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ANALYTICAL MODEL FOR RESTRAINT STRAINS AND SELF-STRESSED IN EXPANSIVE CONCRETE FILLED STEEL TUBES (ECFST) ESTIMATION

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Abstract

In this paper, a modified strains development model (MSDM) for expansive concrete-filled steel tube (ECFST) was formulated and verified on the experimental data, obtained from testing specimens on the expansion stage. The modified strain development model for restraint strains and self-stresses values estimation in concrete with high expansion energy capacity under any type of the symmetrical and unsymmetrical finite stiffness restraint conditions was proposed. Based on proposed MSDM a new model for expansive concrete-filled steel tubes is developed. The main difference between this model and other previously developed models consists in taking into account in the basic equations an induced force in restrain that is considered as an external load applied to the concrete core of the member. For verification of the proposed model-specific experimental studies were performed.

As follows from comparison results restrained expansion strains values calculated following the proposed model shows good compliance with experimental data. The values predicted by the proposed MSDM for concrete-filled steel and obtained experimental data demonstrated good agreement that confirms the validity of the former.

Keywords: steel tubes, expansive concrete, strains, self-stresses.

Introduction

As it was shown in [1, 2], concrete-filled steel tube (CFST) has made significant advances in building and bridge application due to its high strength, high stiffness and high ductility.

One of the main problems of this type of structural elements is the separation between concrete core and steel tube as a result of shrinkage and loading (as a result of different values of Poisson ratio). Autogenous or basic shrinkage is an intrinsic property of concrete and can occur even when the concrete does not lose any moisture to its environment. This type of shrinkage consists of volume reduction due to “self-desiccation” which is caused by water consumption in hydration and pozzolanic reactions [13] in cement. Normally, autogenous shrinkage is more severe when the water to binder ratio of concrete is lower.

To effectively prevent separation of infilled CFST in normal concrete-filled steel tubes, to keep the concrete core under tri-axially compression before applying load and avoid the premature bulking of the steel tube, expansive concrete is filled into the steel tube. Therefore, applying expansive concrete is one of the techniques that can be used to alleviate the shrinkage cracking problem.

The following definition for self-stressing concrete can be formulated: it is expansive concrete in which expansion if restrained, induces in concrete elastic compressive strains of a high enough magnitude and, as a result, a significant compression in the concrete after shrinkage remains. Self-stressed concrete core expands in the incipient stage of the formation of CFST member, exerts an expansive force on the inner side of the tube and at the same time receives an internal pressure from the steel tube [1]. When the expansion of the concrete is restrained, pretension occurs in the steel tubes and compressive stresses in expansive concrete can be obtained at the expansion stage.

It should be noted, that specimens under steel tube restraining can obtain higher self-stresses that those under uniaxial restraining. It is indicated that when the concrete mixes of specimens are kept, both wall thickness and length of the steel tube have an important influence on the value of self-stresses. The different wall thickness of the steel tube can be offered different circumferential confinement levels (restrain ratios). The longitudinal confinement is offered by the friction of the concrete-steel interface, so long the steel-concrete interface is, higher longitudinal confinement level is. Thus, both circumferential self-stress and axial self-stress increases whenever circumferential and longitudinal confinement level is enhanced [1, 2]. It should be mentioned that for proper self-stressing concrete expansion development it is very essential to provide adequate concrete curing conditions. That within real CFST structure manufacturing it is enough difficult to provide water curing conditions for concrete. To initiate the expansion process for produced with these additives expansive concrete providing of the only externally applied moistening is of the low efficiency for this type of structures. In such a situation applying of the internal curing technology is of a high sense.

Internal curing (IC) is a technique to improve concrete quality. This technique uses water-filled inclusion to provide internal curing is to provide internal moisture to still unhydrated cement in the concrete so that hydration can be more complete. In that, there are various types of internal curing materials such as a water-absorbent polymer (SAP), expanded clay etc. These materials have very high water-retaining properties, which are the most significant properties for internal curing materials. Internal curing technology is considered in the providing concrete with own internal of water (so-called “water tanks” uniformly distributed through the concrete volume). As “water tanks” in such "water-entrained light-weight aggregates“ concrete are acting pre-saturated light-weight aggregates (in this case it was LWA, such as ceramsite with different grain sizes).

For the expansive concrete-filled steel tubes (ECFST) practical use, design methods for the restrained strains and self-stresses value estimation required. An only limited number of guides, for example [8, 10], has a chapter devoted to this concern. Even so, models for restrained strains and self-stresses in expansive concrete at early age estimation intensively developed [3, 12]. In general, these models are based on two basic concepts: consideration of chemical energy [7, 8, 11] of initial strain calculation [12]. The disadvantages of the proposed models were found out based on the numerical and experimental studies and described in detail in [3].

Models for restrained strains and self-stresses estimation in expansive concrete-filled steel tubes

Based on experimental results [1, 2] and the unified theory of general CFST paper [12] presents a stress-strain relationship of self-stressed CFST and mainly analyzed the influence of strength grades and magnitudes of self-stress for confined concrete.

According to [12], comparing experimental results with theoretical analysis, the consitutive relationship model of self-stressed CFST members were established as follows:

$$S_c = T_q \cdot S_u \left(2 + 0.1x^{0.745}\right)\left(\frac{e}{e_0}\right) \quad e > e_0\,; \qquad (1)$$

$$\begin{cases} S_c = T_q \cdot S_u\left(1+q\right)+q\left(\ \ \right)^{0.1x} & x \ge 1.12 \\ S_c = T_q \cdot S_u \dfrac{\dfrac{e}{e_0}}{b\left(\dfrac{e}{e_0}+1\right)^2+\dfrac{e}{e_0}} & x < 1.12 \end{cases} \quad e \le e_0 \qquad (2)$$

$$T_q = \left(-20.071h^2+3.0793h+1\right)^{2.5}; \qquad (3)$$

$$S_u = 1.194f_{ck} + \left(\frac{13}{f_{ck}}\right)^{0.45}\left(-0.07485x^2+0.5789x\right); \qquad (4)$$

$$e_0 = e_c + 1400 + 800\left(\frac{f_{ck}-20}{20x^{0.2}}\right); \qquad (5)$$

$$e_c = 1300 + 14.93f_{ck}, \qquad (6)$$

where T_q is the improvement coefficient of confined-concrete strength related to the self-stress level;

h is the level of self-stress, $h = p / f_{cu,k}$;

p is self-stressed magnitude of confined concrete, MPa;

f_{ck} is characteristic value of compressive strength;

q is a coefficient, $q = 0.1x^{0.745} / \left(0.2+0.1x\right)$;

b is a coefficient, $b = \left(2.36 \cdot 10^{-5}\right)^{0.25+(x-0.5)^2} f_{ck}^2 \cdot 5 \cdot 10^{-4}$;

x is confinement coefficient of CFST, $x = af_y / f_{ck}$;

a is sectional steel ratio CFST, $a = A_s / A_c$;

f_y is yield strength of steel, MPa;

m_c is Poisson ratio of concrete, calculated according to Eq (7):

$$m_c = \begin{cases} 0.173 & \dfrac{S_c}{S_0} \ge 0.4 \\ 0.173 + 0.7036\left(\dfrac{S_c}{S_0}-0.4\right)^{1.15} & \dfrac{S_c}{S_0} < 1.12 \end{cases} \quad e \le e_0 \qquad (7)$$

According to the model [11, 12], the circumferential stresses in the steel tube caused by an expansion of the self-stressing concrete can be expressed as follows:

$$\varepsilon_s\left(t\right) = \alpha_f A\left(\alpha\right)\left(1-e^{-b_f B(\alpha)t}\right). \qquad (8)$$

And initial circumferential self-stress σ_{ss} can be calculated following the force balance of the tube, where α_f, b_f $A\left(\alpha\right)$ and $B\left(\alpha\right)$ can be deserved from a regression formula [12]. Since the concrete in the steel tube is under triaxial compression. The initial circumferential self-stress σ_{ss} and the circumferential stress of the steel tube σ'_{st} have the following relationship:

$$\sigma_{ss} \frac{t_s}{r} \sigma'_{st}, \qquad (9)$$

where t_s is the thickness of the steel tube and r the inner diameter of the steel tube, respectively.

Under restrained conditions, the idea of what work stored in restraint steel in expansive material assumed to be constant despite steel amount (chemical conservation law) has been proposed by Tsuju [11] after prof. V. Michajlov [10]. The expansive energy of concrete used for the JIS constant method can be calculated as follows [11]:

$$U_{JIS} = \frac{1}{2}\rho_l E_s \varepsilon_{JIS}^2, \qquad (9a)$$

where U_{JIS} is the calculated expansion energy of concrete per unit volume (N/mm^2) with JIS-method;

ε_{JIS} is the measured expansive stain in the test sample;

ρ_l is the restraint ratio for uniaxially restraining steel bar (0.96 near 1% following [????]);

E_s is the modulus elasticity (Young's modulus) of the steel ($\sim 2.1 \cdot 10^5\, N/mm^2$).

The expansive energies in the circumferential and axial directions of the cylindrical specimens can be obtained with Eq (10) and Eq (11) respectively [11]:

$$U_\theta = \frac{t}{r}\frac{E_s}{\left(1-v^2\right)}\left(\varepsilon_\theta + v\varepsilon_z\right)\varepsilon_\theta; \qquad (10)$$

$$U_z = \frac{2t}{r}\frac{E_s}{\left(1-v^2\right)}\left(\varepsilon_z + v\varepsilon_\theta\right)\varepsilon_z, \qquad (11)$$

where U_θ is the calculated expansive energy of concrete per unit volume (N/mm^2) in the circumferential direction;

U_z is the calculated measured circumferential strain of the cylindrical specimens;

t, *r* is the thickness and inner radius of the steel tube respectively;

v – Poisson ratio of the steel tube ($v = 0.3$).

The relationship of expansive strains can be dedicated from the expansive energy, obtained from Eq (10) and Eq (11) and are expressed in Eq (14) and Eq (15):

$$U_\theta = 2U_{JIS}; \qquad (12)$$

$$U_z = U_{JIS}; \qquad (13)$$

$$\varepsilon_\theta = \left[\frac{r}{t}\left(1-v^2\right)\rho_l\left(1+\frac{-v+\sqrt{v^2+8}}{4}v\right)^{-1}\right]^{1/2} \varepsilon_{JIS} = 1.14\varepsilon_{JIS}; \qquad (14)$$

$$\varepsilon_\theta = \left[\frac{1}{2}\frac{r}{t}\left(1-v^2\right)\rho_l\left(1+\frac{-v+\sqrt{v^2+8}}{3v+\sqrt{v^2+8}}v\right)^{-1}\right]^{1/2} \varepsilon_{JIS} = 0.73\varepsilon_{JIS}. \qquad (15)$$

Here, U_{JIS} and ε_{JIS} are calculated expansive energy per unit volume (N/mm^2) and measured uniaxial strain of the JIS samples when sealed after ageing for 1 day, respectively.

Accounting to model [12], because the stress level of self-stressing is high, the influence of creep and elastic deformation can't be ignored from beginning to expand. Creep can cause stress boss and reduce free expansion, so creep and elastic deformation must be considered in the calculation. The ineffective expansive deformation can not produce self-stresses and compensate elastic and creep deformation either. An effective free expansion is an expansive deformation that expands effectively and produces self-stress. The effective free expansion at age t_i, $\varepsilon_f\left(t_i\right)$ can be expressed a_s [12]:

$$\varepsilon_f\left(t_i\right) = \varepsilon_s\left(t_i\right) + \varepsilon_e\left(t_i\right) + \varepsilon_c\left(t_i, \tau\right), \qquad (16)$$

where $\varepsilon_s\left(t_i\right)$, $\varepsilon_e\left(t_i\right)$, $\varepsilon_c\left(t_i, \tau\right)$ is restrained deformation, elastic deformation and creep at age $\left(t_i\right)$, respectively.

In the general case of an increase in stress, creep strain accords with the principle of superposition. The sum of elastic strain and creep strain can be expressed as:

$$\varepsilon_f\left(t_i,\tau_0\right)=\frac{\sigma\left(t_0\right)}{E_{cm}\left(t_0\right)}\left[1+E_{cm}\left(t_0\right)\cdot C\left(t,t_0\right)\right]+$$
$$+\sum_i\left[\frac{\Delta\sigma\left(t_i\right)}{E_{cm}\left(t_i\right)}\left(1+E\left(t_i\right)C\left(t,t_i\right)\right)\right], \tag{17}$$

where $\varepsilon\left(t,\tau_0\right)$ is the total strain of concrete;

$E_{cm}\left(t_0\right)$, $E_{cm}\left(t_i\right)$ is elastic modulus at $\left(t_0\right)$ and t_i days;

$\sigma\left(t_0\right)$ is the stress at t_0 days;

$\Delta\sigma\left(t_i\right)$ is the stress increment;

$C\left(t,t_0\right)$, $C\left(t,t_i\right)$ is the creep coefficient loaded at t_0 and t_i days.

Based on test results [12], the relationship between elastic modulus and time can be expressed as:

$$E_{cm}\left(t\right)=34.7\left[1-\exp\left(-1.009t^{0.075}\right)\right]. \tag{18}$$

The calculating formula of creep strain can adopt the result of the study of document [4, 5]. Creep coefficient is expressed as:

$$C\left(t,\tau\right)=\left(39.732+\frac{15.261}{\tau^{15.577}}\right)\left(1-e^{-0.422\left(t-\tau\right)}\right)+$$
$$+\left(0.003+\frac{4.279}{\tau^{117.81}}\right)\times\left(1-e^{-0.1197\left(t-\tau\right)}\right)+ \tag{19}$$
$$+0.7958\left(e^{-20.351\tau}-e^{20.351t}\right).$$

According to all analyzed models for estimation the restrained expansion strains self-stresses in case of steel tube restraint conditions some noticeable remarks can be concluded. Despite differences in practical implementation, the above calculation methods in some cases ignore the care of physical processes during the expansive concrete hydration period under steel tube (3D) restraint conditions so loading to the next shortcomings.

1. The effect of plastic strains in the final restrained expansion strains, especially at the early age of expansive concrete, is theoretically proved and experimentally confirmed [12]. However, no one design method, except for the model [12], considers the compliance function when defining the restraint expansion strains of the expansive concrete members.
2. All proposed formulas include the empirical coefficients that are based on the limited experimental data.
3. Models based on the chemical energy conservation law considers the design grades of self-stress of expansive concrete as a basic parameter while a different correlation between the values of free expansion strains and self-stressing grade arises.

The appropriate calculation method should reflect the complex interference of expansive concrete strains during the hydration period for all types of expansive concrete elements under steel tube confinement.

In this paper, a modified strains development model (MSDM) was formulated for expansive concrete-filled steel tube and verified on the experimental data, obtained from testing specimens on the expansion stage.

1. The proposition of the analytical model for estimation of restrained strain and self-stresses in CEFST

In our work [3] the modified strain development model (MSDM) for restraint strains and self-stresses values estimation in concrete with high expansion energy capacity under any type of the symmetrical and unsymmetrical finite stiffness restraint conditions was proposed. The main difference between this model and other previously developed models [8, 10, 12] consist in taking into account in the basic equations (for the all-time intervals Δt_i with exception of the first one) an additional induced force in restrain that is considered as an external load applied to the concrete core of the member.

When proposed MSDM is applied to self-stressed CFST design model development, the following assumptions were accepted:

1. Equilibrium conditions for self-stressed CFST are respected throughout the concrete expansion stage.
2. Incremental restrained strain at any *i-th* time interval is determined as an algebraic sum of the free expansion, elastic and creep strains, plus expansive concrete additional strain produced by the cumulative force induced by the steel tube restraint at any *i-th* time interval beginning. The cumulative force induced by the steel tube restraint at the end of the (*i*-1)-*th* time interval is considered as an additional restraint for the development of the free expansion strains at the j-th time interval.
3. Self-stresses at any *i-th* time interval should be calculated from the cumulative force induced by restraint.
4. The radial stress in the steel tube is ignored and the steel tube is under biaxial stress.
5. No slippage between concrete core and steel tube in early age expansion stage exists.

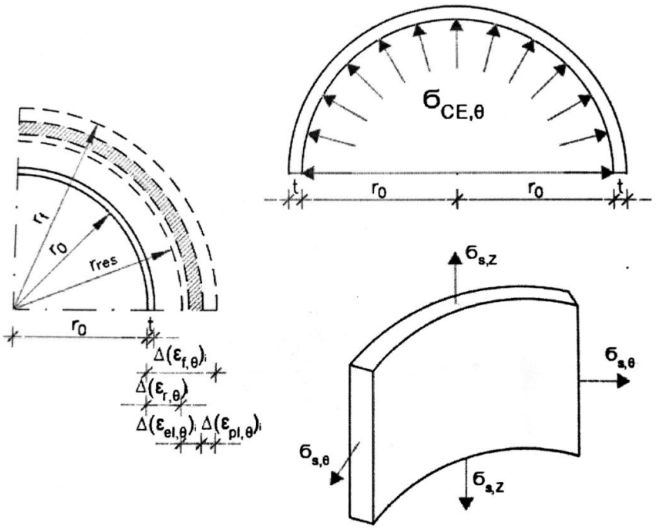

Figure 1 – Scheme of incremental approach in proposed MSDM for expansive concrete-filled steel tube

For the case of the steel tube symmetrical restraint arrangement (see fig. 1), basic equation for the calculation of the incremental restraint strains in circumferential direction $\left(\Delta\varepsilon_{r,\theta}\right)_i$ and in axial direction $\left(\Delta\varepsilon_{r,z}\right)$ at the any *i*-th time interval with regard to restraint reaction can be expressed as follows:

$$\begin{cases}\left(\Delta\varepsilon_{r,\theta}\right)_i=\left(\Delta\varepsilon_{CE,f}\right)_i+\left(\Delta\varepsilon_{\mathrm{CE},\theta}\right)_i\cdot J\left(t_{1+\frac{1}{2}};t_i\right)+\\ +\sum\limits_{j=1}^{i-1}\left[\left(\Delta\sigma_{CE,\theta}\right)_j\frac{\Delta\varphi\left(t_i;t_j\right)}{E_{cm,28}}\right]+\sum\limits_{j=1}^{i-1}\left[\frac{\left(\Delta\sigma_{CE,\theta}\right)}{E_{cm}\left(t_j\right)}E_{c,aw}\left(t_{(i-1)+\frac{1}{2}}\right)\right]; & 20\\ \left(\Delta\varepsilon_{r,z}\right)_i=\left(\Delta\varepsilon_{CE,f}\right)_i+\left(\Delta\varepsilon_{CE,z}\right)_i\cdot J\left(t_{1+\frac{1}{2}};t_i\right)+\\ +\sum\limits_{j=1}^{i-1}\left[\left(\Delta\sigma_{CE,z}\right)_j\frac{\Delta\varphi\left(t_i;t_j\right)}{E_{cm,28}}\right]+\sum\limits_{j=1}^{i-1}\left[\frac{\left(\Delta\sigma_{CE,z}\right)}{E_{cm}\left(t_j\right)}E_{c,aw}\left(t_{(i-1)+\frac{1}{2}}\right)\right]. & 21\end{cases}$$

Taking into account that:

$$\left(\Delta\sigma_{CE,\theta}\right)_j=\frac{t}{r_0}\frac{E_s}{\left(1-\mu_s^2\right)}\left[\left(\Delta\varepsilon_{r,\theta}\right)_i+\mu_s\left(\Delta\varepsilon_{r,z}\right)_i\right]; \tag{22}$$

$$\left(\Delta\sigma_{CE,z}\right)_j = \frac{2t}{r_0}\frac{E_s}{\left(1-\mu_s^2\right)}\left[\left(\Delta\varepsilon_{r,z}\right)_i + \mu_s\left(\Delta\varepsilon_{r,\theta}\right)_i\right]. \quad (23)$$

Substituting eq. (22) and eq. (23) in eq. (20) and in eq. (21), incremental restrained expansion strains at any ***i***-th time interval can be expressed by the following equation:

$$\begin{cases} \left(\Delta\varepsilon_{r,\theta}\right)_i = \left(\Delta\varepsilon_{CE,f}\right)_i + \frac{t}{r_0}\frac{E_s}{\left(1-\mu_s^2\right)}\left[\left(\Delta\varepsilon_{r,\theta}\right)_i + \mu_s\left(\Delta\varepsilon_{r,z}\right)_i\right]\cdot J\left(t_{1+\frac{1}{2}};t_i\right) + \\ +\sum_{j=1}^{i-1}\left[\left(\Delta\sigma_{CE,\theta}\right)_j \frac{\Delta\varphi\left(t_i;t_j\right)}{E_{cm,28}}\right] + \sum_{j=1}^{i-1}\left[\frac{\left(\Delta\sigma_{CE,\theta}\right)}{E_{cm}\left(t_j\right)}E_{c,aw}\left(t_{(i-1)+\frac{1}{2}}\right)\right]; \quad (24) \\ \left(\Delta\varepsilon_{r,z}\right)_i = \left(\Delta\varepsilon_{CE,f}\right)_i + \frac{2t}{r_0}\frac{E_s}{\left(1-\mu_s^2\right)}\left[\left(\Delta\varepsilon_{r,z}\right)_i + \mu_s\left(\Delta\varepsilon_{r,\theta}\right)_i\right]\cdot J\left(t_{1+\frac{1}{2}};t_i\right) + \\ +\sum_{j=1}^{i-1}\left[\left(\Delta\sigma_{CE,z}\right)_j \frac{\Delta\varphi\left(t_i;t_j\right)}{E_{cm,28}}\right] + \sum_{j=1}^{i-1}\left[\frac{\left(\Delta\sigma_{CE,z}\right)}{E_{cm}\left(t_j\right)}E_{c,aw}\left(t_{(i-1)+\frac{1}{2}}\right)\right]. \quad (25) \end{cases}$$

In the proposed model, creep compliance function is accepted in traditional form in accordance with ***fib*** MC2010 [4]:

$$J\left(t_{1+\frac{1}{2}};t_i\right) = \frac{1}{E_{cm}\left(t_j\right)} + \frac{\varphi\left(t_{1+\frac{1}{2}};t_j\right)}{E_{cm,28}}, \quad (26)$$

where $E_c\left(t_j\right)$ – young's modulus of expansive concrete at t_j in temperature adjusted concrete age can be obtained from the relation based on the EN1992 model [5]:

$$E_c\left(t\right) = E_{cm,28}\exp\left[s\left(1-\left(\frac{t_{m,28}-a}{t_i-a}\right)\right)\right], \quad (27)$$

where s: an empirical factor that takes into account cement type; taken as s=0,11 in the present study;

a: empirical factor that takes into account initial setting time effect: taken as a=0, 2 in the present study.

Temperature adjusted concrete age at *t* days is established concerning changes in temperature conditions and is determined in accordance with EC2 model [5].

The creep coefficient $\varphi\left(t;t_0\right)$ for expansive concrete at early ages was evaluated based on the ***fib*** MC2010 proposal [4].

2. Experimental program

For verification on the proposed modified strain development model (MSDM) for expansive concrete-filled steel tubes as the symmetrical finite stiffness restraint conditions, specific experimental studies were performed.

2.1. Specimens

Experimental studies were carried out on two series of expansive concrete-filled steel tubes (ECFST) with the diameter Ø 200 mm with 300 mm; 600 mm length and different values of the steel tube wall thickness: 1,0 mm; 1,5 mm; 2,0 mm (see table 1). In the performed experimental studies, the variation of the following parameters are considered:

- effective restraint ratio $\rho_{l(\theta,z)}$, in circumferential direction modelled by the influence of the steel wall tube thickness $\left(\rho_{l(\theta)} = \frac{r}{t}\right)$;
- length of the concrete-filled steel tube (300 mm; 600 mm);
- self-stressing grade of the concrete established in the standard restraint continuous:
- influence of the internal curing (samples 1=600 mm)

Geometry and restraint ratios of the experimental specimens are listed in table 1 and shown in figure 2.

Table 1 – Geometry parameters of specimens

Series	Specimen marking	Geometry, mm See figure 2			Restraint ratio [%]		Standard self-stressing grade $f_{CE,d}$, MPa	Curing conditions
		D	L	t	$\rho_{l(\theta)}$	$\rho_{l(z)}$		
I	CST-1.0-300(1-4)	200	300	1.0	1.0	2.0	1.41 (1.37)	isolated
	CST-1.5-300(1-4)			1.5	1.5	3.0		
	CST-2.0-300(1-4)			2.0	2.0	4.0		
II	CST-1.0-600(1-4)	200	600	1.0	1.0	2.0	0.61	Isolated Internal curing
	CST-1.0-600(1-4)			1.5	1.5	3.0		
	CST-2.0-600(1-4)			2.0	2.0	4.0		

Notes: *1. Restraint ratios:* $\rho_{l(\theta)} = \frac{r}{t}$, $\rho_{l(z)} = \frac{2r}{t}$.

2. Curing conditions: isolated curing – in the plastic film; internal curing – in plastic film, but with LWA.

2.2 Expansive cement, concrete and steel tube properties

Expansive cement composition consisted of three components in the following proportions (by Portland cement (CEM I – 42,5R) – 80%; high-alumina cement (HAC) = 10%; gypsum ($Ca_2SO_4 \cdot H^2O$) – 10%. Chemical composition of the expansive cement is listed in table 2.

Table 2 – Chemical composition of expansive cement

	Chemical composition, %						
Component	LOI	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	SO_3
Expansive cement	2.6	14.10	4.83	6.53	60.87	0.83	7.0

Table 3 – Expansive concrete mixes proportions (by weight, kg/m^3)

		Mixes proportions									
Series		EC	PC	MC	G	Fine aggregate	Coarse aggregate	Water	Hyper	w/b	Expanded clay
I	a	600	-	-	-	580	910	240	-	0.40	-
	b	600	-	-	-	260	910	240	-	0.40	145
II		-	426	84	90	206	960	222	6	0.37	255

Notes: EC – expansive cement; PC – Portland cement; MC – Metakaolin; G – Gypsum; Hyper – polycarboxylate hyper plasticizer

Table 4 – Expansion and mechanical properties of expansive concrete

Series		Expansion characteristics		Expansion energy U × 10^3 MPa	Mechanical properties	
		Free expansion strain, ε_{CE} ,%	Self-stressing grade, $\varepsilon_{CE,d}$, MPa		Average Compressive strength, MPa	Young's Modulus $E_{cm,28}$
I	A	0.17	1.41	0.497	37.4	32363
	B	0.23	1.37	0.469	38.3	33420
II		0.21	0.75	0.141	36.5	32370

Expansive concrete mixes per 1 m^3 are listed in table 3.

The expansive cement composition was prepared in laboratory conditions.

First, the fine materials including cement (expansive cement), components of an expansive agent, and sand were mixed in a forced mechanical mixer for 30 s to achieve an initial homogeneity. Thereafter, a blend of water and chemical agents were added to the drying mixture followed by 60 s mixing. The wet mixture was mixed for 30 s more to achieve a higher homogeneity. Finally, coarse aggregates were poured in the mixture and incorporated by operating the mixer for 2 min. The fresh state of fabricated concrete mixes was assessed by measuring the slump flow. The consistency class of expansive concrete mix corresponded to S4 and was established with EN206 [6].

Expansion and mechanical characteristics of the expansive concrete are listed in table 4 and mechanical parameters of steel tube in table 4.

Table 5 – Mechanical parameters of the steel tube

Thickness of tube	Strength, MPa		Ultimate Elongation, ε_{su} ,%	Young's Modulus E_s x 10^3
	Yield f_y	Ultimate $f_{u(t)}$		
1.0	420	524	19.2	204.6
1.5	331	435	24.0	205.3
2.0	414	588	22.5	205.1

For cylindrical specimen, the expansive strain has been observed to be almost constant at the middle height, but it decreases at the edge because of closed bottom or opened top. Thus, the strains generated at the mid-height were used as the measurement target. Six strain gauges were glued horizontally (3) and vertically (3) at mid-height on the outside surface of the steel tube as shown in figure 2. At least three duplicate specimens were prepared under each condition, and the average measured value of the three specimens was used for the analysis.

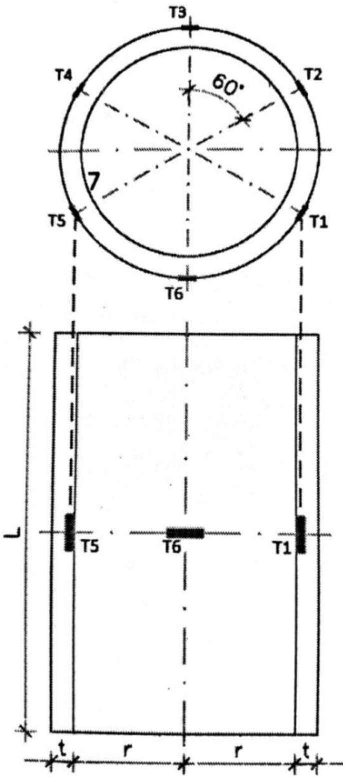

Figure 2 – Specimens geometry and the scheme of wire strain gauges arrangement

3. Results and a brief discussion

Final experimental values of the restrained strains and self – stresses in concrete core and steel tube under different restraint conditions are listed in table 6.

Specimens in Series I have the same inside diameter, concrete mix, and length but different wall thickness of steel tube. It indicates that the wall thickness of the steel tube has an evident influence on the expansive behaviour. With an increasing wall thickness of the steel tube the expansive strain decreases. The expansive behaviours Series II are presented in Table 6. The specimen length also affects the expansive behaviours. The expansive strain of these specimens increases with increasing the specimen length when other parameters are kept the same.

Restrained expansion strains obtained in the experimental campaign (see table 6) were compared to those calculated in accordance with the proposed MSDM for expansive concrete-filled steel tubes. Incremental restrain expansion strains were calculated following MSDM, presented in section 1, using the 1-day time steps.

As follows from comparison results (see table 6) restrained expansion strains values calculated in accordance with the proposed model shows good compliance (agreement) with experimental data. The MSDM hereby proposed, based on the initial strain calculation approaches, is universal [3] and allows obtaining an adequate solution for any boundary conditions.

Conclusions

1. A modified strain development model (MSDM) for expansive concrete-filled steel tubes is proposed.
2. To verify the proposed approach, experiments with symmetrically restrained with steel tube filled with the expansive concrete were performed. The values predicted by the proposed MSDM and obtained experimental data have demonstrated good agreement that confirms the validity of the former.

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Table 6 – Final experimental values of the restrained strains and self-stresses at the concrete expansion stabilization

Specimen marking	$f_{CE,d}$ [N/mm^2]	Mean restrain strains $\varepsilon \times 10^5$		Self-Stress, N/mm^2			
				Steel Tube		Concrete Core	
		$\overline{\varepsilon}_{r,\theta}$	$\overline{\varepsilon}_{r,z}$	$\sigma_{s,\theta}$	$\sigma_{s,z}$	$\sigma_{CE,\theta}$	$\sigma_{CE,z}$
CST-1.0-600	0.61	$\frac{120}{127}$	$\frac{70,0}{81,0}$	$\frac{308}{310}$	$\frac{232,9}{240,1}$	$\frac{3,08}{3,12}$	$\frac{4,66}{4,86}$
CST-1.5-600		$\frac{110}{123}$	$\frac{50,0}{71,0}$	$\frac{246,1}{301,0}$	$\frac{182,4}{178,2}$	$\frac{3,69}{3,82}$	$\frac{5,47}{5,43}$
CST-1.0-300	1.37	$\frac{160}{159}$	$\frac{120}{143}$	$\frac{430}{430}$	$\frac{369}{380}$	$\frac{4,35}{4,40}$	$\frac{8,70}{7,98}$
CST-1.5-300	1.41	$\frac{270}{264}$	$\frac{50,0}{71,0}$	$\frac{435}{430}$	$\frac{288}{320}$	$\frac{6,52}{6,37}$	$\frac{8,63}{8,32}$
CST-2.0-300 (1.2)		$\frac{150}{141}$	$\frac{120}{132}$	$\frac{408,8}{430}$	$\frac{362,6}{430}$	$\frac{4,08}{4,08}$	$\frac{8,16}{8,23}$
CST-2.0-300 (3A)	1.41	$\frac{200}{168}$	$\frac{160}{163}$	$\frac{435}{400}$	$\frac{435}{400}$	$\frac{4,35}{3,08}$	$\frac{8,70}{8,23}$

Note: 1. *Under the time – theoretical values following proposed MSDM; over the line – experimental values.*

2. $\overline{\varepsilon}_{r,\theta}$ *and* $\sigma_{CE,\theta}$ *restraint strains and self-stresses in the circumferential direction;* $\overline{\varepsilon}_{r,z}$ *and* $\sigma_{CE,z}$ *– restraint strains and self-stresses in an axial direction.*

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