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Thermal Deformations in Segmental Concrete Structures
Déformations thermiques des voussoirs en béton armé
Temperaturdeformationen in segmentweisen Betonkonstruktionen

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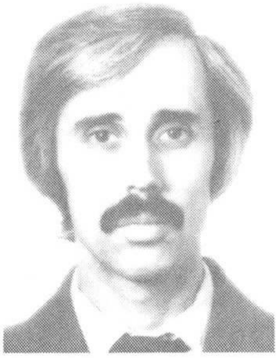

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SUMMARY
The paper deals with the development of a procedure for the analysis of temperature fields, stresses and deformations in segmental concrete structures in the course of their fabrication. Application of the procedure is demonstrated by the example of analysis of three-dimensional deformations of segments fabricated by the match casting method for bridge superstructures.

RÉSUMÉ
Le rapport traite de la méthode de calcul des champs thermiques de contraintes et de déformations dans les voussoirs en béton armé en cours de fabrication. L'application de la méthode est illustrée par l'exemple du calcul des déformations des éléments de voussoirs préfabriqués en béton.

ZUSAMMENFASSUNG
Im Vortrag wird die Entwicklung eines Verfahrens zur Berechnung von Temperaturfeldern, Spannungen und Verformungen in segmentweisen Betonkonstruktionen während der Herstellung behandelt. Eine Anwendung dieses Verfahrens wird am Beispiel der Berechnung von dreidimensionalen Verformungen bei Brückensegmenten gezeigt.

1. METHOD OF ANALYSIS

Lengthy segmental concrete structures are being widely used nowadays for construction industry as a whole and for bridge building in particular. They are, first of all, bridge superstructures and piers field erected from separate segments with usage of reinforcing steel and glued joints. The abovesaid segments are precast constructions which fabrication is carried out by match casting method using purpose-designed forms. According to this method, which is rather popular in the USSR, end face of the earlier built segment is used instead formwork for concreting and hardening of the next segment, which would provide ideal coincidence of segments end faces when erecting a structure. In this case in the course of fabrication fresh concrete, in which intensive heat release due to cement hydration takes place, comes into contact with the "old" concrete of the previously fabricated structure. Similar situation occurs when erecting superstructure by cantilever method and constructing high bridges piers and pylons in a slipform, etc.

As a result of intensive processes of heat release and heat exchange, complicated spatial temperature fields, continuously varying with time, are being formed in the structures under fabrication, which induce growth of temperature stresses and strains. In some cases they may be of critical value and lead to cracks occurence, structure's axis deviation from the design position and other negative post-effects. This is why prediction of such temperature fields and thermostressed state is considered to be challenging engineering problem, especially when designing extraordinary structures.

It should be noted that the problem under consideration, i.e. investigation of thermostressed state of various structures, has been a subject of extensive research and its results are available in the literature. But for our case, the problem seems to be specific, presenting significant difficulties for its solution and requiring development of purpose-designed procedure.

First of all should be considered the effect of cement exothermicity, which conditions largely temperature field to be formed. The intensity of cement heat release is known to have rather sophisticated dependence both on concrete temperature at a given moment and on all the previous "temperature history" beginning from concrete mix placing. This factor necessitates solution of two problems: that of heat conductivity and heat release one, being described by interdependent differential equations.

The structures to be constructed have often rather complex cross-sectional profile (box segments, slab-ribbed structures, etc.). On the other hand, the length of a segment to be cast has sizes, comparable with those of cross-section. All this requires the problem solution in three-dimensional formulation, otherwise it is of no avail.

And the last. It is evident that every time when concreting the next segment increment of design area takes place. When fabricating segments by match casting method the process seems to be more complex, as first takes place increment of design area when concreting a new segment in contact with the previous one, and then its decrease when separating segments. Temperature fields in a "new"segment and earlier built section of the structure have strong reciprocal effect. The latter should be taken into consideration in the design scheme and analysis procedure.

This complicated problem may be more effectively solved by means of temperature fields and stresses simulation on the basis of advanced numerical methods and use of computering devices.

As a result of investigations conducted, special procedure and programs package related have been developed, which make possible calculation of three-dimensional non-stationary temperature field and spatial stress-strain state, induced by change of the field by the structure volume. The procedure is based on plotting of discrete design diagram and use of relevant numerical methods. Digitization is carried out by division of the design area into finite elements in the form of rectangular prisms. Calculation is performed in two stages. First the problem of non-stationary heat conductivity with internal heat sources is solved to determine temperature fields for the time of our interest. Afterwards thermoelasticity is determined and stresses and deformations (displacements), occured under changed temperature field are calculated, assuming structure elastic behaviour.

Programs package features combination of two various numerical methods - finite difference method, being used for solution of heat conductivity problem and finite element method, being used for that of thermal conductivity. In our opinion it makes it possible to realize the both methods advantages and to obtain optimal complex, combining high effectiveness, simplicity and applicability. Finite element's simple form selected allows preservation of the same discrete scheme when changing thermal analysis for thermoelastic one. The difference is in unknown parameters: in the first case they are temperatures in the elements centres, while in the second one-their nodes displacements.

Significant advantage of the complex over the other ones is involvement of the procedure of cement heat release consideration. Advancements in the field of investigations of hardening concrete heat release phenomenon have been used for this complex development. The studies conducted showed that intensity of elementary volume heat release was proportional to maximum heat release by cement weight unit, to cement consumption per 1 m^3 of concrete mix, to portion of the cement, unreacted by the given time and to coefficient, depending on the given point temperature. In its turn, the quantity of unreacted cement depends, in a rather complicated way, on "temperature history" of elementary volume, beginning from the moment of concrete mix placement. So, when solving heat conductivity problem, for every time step is first determined heat release in every element, then change of its heat content due to released heat and heat exchange with the adjacent elements and, finally, change of temperature; afterwards the process is repeated by cycles.

The procedure allows consideration of nonuniform heat release by the structure volume, change of its time intensity and interdependence with temperature field.

The program developed makes it possible to change design area geometry by increasing or decreasing its dimensions, which allows development of mathematical model, featuring adequately technological process, consideration of temperature fields reciprocal effect in structure various sections, being cast at different time.

The programs package developed, not being universal, is meanwhile rather useful and effective means for calculation of temperature fields, stresses and strains in reinforced concrete structures, constructed by concreting by lifts, match casting or some other methods, when change of design area geometry should be considered for calculation. The program requires minimum of initial data, allows partial computerization of their preparation process, has high internal performance and quantitative capabilities. It has easy information input and exchange with external memory. Its programming language is FORTRAN.

2. ANALYSIS OF THERMAL DEFORMATIONS OF REINFORCED CONCRETE BOX SEGMENTS FOR HIGHWAY BRIDGES SUPERSTRUCTURES

On the basis of the procedure developed and program package there has been conducted a series of calculations to determine thermal regime and thermostressed state of reiforced concrete box segments, being constructed by match casting method, for highway bridges superstructures. The purpose of the calculations was to define the effect of thermal treatment various regimes on the mode and size of deformations, developing after segments cooling. Segments had 3,4 m depth, 12,5 m width of upper plate and 2 m length along the axis.

The problem is that coincidence of adjacent end faces of neighbouring segments, which should be provided by the technology used, i.e. due to matching of every next segment to be cast on the end face of the previously cast one, is frequently disturbed in practice. To a considerable extent it is related to thermal deformations growth. The matter is that in the course of hardening on a mould there are being formed temperature fields, which are significantly nonuniform by volume, as a result of thermal treatment as well as concrete self-heating due to cement exothermicity. Segment being at various stages of hardening, those fields are different.Complicated spatial stress-strain state is being developed in segments after their separation and temperatures gradual equalization. The abovementioned state induces, in particular, deformation of end faces, leading to disturbance of segments coincidence. When erecting a superstructure this results in segments turn relatively to each other, structure's axis deviation from the design position and differential size of a gap between adjacent faces. All the said effects negatively on the quality of glued joints used, aggravating their physical and mechanical properties.

To improve the quality of segments production optimal technological regimes should be selected, which would provide minimum thermal deformations or would compensate their growth by structural means. To this end, should be studied the nature of various thermal regimes effect on segments deformation, developing after cooling.

We set the problem basing on the assumption that after thermal treatment, i.e. by the moment of segments separation, their adjacing faces coincide completely. To find out mutual arrangement of segments during structure assemblage, first of all we have to obtain spatial pattern of deformed end faces. This pattern would be dependent on the thermostressed state, developing in every segment under change of temperature field - from that for separation moment to some constant by volume (equal to ambient air temperature). It should be noted that the absolute value of that constant is of no importance, as change of temperature by the whole volume of a free body by the same value results in the only uniform change of its linear dimensions, but doesn't change its stress-strain state. Besides, accounting for the assumption accepted, the problem of initial stresses by the separation moment, being rather complicated, may not be considered as a solved one. The object of our interest should be alteration of thermostressed state within two specified periods of time, leading to occurence of deformations under consideration. The problem was formulated for elastic behaviour, without consideration of reinforcement. Concrete was considered as homogeneous isotropic medium with constant mechanical and thermophysical characteristics.

As per the procedure developed, analysis of temperature fields, being generated in segments by the moment of their separation, was conducted in several phases with alteration of design scheme when changing one phase for the other according to technological cycle stages. The said allowed consideration of mutual effect of segment-matrix and segment-match temperature fields. Various thermal treatment regimes were considered for the analysis. Temperature of heating, conditions of thermal exchange on the surface, etc. varied. (In all the cases heating formwork was on the segment's exterior surface, except the upper slab).

As a result of calculations data have been obtained on temperature distribution by the volume of each of two segments by the moment of their separation. Data on the magnitudes of thermoelastic displacements of points, being on the segments end faces, have been obtained as well. The latter characterize the nature and extent of end faces deformation after complete cooling of segments up to ambient air temperature, providing that temperature field at the separation moment is taken as initial state. Just those values show the possible degree of non-coincidence of adjacent segments end faces, resulting from temperature deformations, induced in the course of cooling. Here, the final objective of the calculations was determination of surface points displacement, but not stresses field, which is typical of the most problems.

Analysis of the results obtained showed that temperature fields in segments after thermal treatment completion have complicated non-uniform and pronounced three-dimensional mode, conditioned, to a considerable extent, by segments reciprocal effect. Here, temperature fields of the segment-matrix and segment-match differ significantly, which is obvious in Fig.1 and 2. As the structure and boundary conditions are symmetrical relatively to vertical plane, passing through segment's axis, then all the fields of temperatures and displacements appear to become symmetrical as well. That's why the fields, given below, are plotted for the half of a segment cross-section.

The results of thermoelastic analysis evidence that after segments cooling their end faces are being deformed and have complicated curved shape. Here, adjacent end faces of the neighbouring segments deform differently, which results in their non-coincidence. It should be noted that though analysis data describe completely three-dimentional mode of segments deformation, they don't give answer to the question about the position of segments and gap size between them, when trying to assemble those segments with deformed end faces, joining them by means of cantilever method. To answer the above question complicated geometrical problem on tangency of two curved faces should be solved. We managed to obtain rather simple solution of the problem on the basis of graphoanalytical methods used. But its description cannot be presented because of the paper content limitation. Use of this procedure made it possible to determine for all the variants considered the angle of segments turn relatively to one another, which is the result of non-coincidence of end faces during segment assemblage, and to define deviation of superstructure's axis from the design position. Besides, fields have been plotted, featuring distribution of gap size (glued joint thickness)on the latter surface, one of which is given in Fig.3. Attention should be paid to the fact that there are given not absolute values of joint thickness, but values for this thickness excess over some minimum one, which would be in "tangential points, marked by circles.

As a result of investigations conducted all the necessary conclusions have been drawn and measures have bee proposed to improve the technology for superstructure segments fabrication by match casting method.

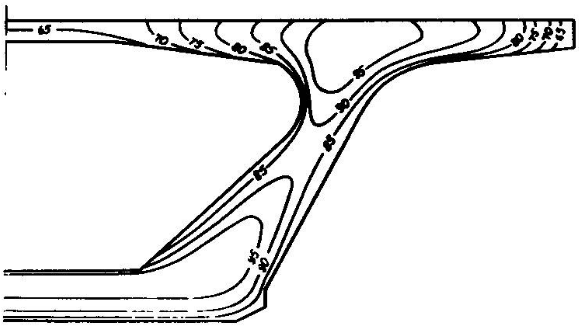

Fig.1 Temperature field in the middle section of a segment-matrix (isolines values are given in °C)

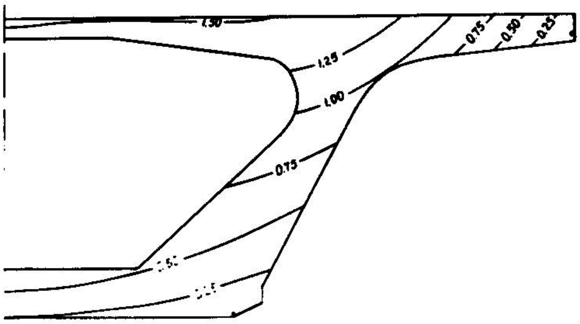

Fig.3 Distribution of glued joint thickness along its surface (isolines values are given in mm)