \frac{\text{cm}^2\cdot\text{C}}{\text{Kkal}}; \)

\[
R_0 = \frac{1}{23} = 0.04 \frac{\text{cm}^2\cdot\text{C}}{\text{Kkal}}; \\
R_0 = 0.115 + 0.04 = \frac{0.35}{0.35} = 1.155 \frac{\text{cm}^2\cdot\text{C}}{\text{Kkal}}; \\
T_{н.п.} = -29 + (-29 - 18) \frac{0.04}{1.155} = -27.4 \text{ C}; \\
T_{в.п.} = +18 + (-29 - 18) \frac{0.115}{1.155} = +13.3 \text{ C}.
\]

Accepting the condition that the temperature varies along the wall thickness according to a linear dependence and accounting the coefficient of linear expansion (for example, for expanded clay walls), using formula (1) we obtain:

\[ \varepsilon^t = 0.8 \times 10^{-5} \left( 18 - 13.3 + \frac{13.3 - (-27.4)}{35} \times \frac{14.2+17.5+1.017}{1+1.017} \right) = 18.4 \times 10^{-5} \]

In addition to temperature axial deformations, strains caused by the difference in shrinkage of the external and internal walls are possible. According to experimental data, we take: \( \varepsilon^{shr} = 9 \times 10^{-5} \)

Then \( \varepsilon^{tot} = \varepsilon^t + \varepsilon^{shr} = 18.4 \times 10^{-5} + 9 \times 10^{-5} = 27.5 \times 10^{-5}. \)

When the temperature of the outer walls decreases, a partial hovering of the outer wall panels on the inner walls is possible, accompanied by the opening of horizontal mortar joints between the panels of the outer walls. The number of “hovering” external panels depends on the difference in relative forced deformations \( \varepsilon^{tot}. \) The calculation is performed with the following characteristics of the bonds and bands[1]:

\[
\beta_1^{\alpha} = 0.5 \times 1.21 \times 10^3 = 0.605 \times 10^3 \text{ кгс/см}^2; \\
F_1 = 150 \times 35 = 5250 \text{ см}^2 = 0.53 \text{ см}^2; \\
E_1^{\alpha} = 0.242 \times 10^5 \text{ кгс/см}^2 = 24.2 \times 10^5 \text{ кгс/м}^2; \\
EF_1^{\alpha} = 24.2 \times 10^5 \times 5250 = 1.27 \times 10^8 \text{ кгс} = 127 \times 10^8 \text{ кН}.
\]

For the inner wall, it is necessary to take into account the uneven distribution of additional forces along its length. The bandwidth is introduced from the condition that \( b_{н.i} = 0.2 H_{н.i} \)

Here \( i \) - number of floors in which the joints of the outer panels are not disclosed to the horizons.

The calculation results for temperature and humidity exposure are summarised in tables 2-5.
The forced deformation $\sum \Delta g$ at which the junction of the outer panels between the eighth and ninth floors is revealed is opening up:

**Table 1.**

| i  | $\sigma_i = 0.2H_{m,i}$ | $F_2^{(i)}$ | $E F_2^{36} \cdot 10^{-8}$, krc | $\gamma_1^{(i)} \cdot 10^{8}$, 1/krc | $\gamma_1^{(i)} \cdot \beta^{36} \cdot 10^{-6}$ | $\mu^{(i)}$ |
|----|-------------------------|------------|-----------------------------|--------------------------------|--------------------------------|-----------|
| 9  | 504                     | 6050       | 3.08                         | 1.112                          | 6.7                            | 0.725     |
| 8  | 458                     | 5500       | 2.80                         | 1.145                          | 6.88                           | 0.733     |
| 7  | 382                     | 4580       | 2.33                         | 1.217                          | 7.31                            | 0.755     |
| 6  | 336                     | 4030       | 2.05                         | 1.276                          | 7.66                            | 0.772     |
| 5  | 280                     | 3360       | 1.71                         | 1.373                          | 8.25                            | 0.805     |
| 4  | 224                     | 2690       | 1.37                         | 1.518                          | 9.13                            | 0.845     |
| 3  | 168                     | 2018       | 1.028                        | 1.763                          | 10.68                           | 0.913     |
| 2  | 112                     | 1344       | 0.685                        | 2.248                          | 13.6                            | 1.032     |
| 1  | 56                      | 674        | 0.342                        | 3.708                          | 22.4                            | 1.325     |

**Table 2.**

| i  | $i \mu_g$ | $C_i^{(o)} = ch(i \mu_g)$ | $C_i^{(o)} / C_g^{(o)}$ | $1 - C_i^{(o)} / C_g^{(o)}$ | $N_i^{(o)} \cdot 10^{-3}$, krc | $T_1^{(i)} \cdot 10^{-3}$, krc | $N_i^{(1)} \cdot 10^{-3}$, krc |
|----|-----------|---------------------------|-------------------------|-------------------------------|-------------------------------|---------------------|---------------------|
| 9  | 6.53      | 342.7                     | 1                       | 0                             | 0                             | 0                   | 0                   |
| 8  | 5.80      | 165.1                     | 0.482                   | 0.518                         | 6.6                           | 6.60                | 0                   |
| 7  | 5.06      | 78.8                      | 0.229                   | 0.771                         | 11.6                          | 9.81                | 1.79                |
| 6  | 4.35      | 38.7                      | 0.113                   | 0.887                         | 16.6                          | 11.29               | 5.31                |
| 5  | 3.62      | 18.7                      | 0.055                   | 0.945                         | 21.6                          | 12.02               | 9.58                |
| 4  | 2.90      | 9.11                      | 0.027                   | 0.973                         | 26.6                          | 12.40               | 14.20               |
| 3  | 2.17      | 4.44                      | 0.013                   | 0.987                         | 31.6                          | 12.55               | 19.50               |
| 2  | 1.45      | 2.25                      | 0.007                   | 0.993                         | 36.6                          | 12.62               | 23.98               |
| 1  | 0.725     | 1.274                     | 0.004                   | 0.996                         | 41.6                          | 12.68               | 28.92               |
| 0  | 0         | 1                         | 0.003                   | 0.997                         | 46.6                          | 12.70               | 33.90               |

$i=9; \mu_g = 0.725; \gamma_9 = 0.01112 * 10^{8} 1 / \text{kH};$

$$\Delta g = \frac{6.6 \times 10^{8} + 0.01112 \times 10^{8}}{0.518} = 14.17 \times 10^{-5};$$

$$\frac{\Delta g}{\gamma_9} = \frac{14.17 \times 10^{-5}}{0.01112 \times 10^{8}} = 12.74 \times 10^{3} \text{ kH};$$

$$\sum \Delta g = 14.17 \times 10^{-5} < \varepsilon_{\text{tot}} = 27.5 \times 10^{-5}.$$
Therefore, the horizontal joint between the outer panels of the eighth and ninth floors is revealed. Repeat the calculation until the condition is met $\sum \Delta_0 \leq \varepsilon_{\text{tot}}$.

$l=8; \mu_8 = 0,733; \gamma_0 = 0,01145 \times 10^{81} \text{kH}$.

| $i$ | $i\mu_i$ | $C_i^{(1)} = ch(i\mu_i)$ | $C_i^{(1)} / C_8^{(1)}$ | $1 - C_i^{(1)} / C_8^{(1)}$ | $T_i^{(2)} \cdot 10^{-3}$, кгс | $N_i^{(2)} \cdot 10^{-3}$, кгс |
|-----|----------|-------------------|--------------------|------------------|-----------------|------------------|
| 8   | 5,87     | 177,1             | 1                  | 0                | 0               | 0                |
| 7   | 5,13     | 84,5              | 0,477              | 0,523            | 1,79            | 0                |
| 6   | 4,4      | 40,7              | 0,230              | 0,770            | 2,64            | 2,67             |
| 5   | 3,66     | 19,4              | 0,1094             | 0,890            | 3,05            | 6,53             |
| 4   | 2,93     | 9,39              | 0,0530             | 0,947            | 3,24            | 10,96            |
| 3   | 2,2      | 4,57              | 0,0258             | 0,974            | 3,34            | 16,16            |
| 2   | 1,46     | 2,27              | 0,0128             | 0,987            | 3,38            | 20,60            |
| 1   | 0,733    | 1,28              | 0,00723            | 0,993            | 3,40            | 25,52            |
| 0   | 0        | 1                 | 0,00565            | 0,994            | 3,41            | 30,49            |

$\Delta_8 = \frac{1,79 \times 10^3 \times 0,01145 \times 10^{-8}}{0,523} = 3,92 \times 10^{-5}$;

$\frac{\Delta_8}{\gamma_0} = \frac{3,92 \times 10^5}{0,01145 \times 10^{-8}} = 3,42 \times 10^3 \text{kH}$;

$\sum \Delta_0 = (14,15 + 3,92) \times 10^{-5} = 18,07 \times 10^{-5} < \varepsilon_{\text{tot}} = 27,5 \times 10^{-5}$,

$l=7; \mu_7 = 0,755; \gamma_7 = 0,01217 \times 10^{81} \text{kH}$.

| $i$ | $i\mu_i$ | $C_i^{(2)} = ch(i\mu_i)$ | $C_i^{(2)} / C_7^{(2)}$ | $1 - C_i^{(2)} / C_7^{(2)}$ | $T_i^{(3)} \cdot 10^{-3}$, кгс | $N_i^{(3)} \cdot 10^{-3}$, кгс |
|-----|----------|-------------------|-------------------|------------------|-----------------|------------------|
| 7   | 5,28     | 98,19             | 1                 | 0                | 0               | 0                |
| 6   | 4,53     | 46,38             | 0,472             | 0,528            | 2,67            | 0                |
| 5   | 3,77     | 21,70             | 0,221             | 0,779            | 3,92            | 2,61             |
| 4   | 3,02     | 10,27             | 0,104             | 0,896            | 4,52            | 6,44             |
| 3   | 2,26     | 4,84              | 0,049             | 0,951            | 4,79            | 11,37            |
| 2   | 1,51     | 2,37              | 0,024             | 0,976            | 4,82            | 15,78            |
| 1   | 0,755    | 1,295             | 0,013             | 0,987            | 4,97            | 20,55            |
| 0   | 0        | 1                 | 0,010             | 0,990            | 4,99            | 25,50            |
\[ \Delta_7 = \frac{2.67\times10^3+0.01217\times10^{-8}}{0.528} = 6.15\times10^{-5}; \]

\[ \frac{\Delta_7}{\gamma_7} = \frac{6.15\times10^{-5}}{0.01217\times10^{0}} = 5.05 \times 10^3 \text{ kH}; \]

\[ \sum \Delta_7 = (18.07 + 6.15) \times 10^{-5} = 24.22 \times 10^{-5} < \varepsilon_{\text{tot}} = 27.5 \times 10^{-5}; \]

\[ I=6; \mu_6 = 0.772; \gamma_6 = 0.01276 \times \frac{10^{-8}}{1} \text{ kH}. \]

| \( i \) | \( i\mu_6 \) | \( C_i^{(3)} = ch(i\mu_6) \) | \( C_i^{(3)} / C_6^{(3)} \) | \( 1 - C_i^{(3)} / C_6^{(3)} \) | \( T^{(4)} \times 10^{-3}, \text{ krc} \) | \( N_i^{(4)} / C_6^{(3)}, \text{ krc} \) |
|---|---|---|---|---|---|---|
| 6 | 4.62 | 50.25 | 1 | 0 | 0 | 0 |
| 5 | 3.85 | 23.51 | 0.468 | 0.532 | 2.61 | 0 |
| 4 | 3.08 | 10.90 | 0.217 | 0.783 | 3.84 | 2.60 |
| 3 | 2.31 | 5.08 | 0.101 | 0.899 | 4.41 | 11.12 |
| 2 | 1.54 | 2.44 | 0.0485 | 0.9515 | 4.66 | 6.96 |
| 1 | 0.772 | 1.31 | 0.0261 | 0.9739 | 4.78 | 15.77 |
| 0 | 0 | 0 | 1 | 0.0199 | 0.9801 | 4.81 | 20.69 |

\[ \Delta_6 = \frac{2.61\times10^3+0.01276\times10^{-8}}{0.532} = 6.27\times10^{-5}; \]

\[ \frac{\Delta_6}{\gamma_6} = \frac{6.27\times10^{-5}}{0.01276\times10^{0}} = 4.91 \times 10^3 \text{ kH}; \]

\[ \sum \Delta_6 = (24.22 + 6.27) \times 10^{-5} = 30.49 \times 10^{-5} < \varepsilon_{\text{tot}} = 27.5 \times 10^{-5}. \]

Therefore, the horizontal joint of the exterior wall panels between the fifth and sixth floors is not disclosed.

### 4. Conclusion

The performed numerical studies have confirmed that as a result of temperature and humidity exposure, the outer wall is unloaded, and the inner wall is additionally loaded.

The above calculations show that due to temperature and humidity deformations, more than 50% of the load on the outer walls can be redistributed to the inner wall. This indicates the need to account for deformations when calculating the joint work of the external and internal walls of buildings.

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