

STRAINS AND SELF-STRESSES ESTIMATION IN THE EXPANSIVE CONCRETE MEMBERS REINFORCED WITH GFRP BARS

Victar TUR (Prof., Dr. Sc., PhD., Eng., Head of Department of Concrete Technology and Building Materials,
Brest State Technical University)

profturvic@gmail.com

Volha SEMIANIUK (M. Sc., Eng.)

olgasiemieniuk@gmail.com

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Summary

Advantages of the self-stressed concrete members with FRP reinforcement are described. Analytical model for the restrained expansion strains (self-stresses) estimation in the self-stressed concrete members reinforced with FRP bars is proposed. Established modified strains development model (MSDM) is based on deformation compatibility approach in combination with taking into account imposed internal force in reinforcement as an additional restriction for the expansion strains development. Comparison of experimentally established and predicted data that was obtained in accordance with the proposed model for the case of GFRP bars uniaxially symmetrically reinforced high expansion energy capacity concrete members is presented. Verification of the proposed MSDM has shown a good agreement between calculated and experimental values that indicates its validity for the design of the self-stressed concrete members with GFRP reinforcement.

Keywords: expansive concrete, GFRP bars, restrained strain, self-stress, estimation model

Introduction

At present concrete members reinforced with FRP bars are widely applied in the world building practice for erecting of the following type of structures such as: structural members, exploiting under the influence of the aggressive environment, industrial buildings of special purpose, as well as a highway bridge deck slabs. One of the main purposes of FRP bars application is a substitution of the traditional steel reinforcement (as a more inclined to corrosion) by composite reinforcement.

FRP bars have a high strength (the ultimate tensile strength rises up to 1 600 MPa) in combination with a low modulus of elasticity (it's about 30-60 GPa). This feature of FRP bars creates difficulties with its utilization: the main problems appear at service limit state (SLS) checking calculation. In accordance with sufficiently conservative guideline (CNR-DT 203/2006) the partial factor γ_m shall be set equal to 1,5 for ULS checking calculation; and for SLS checking calculation, stresses in FRP bars shall be limited up to $0,3 \cdot f_{frpu}$.

Effectiveness of FRP reinforcement in concrete structures can be advanced by its pretensioning. It becomes possible to realize due to perfectly elastic behavior of FRP bars. But it is rather laborious to realize mechanical pretensioning of FRP bars based on traditional technology (necessity of complicated anchorage systems manufacturing, usage of the special tensioning devices and temperature limitation during heat treatment as well as a highly qualified personnel are required).

To avoid all the difficulties observed during mechanical pretensioning of FRP bars, the utilization of

physicochemical method of structural prestressing, based on the usage of self-stressing concrete could be effective. Experimentally-theoretical background of self-stressed structures is presented in (Król et al. 1998).

Moreover, in the case of the steel reinforced self-stressed members it is possible to reach rather high value of self-stress against the comparatively low value of the restrained strain. Finally obtained restrained strain can be considerably reduced by concrete shrinkage developing in the air-dry curing conditions. Lower modulus of elasticity of FRP reinforcing bars allows to reach higher value of restrained strain in comparison with steel reinforcement that is coupled with the same level of the obtained self-stress in the concrete.

It should be noted that no codes include methods for self-stressed structure design. Only a limited number of guides, for example (TKP 45-5.03-158-2009), have a chapter devoted to this concern. Even so, models for the estimation of restrained strains and self-stresses in expansive concrete at early age are intensively developed (Tsuji 1984; Ito et al. 2004).

2. Modified early age strains development model (MSDM)

In the last years, models for the calculation of initial strains in expansive concrete based on the consideration of the free expansion (shrinkage) strains development history, together with creep and Young's modulus development of the expansive concrete at early age, plus parameters of the restraint conditions, have been developed (Ito et al. 2004; Lei et al. 2007). These models consider the expansion process on the elementary time intervals $-\Delta t_i$.

2.1. Modified strains development model (MSDM) for uniaxial symmetrical restraint conditions

In this article, the modified strains development model for the restrained strains and self-stresses values estimation in the concrete with high expansion energy capacity under the uniaxial symmetrical finite stiffness restraint conditions is proposed.

For the proposed MSDM, the following assumptions were accepted:

1. Equilibrium conditions are respected throughout the concrete expansion stage.
2. Incremental restrained strain at the any i -th time interval $(\Delta\varepsilon_r)_i$ is determined as an algebraic sum of the incremental free expansion $(\Delta\varepsilon_{CE,f})_i$, elastic $(\Delta\varepsilon_{c,el})_i$ and creep $(\Delta\varepsilon_{c,pl})_i$ strains, plus expansive concrete additional strain $\sum_{j=1}^{i-1} (\Delta\sigma_c)_j / E_c(t_{(i-1)+1/2})$ produced by the cumulative force induced by the restraint at the any i -th time interval beginning:

$$(\Delta\varepsilon_r)_i = (\Delta\varepsilon_{CE,f})_i + (\Delta\varepsilon_{c,el})_i + (\Delta\varepsilon_{c,pl})_i + \frac{\sum_{j=1}^{i-1} (\Delta\sigma_c)_j}{E_c(t_{(i-1)+1/2})}. \quad (2.1)$$

The cumulative force induced by the restraint at the end of the (i-1)-th time interval is considered as an additional restraint for the development of free expansion strains at the i-th time interval.

3. Strain compatibility of the expansive concrete and restraint takes place when concrete achieves initial compressive strength $f_{cm,0}(t) \geq 7,5$ MPa as it was shown in (Tur 1998).
4. Plane cross section hypothesis is valid on the concrete expansion stage.
5. Self-stresses at the any i -th time interval should be calculated from the cumulative force induced by the restraint.

The sum of expansive concrete elastic and creep incremental strains at the any i -th time interval can be expressed by the following equation:

$$(\Delta\varepsilon_{c,el})_i + (\Delta\varepsilon_{c,pl})_i = (\Delta\sigma_c)_i \cdot J(t_{i+1/2}; t_i) + \sum_{j=1}^{i-1} \left[(\Delta\sigma_c)_j \cdot \frac{\Delta\phi(t_i; t_j)}{E_{cm,28}} \right], \quad (2.2)$$

$$\Delta\phi(t_i; t_j) = \phi(t_{i+1/2}; t_j) - \phi(t_{(i-1)+1/2}; t_j), \quad (2.3)$$

where, $(\Delta\sigma_c)_i$ incremental self-stress at the considered i -th time interval; $J(t_{i+1/2}; t_j)$: creep compliance function; $(\Delta\sigma_c)_j$: incremental self-stress at the j -th time interval; $E_{cm,28}$: Young's modulus of expansive concrete at 28 days; $\phi(t_{i+1/2}; t_j)$ and $\phi(t_{(i-1)+1/2}; t_j)$: creep coefficients at $t_{i+1/2}$ and $t_{(i-1)+1/2}$ respectively under constant incremental self-stress applied at t_j ;

Incremental restrained expansion strains $(\Delta\varepsilon_r)_i$ at the any i -th time interval can be expressed by the following equation:

$$(\Delta\varepsilon_r)_i = (\Delta\varepsilon_{CE,f})_i - (\Delta\sigma_c)_i \cdot J(t_{i+1/2}; t_i) - \sum_{j=1}^{i-1} \left[(\Delta\sigma_c)_j \cdot \frac{\Delta\phi(t_i; t_j)}{E_{cm,28}} \right] - \frac{\sum_{j=1}^{i-1} (\Delta\sigma_c)_j}{E_c(t_{(i-1)+1/2})}. \quad (2.4)$$

For the case of the uniaxial symmetrical cross sectional reinforcement arrangement, incremental self-stress at the any i -th time interval can be expressed:

$$(\Delta\sigma_c)_i = (\Delta\varepsilon_r)_i \cdot E_r \cdot \rho_i, \quad (2.5)$$

where, E_r : Young's modulus of restraint; ρ_i : cross sectional reinforcement ratio.

Substituting Eq. (2.5) into Eq. (2.4), the incremental restrained expansion strain $(\Delta\varepsilon_r)_i$ at the i -th time interval is determined by the finally obtained equation solving and then in accordance with Eq. (2.5) incremental self-stress at the considered i -th time interval $(\Delta\sigma_c)_i$ is calculated.

Finally, self-stress of the concrete at the end of the i -th time interval $(\sigma_c)_i$ is calculated as a sum of the incremental self-stresses at the time intervals $j \in [1; i]$:

$$(\sigma_c)_i = \sum_{j=1}^i (\Delta\sigma_c)_j. \quad (2.6)$$

In the considered model creep compliance function is accepted in the traditional form in accordance with (**fib** Model Code 2010) and Young's modulus of expansive concrete at early age, $E_c(t)$, can be obtained from the relation based on the model from (EN 1992-1 2001).

Creep coefficient $\phi(t, t_0)$ was evaluated based on proposal from (**fib** Model Code 2010).

3. Experiments

For the verification of the proposed modified strains development model (MSDM) in case of the uniaxial symmetrical GFRP reinforcement, experimental studies were performed.

3.1. Experimental specimens

Experimental studies were carried out on two identical series of expansive concrete beam- specimens. Each of the series consisted of two unreinforced (free) expansive concrete beam-specimens with cross sectional sizes 150×150 mm and 900 mm length and two uniaxially symmetrically reinforced with GFRP bars beam-specimens with cross sectional sizes 90×150 mm and 1500 mm length. Cross sectional geometry of the experimental beam-specimens is presented on Fig. 3.1. Geometry and reinforcement details of the experimental beam-specimens are listed in Table 3.1. To prevent GFRP bars slipping relative to concrete on the expansion stage, reinforced beam-specimens of the both series had got an additional confinement reinforcement made of S500 grade steel wire ($\varnothing 4$ mm) coils (with 35 mm external diameter and 25 mm coiling spacing) that were arranged by its connecting with the bottom GFRP bar with plastic clamp in the ends of the beam-specimens (350 mm length from the end faces).

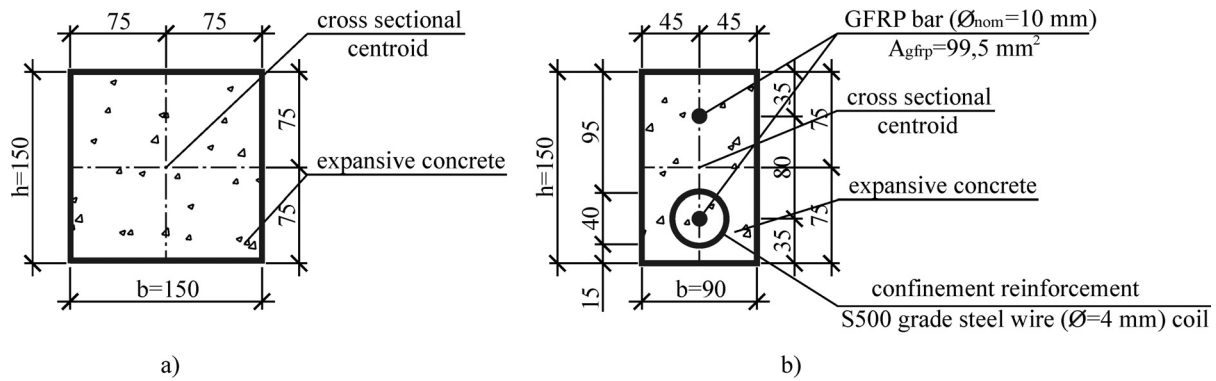


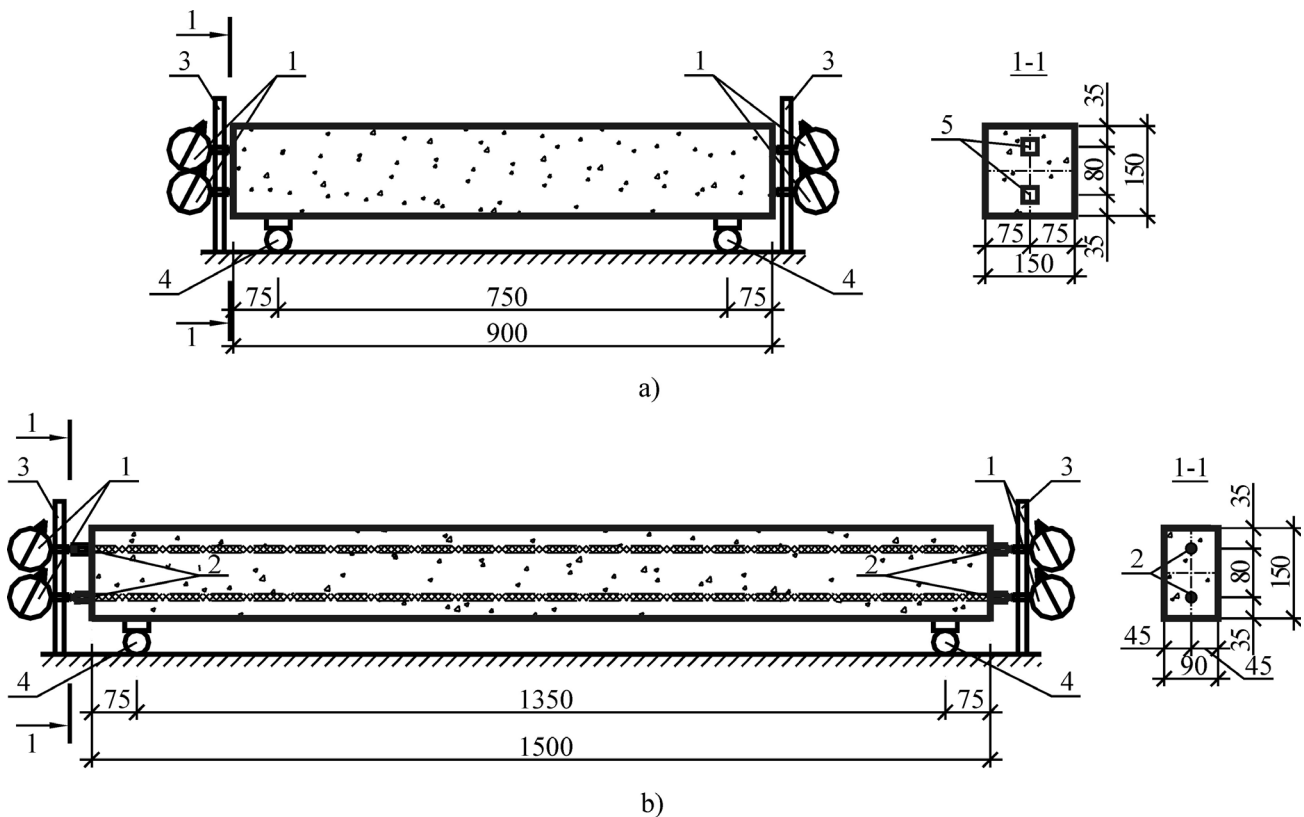
Fig. 3.1. Cross sectional geometry of the experimental beam-specimens
a) unreinforced (free) beam-specimen; b) reinforced beam-specimen

Table 3.1. Geometry and reinforcement details of the experimental beam-specimens

Series	Specimen marking	Geometry, mm		GFRP reinforcement		Curing conditions
		b×h, mm	l, mm	A_{gfrp} , mm ²	ρ_p , %	
I, II	x-BECF-(1, 2)	150×150	900	reinforcement without		water curing
	x-BECC-(3, 4)	90×150	1500	199,1	1,47	

Notes: In the table the following marking of specimens was accepted: x – number of the series (I, II); sign in the brackets – number of beam-specimen in the series;

Strain measurement on expansion stage was realized with mechanical strain gages (0,01 mm accuracy). Arrangement of the strain measuring devices on the concrete expansion stage for the series I and II beam-specimens is presented on Fig. 3.2.



1 – mechanical strain gage (0,01 mm accuracy); 2 – GFRP bar;
3 – immovable steel leg for gages fixing; 4 – movable roll-supports; 5 – glass plate.

Fig. 3.2. Arrangement of the strain measuring devices on the concrete expansion stage for the series I and II beam-specimens
(a) – unreinforced (free) beam-specimen; b) –reinforced beam-specimen)

Demolding of the specimens was carried out 9 to 12 hours after casting. At that time, expansive concretes of the series I and II achieved compressive strengths of 7,0 MPa and 7,6 MPa respectively. Immediately after demolding beam-specimens were wrapped with a water-saturated foam rubber and covered with a plastic film. In such a conditions series I and II beam-specimens stayed over a period of 28 days.

3.2. Reinforcement

For the series I and II beam-specimens reinforcing GFRP bars were utilized. The main physical-mechanical characteristics of the GFRP bars are listed in Table 3.2.

Table 3.2. The main physical-mechanical characteristics of the GFRP bars

Nominal diameter, mm	Actual diameter ¹ , mm	Young's modulus E_{frpm} , GPa	Tensile strength f_{frpm} , MPa	Ultimate tensile strain ϵ_{frpm} , %
10	11,26	45,7	1 192	2,61

Notes:
1. Actual diameter of the GFRP bar was established in accordance with (CNR-DT 203/2006).
2. Mechanical characteristics of the GFRP bars were established during tensile test of 13 GFRP bars specimens and average values were calculated.

3.3. Expansive cement

Expansive cement consisted of three components (by weight): Portland cement (CEMI-42,5R) – 80%; high-alumina cement (HAC) – 10%; natural gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) – 10%.

The main physical-mechanical characteristics of the expansive cement established in accordance with (STB 1335) and (EN 196-1) are listed in Table 3.3.

Table 3.3. The main physical-mechanical characteristics of the expansive cement

Expansive cement grade	Expansion characteristics		Strength characteristics	
	free expansion strain ϵ_p , %	self-stressing grade $f_{CE,p}$, N/mm ²	flexural strength f_{flexm} , MPa	compressive strength f_{cm} , MPa
CE-6	2,63 ¹	7,94 ²	3,71 ¹	30,0 ¹

Notes:
1. Free expansion strain and strength characteristics were established at the 28 days age of the mortar bars hardened in the unrestrained conditions.
2. Self-stressing grade, $f_{CE,p}$ was established in standard restraint conditions: $\rho_f=1\%$ and $E_s=200$ GPa.

3.4. Expansive concrete

Expansive concrete mix composition per 1 m³ was as follows: expansive cement CE-6 – 600 kg; fine aggregate ($d_{max}=8$ mm) – 600 kg; coarse aggregate ($D_{max}=16$ mm) – 960 kg; water – 240 kg (w/c=0,4). Concrete consistency was reached by polycarboxilic hyperplasticizer with the consumption by cement weight 0,6% for series I and 0,5% for series II. The consistency class of concrete mix corresponded to S4 in accordance with (EN 206).

Characteristics of the expansive concrete to the 28 days of age are listed in the Table 3.4.

Table 3.4. Characteristics of the expansive concrete to the 28 days of age

Series	Expansion characteristics		Mechanical characteristics	
	free expansion strain ¹ $\epsilon_{CE,p}$, %	self-stressing grade ² $f_{CE,p}$, MPa	compressive strength ³ $f_{cm,28}$, MPa	Young's modulus ⁴ $E_{cm,28}$, MPa
I	0,341	4,64	36,4	28 887
II	0,351	4,83	43,9	29 481

Notes:
1. Free expansion strain, $\epsilon_{CE,p}$ was established on the unrestrained beam-specimens.
2. Self-stressing grade, $f_{CE,p}$ was established in the following restraint conditions: $\rho_f=1,1\%$ and $E_s=200$ GPa;
3. Expansive concrete compressive strength was established in accordance with (EN 12390-3);
4. Young's modulus of expansive concrete was established on the standard cylindrical samples ($\varnothing=150$ mm, $h=300$ mm).

6. Conclusions

In the self-stressed concrete members with FRP reinforcement becomes possible to realize in an effective way properties of both materials: low Young's modulus of FRP bars in combination with concrete high expansion energy capacity allows to reach considerable value of the restrained strains, that will not be reduced entirely by shrinkage.

Verification of the described modified strain development model (MSDM) has shown that the latter is applicable for restrained strains (self-stresses) of the self-stressed high expansion energy capacity concrete members with GFRP reinforcing bars calculation.

In the case of GFRP bars utilizing in combination with the high expansion energy capacity concrete in the self-stressed members, the end zones of the bars have to be additionally reinforced to prevent slipping of the bars.

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