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ASSESSMENT OF UNCERTAINTY MODEL OF RESTRAINED EXPANSION STRAINS OF FIBER REINFORCED SELF-STRESSING CONCRETE AT THE EXPANSION STAGE

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Abstract

The article presents an analysis of existing approaches to predicting the self-strains and stresses of self-stressing concrete. The main premises and equations of the modified strains development model for determining the self-strains and stresses of fiber reinforced self-stressing concrete at the expansion stage. This mutual influence model constrains the elements in three directions. The presented model was verified against the background of experimental data. An assessment of the model uncertainties of the modified strains development model of fiber reinforced self-stressing concrete on the 3rd, 7th, 14th and 28th day of concrete age is estimated.

The developed model is applicable for any composition of self-stressing concrete, as well as for various combinations of dispersed reinforcement.

Keywords: fiber reinforced self-stressing concrete, restrained expansion strains, self-stressing, volumetric constraint, modified strains development model, model uncertainty.

ОЦЕНКА ОШИБКИ МОДЕЛИРОВАНИЯ СОБСТВЕННЫХ ДЕФОРМАЦИЙ НАПРЯГАЮЩЕГО ФИБРОБЕТОНА НА СТАДИИ РАСШИРЕНИЯ

И. П. Павлова, И. В. Белкина, А. А. Лизогуб

Реферат

В статье представлен анализ существующих подходов к прогнозированию собственных напряжений и связанных деформаций напрягающего бетона. Изложены основные предпосылки и уравнения модифицированной деформационной модели для определения собственных напряжений и связанных деформаций напрягающего фибробетона на стадии расширения. Представленная модель учитывает взаимное влияние ограничивающих элементов в трёх направлениях. Выполнена верификация представленной модели на фоне экспериментальных данных. Оценена ошибка моделирования собственных деформаций напрягающего фибробетона на 3-е, 7-е, 14-е и 28-е сутки возраста бетона.

Разработанная модель применима для любых составов напрягающего бетона, а также при различных комбинациях дисперсного армирования.

Ключевые слова: напрягающий фибробетон, собственные деформации, самонапряжение, объёмное ограничение, модифицированная деформационная модель, ошибка моделирования.

Introduction

Self-stressing concretes occupy a special place in the field of concrete science. The variety of ways to create expansion has led to the emergence of more than 50 types of expansive concretes. Concrete based on alumina cement, as well as Portland cement using sulfoaluminate expanding additives, are widely known. These concretes are used in road surfaces, floors, foundations and massive structures. The main advantage of using this type of concrete is multitasking. During the hardening process, expansion can not only compensate for chemical shrinkage, but also create prestress under construction conditions without prestressing the reinforcement bars. Concrete with expanding binders has high corrosion resistance, waterproofing capacity and frost resistance [1].

However, the use of self-stressing concrete is still quite limited and causes a lot of discussion. Despite the unique properties, instability of compositions remains one of the main problems. Thus, the impossibility of completely eliminating late recrystallization of highly basic calcium hydrosulfoaluminates negatively affects the final properties of the composite. Some patterns of processes occurring in self-stressing concrete remain unexplored to this day.

The lack of reliable models for predicting expansion strains of self-stressing concrete has led to a situation where the main research method is experiment. With this approach, it is quite difficult to establish the cause of failure: incorrectly selected compositions or unforeseen negative processes in concrete during hardening and (or) operation.

One of the problems with expandable composites is unlimited expansion. This process is most dangerous in the later stages of hardening, as it leads to cracking in the cement matrix and a decrease in the strength of the material. The purpose of self-stressing concrete is to create prestresses, which implies some restraints that solve the above problems. As a limiter, various types of rod reinforcement are used, which are placed in one or several planes of the structure. Self-stressing concrete is most effective in structures with triaxial or spatial constraints. Such reinforcement is most often used in floors, slabs, bridges, and pipe concrete.

The next question was to determine the amount of reinforcement needed to achieve the required self-stressing values. At the moment, there is no universal approach to determining self-strains and stresses. Most methods are valid only for the case of uniaxial reinforcement, for example, proposed by the founder of the scientific school "Concrete with expanding binders and structures made from them", Professor V.V. Mikhailov [2] or the approach set out in regulatory documents (STB 1335, STB 2101).

Prediction of self-strains and stresses for the case of uniaxial constraint is considered in [3]. Scientists from Belarus [4–6], under the guidance of a professor Tur V.V., modified the existing deformation model [3] of self-stressing concrete for the case of uniaxial asymmetrical reinforcement [4], and biaxial constraint [5, 6].

With the development of self-stressing concrete, approaches to controlling processes in its structure have also improved. Researchers have been trying to find a way to reduce the negative effects of expansion and simultaneous declines in strength. Such modifications led to the emergence of self-stressing fiber-reinforced concrete. At first, fiber was used as an addition to rod reinforcement, but at the moment dispersed fiber reinforcement is considered as an independent spatial constraint [7–10].

The aim of the article is to present and verify a model for predicting the self-strains and stresses of fiber reinforced self-stressing concrete at the expansion stage.

MSDM for different types of self-stressing concrete restraint. There are many approaches to determining restrained expansion strains and stresses in self-stressing concrete. A detailed review of studies on this theme is presented in [11]. Recently, much attention has been paid to models based on the deformation approach [3, 6, 11–16]. The basic provisions of the deformation model of an expanding composite system for different levels of modeling are considered in [12].

In 2004, Ito et al. [3] proposed a model for determining the self-stress of uniaxially reinforced prestressed beams based on the finite element method, which took into account the principle of superposition and the linear dependence of stresses on strains and estimated the stresses and strains of concrete under constrained conditions using Young's modulus models, creep coefficient, changes in autogenous shrinkage and temperature. The proposed method modeled the behavior of stressed concrete beams with high accuracy. At the same time, the model did not take into account the influence of the reaction that occurs in the elastic constraint at the next stages of strain growth.

Subsequently, the authors [11, 13] proposed a deformation model for calculating restrained expansion strains (self-stresses) in elements made of prestressing concrete, based on the hypothesis of the compatibility of deformations, equilibrium conditions and physical laws describing the behavior of self-stressing concrete at an early age, in which, in contrast to [3], the influence in the limiting relation (ΔF) is taken into account (Figure 1).

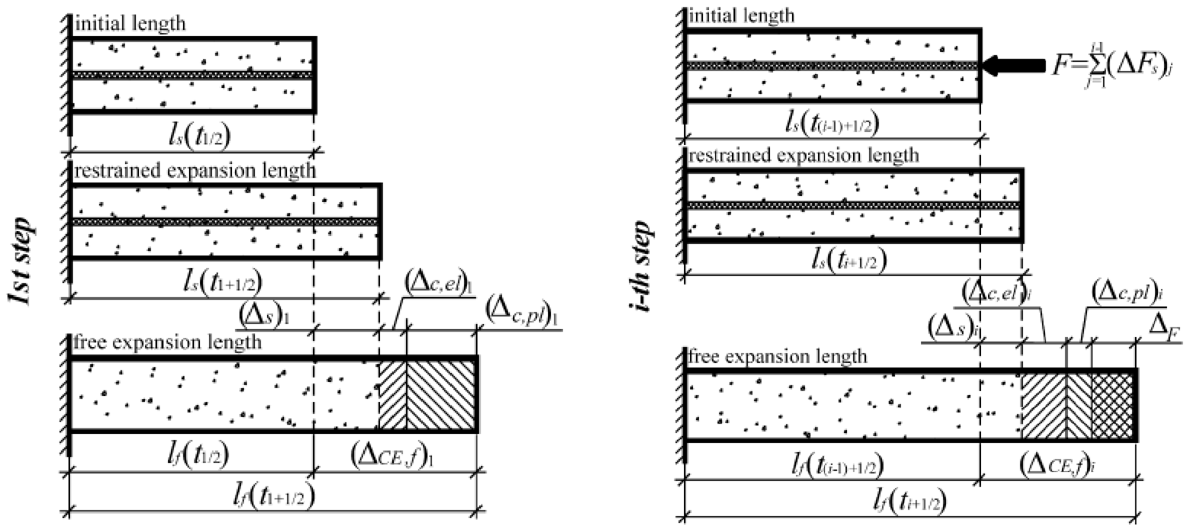

Figure 1 – Scheme of expansion development under uniaxial symmetrical finite stiffness restraint conditions [13]

The next stage in the development of the deformation model was the transition from structures with uniaxially constrained self-stressing concrete to the case of biaxial constraint. The authors of [6] developed a modified model (2D MSDM) to evaluate the stress and strain parameters of biaxially constrained tensioned concrete elements at an early age, which makes it possible to determine the associated strains and the corresponding self-stresses under arbitrary constraint conditions in orthogonal directions, taking into account the elastoplastic behavior of concrete on expansion stages (Figure 2). A distinctive feature of the proposed analytical model is the consideration of the mutual influence of limiting constraints by introducing Poisson's ratio for concrete at an early age to the selected elastic strains of concrete.

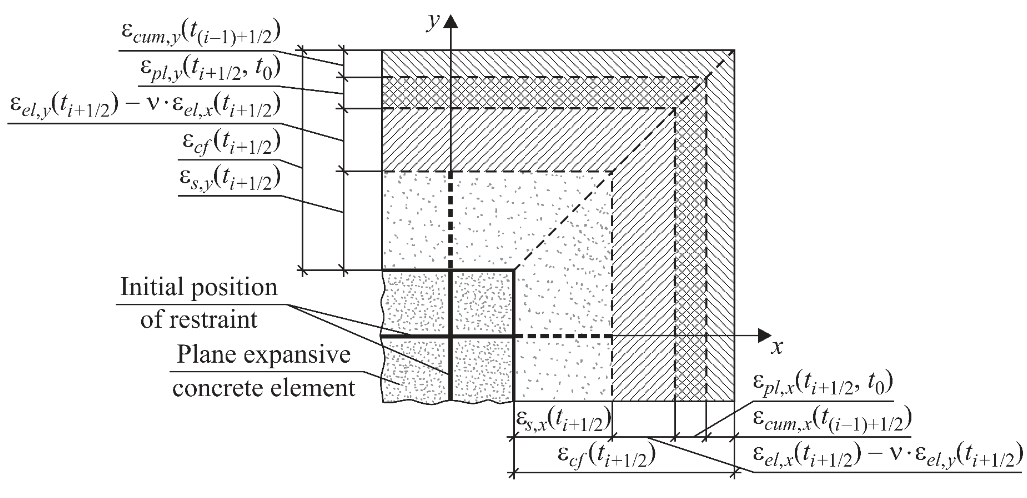

Figure 2 – Development of strains in the plane expansive concrete element [6]

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The final possible option for limiting tension concrete in a structure is a tri-axial (volumetric) constraint. One example of such a constraint is the expansive concrete-filled steel tube (ECFST) structure. The model developed in [14] took into account all previous modifications. However, it is important to note that the radial stress in the steel pipe is not taken into account and the pipe material is in a biaxial stress state (Figure 3).

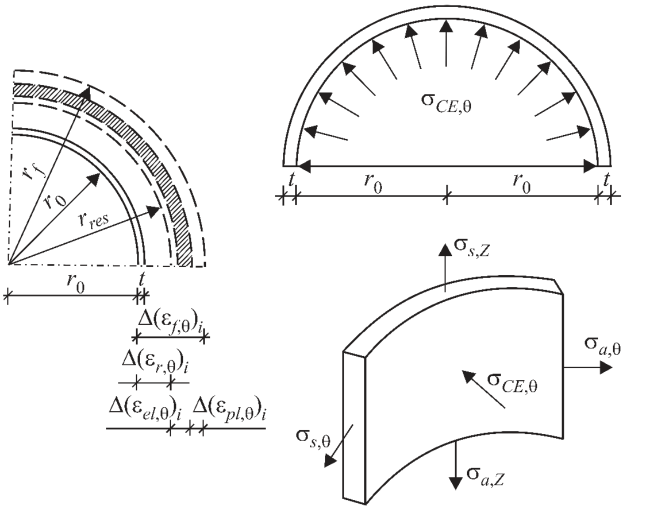

Figure 3 – Scheme of incremental approach in proposed MSDM for expansive concrete-filled steel tube [14]

Premises and assumptions of the modified strains development model for the case of a triaxial constraint. As mentioned above, often FRSSC is usually considered as a modified self-stressing concrete with bar reinforcement. However, this approach to the determination of strains is not correct, since FRSSC represents the following structure – self-stressing concrete with micro-reinforcement. The hypothesis we propose (taking into account the provisions of [3, 6, 12–15]) is as follows:

1. The calculation model is based on the premise that self-stressing fiber reinforced concrete can be represented as a sphere of an expansive concrete core and a homogeneous shell of constant thickness covering it, consisting of fiber material (Figure 4).
2. The ratio of the shell thickness to the radius of the sphere is proportional to the fiber consumption per unit volume of concrete.
3. The shell is connected to the core and does not slip over the concrete surface when the sphere is deformed.
4. The internal forces arising in the expanding concrete core and the internal forces arising in the shell constraining it are mutually balanced.
5. When the sphere of self-stressing concrete expands with radius r, the shell perceives a radial uniformly distributed load q, as a result, circumferential (equatorial) and meridional stresses arise in the plane of the shell with thick-ness t, which due to spherical symmetry, are equal to $\sigma_t = \sigma_m = \sigma$:

$$\sigma = \frac{qr}{2t}. \tag{1}$$

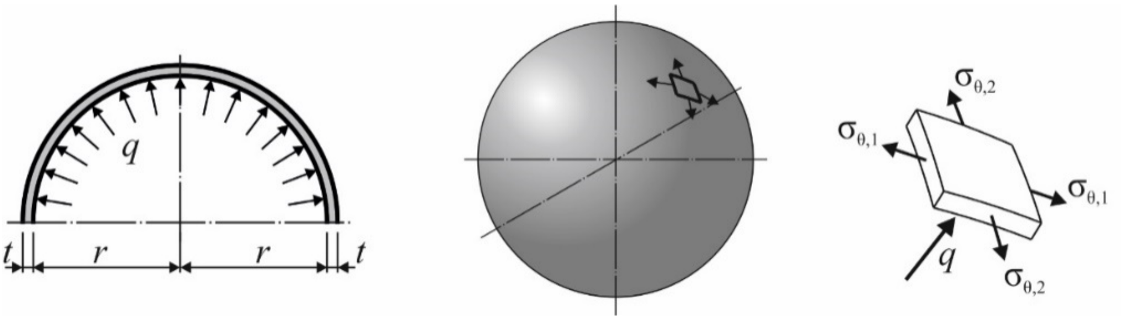

Figure 4 – Scheme of a spherical shell made of fiber with stresses σ_t and σ_m arising in it from the action of a radial uniformly distributed load q

The circumferential strain ε_t and the meridional strain ε_m equal to it are determined in accordance with Hooke's law:

$$\varepsilon_t = \frac{1}{E_s}\cdot\left(\sigma_t - \sigma_m \cdot \mu_s\right);$$
$$\varepsilon_m = \frac{1}{E_s}\cdot\left(\sigma_m - \sigma_t \cdot \mu_s\right). \tag{2}$$

Taking into account the equality $\varepsilon_t = \varepsilon_m = \varepsilon_r$, the strain ε_r will take the form:

$$\varepsilon_r = \frac{\sigma}{E_s}\cdot\left(1-\mu_s\right), \tag{3}$$

where μ_s is Poisson's ratio for the shell material; E_s is the modulus of elasticity of the shell material.

6. The expansion of the self-stressing concrete core is uniform in all directions.
7. When determining the elastic strains of self-stressing concrete, the volumetric expansion is taken into account by introducing the Poisson's ratio for concrete at an early age, taken $\mu = 0{,}2$.
8. The restrained expansion strains ε_r for each orthogonal direction (*X, Y, Z*) are determined by subtracting from the free expansion strains ε_{cf} the elastic and inelastic strains due to concrete creep ($\varepsilon_{c,el} + \varepsilon_{ac,pl}$), as well as the elastic strains in as a result of the additional elastic constraint reaction ε_{acc}.

To determine the stresses from the action of a radial uniformly distributed load q, we use the solution of the problem of a thin-walled spherical shell (Figure 4) loaded with an internal uniform pressure.

From the Laplace equation, we obtain the stresses arising in the shell:

$$q = \sigma_{cf} = \frac{2t}{r}\cdot\sigma_m; \quad \sigma_m = \frac{E_s}{1-\mu_s}\cdot\varepsilon_m;$$
$$q = \sigma_{cf} = \frac{2t}{r}\cdot\sigma_t; \quad \sigma_t = \frac{E_s}{1-\mu_s}\cdot\varepsilon_t. \tag{4}$$

Considering that $\sigma_m = \sigma_t = \sigma$, $\varepsilon_m = \varepsilon_t = \varepsilon$ and assuming that $\varepsilon = \varepsilon_{cr}$, we get:

$$\left(\Delta\sigma_{cf}\right)_i = \frac{2t}{r} \cdot \frac{E}{1-\mu_s} \cdot \left(\Delta\varepsilon_r\right)_i. \quad (5)$$

In the general case, the increment of the restrained expansion strain $\left(\Delta\varepsilon_r\right)_i$ on an arbitrary *i*-th time interval can be represented as follows (Figure 5):

$$\left(\Delta\varepsilon_r\right)_i = \left(\Delta\varepsilon_f\right)_i - \left(\Delta\varepsilon_{el}\right)_i - \left(\Delta\varepsilon_{pl}\right)_i - \left(\Delta\varepsilon_{acc}\right)_i, \quad (6)$$

where $\left(\Delta\varepsilon_f\right)_i$ – increment free expansion strain on arbitrary *i*-th time interval;

$\left(\Delta\varepsilon_{el}\right)_i$ – increment of elastic strain on arbitrary *i*-th time interval;

$\left(\Delta\varepsilon_{pl}\right)_i$ – increment of plastic strain on arbitrary *i*-th time interval;

$\left(\Delta\varepsilon_{acc}\right)_i$ – increment of elastic strain as a result of the action of the elastic constraint reaction on an arbitrary *i*-th time interval.

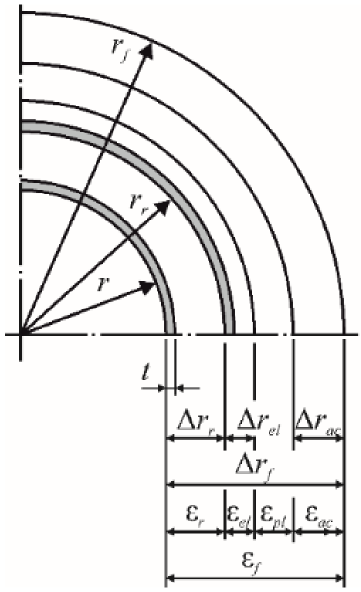

Figure 5 – Scheme of development of expansion strains in time

The sum of increments of elastic $\left(\Delta\varepsilon_{el}\right)_i$ and plastic $\left(\Delta\varepsilon_{pl}\right)_i$ relative strains on an arbitrary *i*-th time interval can be represented as:

$$\left(\Delta\varepsilon_{el}\right)_i + \left(\Delta\varepsilon_{pl}\right)_i = \left(\Delta\sigma_{cf}\right)_i \cdot J\left(t_{i+1/2};t_i\right) + \sum_{j=1}^{i-1}\left[\left(\Delta\sigma_{cf}\right)_j \cdot \frac{\Delta\phi\left(t_i;t_j\right)}{E_{cm,28}}\right], \quad (7)$$

where $J\left(t_{i+1/2};t_j\right)$ is the concrete creep function:

$$J\left(t_{i+1/2};t_j\right) = \frac{1}{E_c\left(t_j\right)} + \frac{\phi\left(t_{i+1/2};t_j\right)}{E_{cm,28}}, \quad (8)$$

where $E_c\left(t\right)$ is the modulus of elasticity of concrete at a modified age corresponding to the actual age of concrete t_j:

$E_{cm,28}$ is the modulus of elasticity of concrete, corresponding to 28 days of the actual age of concrete;

$\Delta\phi\left(t_i;t_j\right)$ is increment of the concrete creep coefficient on an arbitrary *i*-th time interval:

$$\Delta\phi\left(t_i;t_j\right) = \phi\left(t_{i+1/2};t_j\right) - \phi\left(t_{(i-1)+1/2};t_j\right). \quad (9)$$

Modified age of concrete t_i, corresponding to t days of the real age of concrete, taking into account the influence of the temperature regime at the stage of hardening and expansion of concrete:

$$t_i = \sum_{j=1}^{n} \Delta t_j \cdot e^{13{,}65 - \frac{4000}{273+T(\Delta t_j)/T_0}}, \quad (10)$$

where Δt_j is the number of day(s) with temperature T (°C); T_0 = 1°C.

The modulus of elasticity of concrete at a modified age corresponding to the actual age of concrete t_j can be derived from:

$$E_c\left(t\right) = E_{cm,28} \cdot \exp\left\{s\left[1-\left(\frac{t_{m,28}-a}{t_i-a}\right)^{0{,}5}\right]\right\}, \quad (11)$$

where s is an empirical coefficient that takes into account the type of binder; a is an empirical coefficient that takes into account the effect of the concrete setting start time.

The concrete creep coefficient $\phi\left(t;t_0\right)$ is calculated using the following formula:

$$\phi\left(t;t_0\right) = \phi_0 \cdot \beta\left(t;t_0\right), \quad (12)$$

where ϕ_0 is the notional creep coefficient;

$$\phi_0 = 5{,}31 \cdot \left[\frac{E_c\left(t_0\right)}{E_{cm,28}} - 1{,}0\right]^2 + 1{,}11, \quad (13)$$

where $\beta_c\left(t,t_0\right)$ is the coefficient describing the development of creep over time after loading.

$$\beta_c\left(t,t_0\right) = \frac{\left(t-t_0\right)}{\beta_H + \left(t-t_0\right)}, \quad (14)$$

β_H is the coefficient that takes into account the influence of concrete age:

$$\beta_H \Leftarrow \begin{cases} 0 \le E_c\left(t\right)/E_{cm,28} < 0{,}346; \\ \beta_H = 0{,}000001; \\ 0{,}346 \le E_c\left(t\right)/E_{cm,28} < 1; \\ \beta_H = 40{,}5 \cdot \left[E_c\left(t\right)/E_{cm,28} - 0{,}346\right] + 0{,}485. \end{cases} \quad (15)$$

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The increments of elastic strain $\left(\Delta\varepsilon_{acc}\right)_i$ as a result of the action of the elastic constraint reaction on an arbitrary *i*-th time interval can be represented as:

$$\left(\Delta\varepsilon_{acc}\right)_i = \sum_{j=1}^{i-1}\left[\frac{\left(\Delta\sigma_{cf}\right)_j}{E_{cm}\left(t_j\right)}\right]\cdot\frac{E_{cm,aw}\left(t_{(i-1)+1/2}\right)}{E_{cm}\left(t_{(i-1)+1/2}\right)}, \quad (16)$$

where $E_{cm,aw}\left(t_{i+1/2}\right)$ is weight-average modulus of elasticity of self-stressing concrete by the end of the *i*-th elementary time interval:

$$E_{cm,aw}\left(t_{i+1/2}\right) = \frac{\sum_{j=1}^{i}\left(\Delta\sigma_{cf}\right)_j\cdot E_c\left(t_j\right)}{\sum_{j=1}^{n}\left(\Delta\sigma_{cf}\right)_j}, \quad (17)$$

where $\left(\Delta\sigma_{cf}\right)_j$ is the increment of the self-stress value on the *j*-th elementary time interval;

$E_c\left(t_j\right)$ is the modulus of elasticity of the self-stressing concrete at the modified age corresponding to the real age t_j;

$E_c\left(t_{i+1/2}\right)$ is the modulus of elasticity of the self-stressing concrete at the modified age corresponding to the real age of the self-stressing concrete $t_{i+1/2}$, which corresponds to the end of the *i*-th elementary time interval under consideration.

Solving together (5) and (6) for each orthogonal direction (*X, Y, Z*), we obtain increments of intrinsic associated strains at each *i*-th time interval:

$$\begin{cases}\left(\Delta\sigma_{cf,x}\right)_i = \frac{2t}{r}\cdot\frac{E_s}{1-\mu_s}\cdot\left(\Delta\varepsilon_{r,x}\right)_i;\\ \left(\Delta\sigma_{cf,y}\right)_i = \frac{2t}{r}\cdot\frac{E_s}{1-\mu_s}\cdot\left(\Delta\varepsilon_{r,y}\right)_i;\\ \left(\Delta\sigma_{cf,z}\right)_i = \frac{2t}{r}\cdot\frac{E_s}{1-\mu_s}\cdot\left(\Delta\varepsilon_{r,z}\right)_i.\end{cases} \quad (18)$$

$$\begin{cases}\left(\Delta\varepsilon_{r,x}\right)_i = \left(\Delta\varepsilon_{f,x}\right)_i - \left[\left(\Delta\sigma_{cf,x}\right)_i - \mu_c\cdot\left(\Delta\sigma_{cf,y}\right)_i - \mu_c\cdot\left(\Delta\sigma_{cf,z}\right)_i\right]\cdot J\left(t_{i+1/2};t_i\right) -\\ -\sum_{j=1}^{i-1}\left[\left(\Delta\sigma_{cf,x}\right)_j\cdot\frac{\Delta\phi\left(t_i;t_j\right)}{E_{cm,28}}\right] - \sum_{j=1}^{i-1}\left[\frac{\left(\Delta\sigma_{cf,x}\right)_j}{E_{cm}\left(t_j\right)}\right]\cdot\frac{E_{cm,aw}\left(t_{(i-1)+1/2}\right)}{E_{cm}\left(t_{(i-1)+1/2}\right)};\\ \left(\Delta\varepsilon_{r,y}\right)_i = \left(\Delta\varepsilon_{f,y}\right)_i - \left[\left(\Delta\sigma_{cf,y}\right)_i - \mu_c\cdot\left(\Delta\sigma_{cf,x}\right)_i - \mu_c\cdot\left(\Delta\sigma_{cf,z}\right)_i\right]\cdot J\left(t_{i+1/2};t_i\right) -\\ -\sum_{j=1}^{i-1}\left[\left(\Delta\sigma_{cf,y}\right)_j\cdot\frac{\Delta\phi\left(t_i;t_j\right)}{E_{cm,28}}\right] - \sum_{j=1}^{i-1}\left[\frac{\left(\Delta\sigma_{cf,y}\right)_j}{E_{cm}\left(t_j\right)}\right]\cdot\frac{E_{cm,aw}\left(t_{(i-1)+1/2}\right)}{E_{cm}\left(t_{(i-1)+1/2}\right)};\\ \left(\Delta\varepsilon_{r,z}\right)_i = \left(\Delta\varepsilon_{f,z}\right)_i - \left[\left(\Delta\sigma_{cf,z}\right)_i - \mu_c\cdot\left(\Delta\sigma_{cf,x}\right)_i - \mu_c\cdot\left(\Delta\sigma_{cf,y}\right)_i\right]\cdot J\left(t_{i+1/2};t_i\right) -\\ -\sum_{j=1}^{i-1}\left[\left(\Delta\sigma_{cf,z}\right)_j\cdot\frac{\Delta\phi\left(t_i;t_j\right)}{E_{cm,28}}\right] - \sum_{j=1}^{i-1}\left[\frac{\left(\Delta\sigma_{cf,z}\right)_j}{E_{cm}\left(t_j\right)}\right]\cdot\frac{E_{cm,aw}\left(t_{(i-1)+1/2}\right)}{E_{cm}\left(t_{(i-1)+1/2}\right)}.\end{cases} \quad (19)$$

Due to the spherical symmetry, the systems of equations (18) and (19) for each orthogonal direction (*X, Y, Z*) can be represented as two equations:

$$\left(\Delta\sigma_{cf}\right)_i = \frac{2t}{r}\cdot\frac{E_s}{1-\mu_s}\cdot\left(\Delta\varepsilon_r\right)_i; \quad (20)$$

$$\left(\Delta\varepsilon_r\right)_i = \left(\Delta\varepsilon_f\right)_i - \left(\Delta\sigma_{cf}\right)_i\cdot\left(1-2\mu_c\right)\cdot J\left(t_{i+1/2};t_i\right) - \sum_{j=1}^{i-1}\left[\left(\Delta\sigma_{cf}\right)_j\cdot\frac{\Delta\phi\left(t_i;t_j\right)}{E_{cm,28}}\right] - \sum_{j=1}^{i-1}\left[\frac{\left(\Delta\sigma_{cf}\right)_j}{E_{cm}\left(t_j\right)}\right]\cdot\frac{E_{cm,aw}\left(t_{(i-1)+1/2}\right)}{E_{cm}\left(t_{(i-1)+1/2}\right)}. \quad (21)$$

Results and discussion. To test the main provisions of the model, we used a sample that consisted of data presented in studies [16–18]. Based on the initial data, the values of the associated expansion strains were calculated, which were then compared with the experimental results. To assess the model uncertainties of the computational model, graphs were constructed (Figure 6), which show the values of restrained expansion strains ($\varepsilon_{r,calc.}$) calculated by the model on the 3rd, 7th, 14th and 28th days in relation to the corresponding experimental data ($\varepsilon_{r,exp.}$).

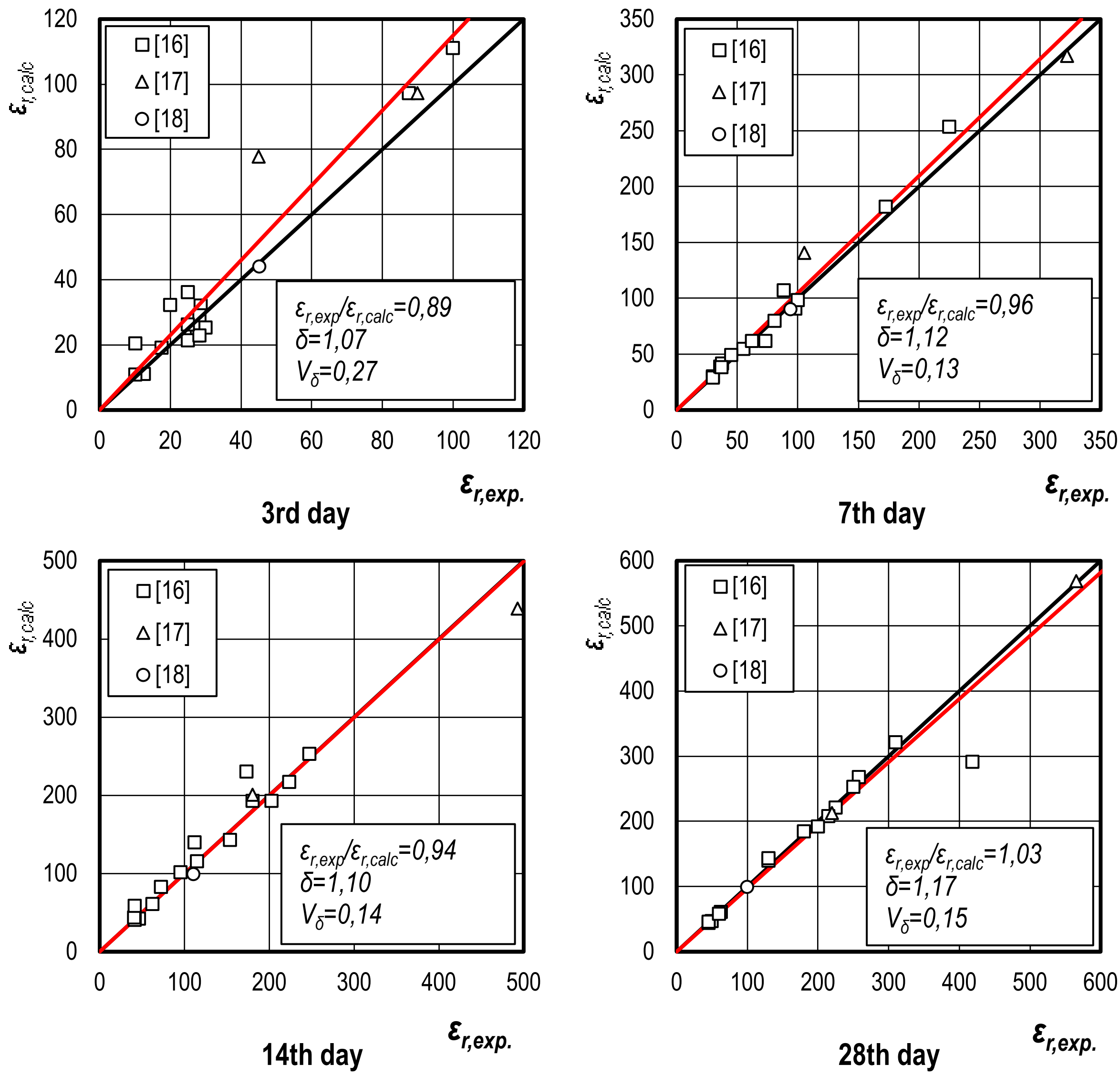

Figure 6 – Assessment of uncertainty model of restrained expansion strains of fiber reinforced self-stressing concrete at the expansion stage

As follows from Figure 6, the largest scatter between theoretical and experimental data occurs at the early age of concrete – day 3, where the coefficient of variation for the model uncertainties was 27 %. This is explained by the instability of the expansion and shrinkage processes occurring during the period of active action of the expanding additive, which is quite difficult to describe with a model. However, by the time of stabilization, the coefficient of variation decreases (15 %), which indicates more reliable results.

Conclusion

The modified analytical model has been developed to determine the restrained expansion stresses and strains at the stage of expansion of self-stressing concrete under conditions of spatial limitation of free strains by dispersed reinforcing elements of arbitrary stiffness. The proposed model differs from existing models in that it takes into account the mutual influence of limiting elements in three directions in the calculations by introducing Poisson's ratio for concrete to the selected elastic strains of concrete. This makes it possible to determine stresses in concrete and strains in the limiting element, represented by dispersed reinforcement, in an arbitrary time interval until the stabilization of free expansion. The model is able to determine the required amount of dispersed reinforcement by the specified values of the restrained expansion strains. The developed analytical model is applicable for every mixes of self-stressing concrete, as well as for various combinations of dispersed reinforcement.

The proposed modified strains development model is quite universal and covers a significant list of compositions suitable for research. It can be concluded that the model allows one to calculate the associated expansion strains of self-stressing fiber-reinforced concrete with a sufficient degree of accuracy. The identified deviations in the experimental and calculated values of strains should be associated with uncertainties in modeling the characteristics of materials.

References

1. Tur, V. V. Eksperimental'no-teoreticheskie osnovy predvaritel'nogo. napryazheniya konstrukcij pri primenenii napryagayushchego betona : monografiya / V. V. Tur. – Brest : BrPI, 1998. – 246 s.
2. Mihajlov, V. V. Rasshiryayushchie i napryagayushchie cementy i samonapryazhennye konstrukcii / V. V. Mihajlov, S. L. Litver. – M. : Strojizdat, 1974. – 389 s.
3. Early age deformation and resultant induced stress in expansive high strength concrete / H. Ito [et al.] // Journal of Advanced Concrete Technology. – 2004. – No. 2. – P. 155–174.
4. Tur, V. V. K ocenke velichiny samonapryazheniya v konstrukciyah iz napryagayushchego betona / V. V. Tur, O. S. Semenyuk // Vestnik Brestskogo gosudarstvennogo tekhnicheskogo universiteta. Seriya: Stroitel'stvo i arhitektura. – 2014. – № 1. – S. 16–24.

5. Sannikova, O. G. Verifikaciya raschetnoj modeli dlya opredeleniya svyazannyh deformacij i napryazhenij ploskih elementov iz napryagayushchego betona / O. G. Sannikova, V. V. Tur // Vestnik Brestskogo gosudarstvennogo tekhnicheskogo universiteta. Seriya: Stroitel'stvo i arhitektura. – 2020. – № 1. – S. 86–92.
6. Sannikava, V. The modified early age strains development model for the case of two-way restraint conditions / V. Sannikava, V. Tur // MATEC Web of Conferences. – 2021. – Vol. 350. – 10 p.
7. Sugathan, A. Self-Compacting High Performance Concrete with Steel Fibres / A. Sugathan // International Journal of Scientific Engineering and Research (IJSER). – Vol. 4. No. 6. – June 2016. – P. 35–40.
8. Suta, M. Determination of material design values for Steel Fibre Reinforced Self-Stressing Concrete (SFRSSC) structures / M. Suta, A. Lukasenoks, R. Cepuritis // Engineering for rural development. – 2020. – P. 631–637.
9. Wang, B. Flexural Behavior of Fiber-Reinforced Self-Stressing Concrete T-Shaped Composite Beams / B. Wang, R. Fang, Q. Wang // Advances in Civil Engineering. – 2020. – P. 1–17.
10. Impact resistance of steel fiber-reinforced selfcompacting concrete / S. R. Abid [et al.] // Magazine of Civil Engineering. – 2021. – Vol. 5. – 12 p.
11. Tur, V. Modeli, primenyaemye dlya rascheta svyazannyh deformacij i samonapryazhenij v elementah iz napryagayushchego betona / V. Tur, V. Semianiuk // Vestnik Brestskogo gosudarstvennogo tekhnicheskogo universiteta. Seriya: Stroitel'stvo i arhitektura. – 2016. – № 97 (1). – S. 53–69.
12. Tur, V. K ocenke velichiny samonapryazheniya v konstrukciyah iz napryagayushchego betona / V. Tur, V. Semianiuk // Vestnik Brestskogo gosudarstvennogo tekhnicheskogo universiteta. Seriya: Stroitel'stvo i arhitektura. – 2014. – № 119 (1). – S. 16–24.
13. Semianiuk, V. Early age strains and self-stresses of Expansive concrete members under uniaxial restraint conditions / V. Semianiuk, V. Tur, M. F. Herrador // Construction and Building Materials. – 2017. – № 131. – P. 39–49.
14. Analytical model for restraint strains and self-stressed in expansive concrete filled steel tubes (ecfst) estimation / V. V. Tur [i dr.] // Vestnik Brestskogo gosudarstvennogo tekhnicheskogo universiteta. Seriya: Stroitel'stvo i arhitektura. – 2020. – № 119 (1). – S. 93–98.
15. Chang, X. Expansive behaviors of self-stressing concrete under different restraining conditions / X. Chang, C. Huang, P. Zhang // Journal of Wuhan University of Technology-Mater. Sci. Ed. – 2011. No. 26 (4). – P. 780–785.
16. Paulava, I. P. Verifikaciya modificirovannoj deformacionnoj modeli napryagayushchego fibrobetona na fone eksperimental'nyh issledovanij / I. P. Paulava, I. V. Belkina, A. A. Lizahub // Vesnik Grodzenskaga dzyarzhaўnaga ўniversiteta imya YAnki Kupaly. Ser. 6. Tekhnika. – 2023. – T. 13. № 2. – S. 74–87.
17. Pavlova, I. P. Issledovaniya sobstvennyh deformacij i prochnostnyh harakteristik napryagayushchih betonov, armirovannyh bazal'tovym fibrovoloknom / I. P. Pavlova, K. Yu. Belomesova // Perspektivnye napravleniia innovatsionnogo razvitiia stroitel'stva i podgotovki inzhenernykh kadrov: sb. nauch. st. XXI Mezhdunarodnogo nauchno-metodicheskogo seminara, Brest, 25–26 oktiabria 2018 goda : v 2 chastiakh / M-vo obr. Resp. Belarus', Brest. gos. tekhn. un-t, Stroit. f-t ; ed. board: V. V. Tur [et al.]. – Brest, 2018. – Vol. 2. – P. 75–79.
18. He, H. A. Performance on Steel Fiber Reinforced Self-Stressing Concrete / H. A. He, B. X. Wang, J. T. Lin // Key Engineering Materials. – 2008. – Vol. 400–402. – P. 427–432.

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