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This thesis "Mechanical Behaviour at Fire of Concrete and Hyperstatic Concrete Structures" embraces the publications

A. Yngve Anderberg Sven Thelandersson	Stress and Deformation Characteristics of Concrete at High Temperatures. 2. Experimental Investigation and Material Behaviour Model. Division of Structural Mechanics and Concrete Construction, Lund Institute of Technology, Bulletin 54, Lund 1976.
B. Yngve Anderberg	Fire-exposed Hyperstatic Concrete Structures - An Experimental and Theoretical Study. Division of Structural Mechanics and Concrete Construction, Lund Institute of Technology, Bulletin 55, Lund 1976.

In summarized form, the publications have been accepted for publication as research papers for the Douglas McHenry symposium on concrete and concrete structures in Mexico City, October 1976, under the heading "A Constitutive Law for Concrete at Transient High Temperature Conditions" and "Fire-exposed Hyperstatic Concrete Structures - An Experimental and Theoretical Study", respectively.

Introduction

At present, a development of the design codes and regulations takes place in several countries towards an increased degree of functionally based requirements and performance criteria. This trend gives a high priority to a development of differentiated systems for a fire engineering design, based on a real, complete process of a fire development. In the structural fire protection field such a design procedure has been developed for a general practical application recently in Sweden for steel structures, whereas for concrete structures the design hitherho is made in a more schematic way. This is mainly due to the lack of a thorough understanding of the mechanical behaviour of reinforced and prestressed concrete structures under high temperature conditions. It is therefore of vital importance to develop analytical models for a realistic prediction of the complete structural behaviour and the load-carrying capacity of concrete structures at different fire exposures. The models also have to be verified by experimental investigations, carried out at well-defined test conditions.

The aim of this research project was to follow these lines of thought which means that a new material behaviour model of concrete valid at transient high-temperature conditions and connected computer programs were derived. The programs have the capability of predicting the thermal and structural behaviour and the load-carrying capacity of hyperstatic, continuous beams and frames of reinforced concrete subjected to fire. Furthermore the evaluated structural response was compared with the measured behaviour in a great number of experimental tests.

Material behaviour models /A/

The mechanical behaviour of loaded concrete at transient, high-temperature conditions is considerably different from that observed under steady-state temperature conditions. The compressive strains induced by a compressive stress are much greater during heating than at constant temperature.

A computer-oriented model has been constructed for the mechanical behaviour of concrete in compression, based on tests at transient as well as steady-state temperature conditions. The model was developed on a purely phenomenological level and describes the material behaviour at varying stress under instationary temperature exposure at a first heating and a subsequent cooling phase. Consequently the behaviour model takes into account the history of the temperature and stress as well as any arbitrary process of unloading in the stress-strain diagram. The validity of the model is checked against independent tests which represent arbitrary stress, strain and temperature histories. The application of the model is intended for conditions typical for fire exposure i.e. relatively rapid heating in the temperature range up to about 800^{o}C. This means that the conditions at temperatures below 200^{o}C, where the influence of moisture is important are less emphasized. A more appropriate modelling in this range requires that the complex interaction between heat and moisture flow and its influence on the mechanical behaviour must be considered. Quantitatively the model is developed for a specified concrete mixture with quartzite aggregate. But it is reasonable to assume that qualitatively the model is valid for a wide range of concretes, provided that the variation in temperature of the thermal expansion, the strength and the ultimate strain has been determined.

The analytical description of the model i.e. the constitutive law valid under transient, high-temperature conditions is expressed as follows

$$\varepsilon = (\sigma(t),\ T(t),\ \tilde{\sigma}) \qquad (1)$$

where

ε = total strain at time t
σ = stress
T = temperature
$\tilde{\sigma}$ = stress history

Phenomenologically, an adequate formulation is obtained if the total strain is seen as the sum of four different strain components each of which is connected to and corelated with a specified type of test. Eq. (1) can thus be rewritten

$$\varepsilon = \varepsilon_{th}(T)+\varepsilon_{\sigma}(\tilde{\sigma},\sigma,T)+\varepsilon_{cr}(\sigma,T,t)+\varepsilon_{tr}(\sigma,T) \qquad (2)$$

where

ε_{th} = thermal strain, including shrinkage, measured on unstressed specimens under variable temperature

ε_{σ} = instantaneous, stress-related strain, based on stress-strain relations obtained under constant, stabilized temperature

ε_{cr} = creep strain or time-dependent strain measured under constant stress at constant, stabilized temperature

ε_{tr} = transient strain, accounting for the effect of temperature increase under stress, derived from tests under constant stress and variable temperature.

A general implication of the model, applied on a circular cross-section of concrete under sustained axial compressive load and exposed to axisymmetrical heating, is that the stresses created due to differential or restrained thermal expansion are very insignificant or even nonexistant. Such stresses cannot in themselves contribute to a compression failure. It is furthermore obvious that an elastic stress distribution bears little resemblance to reality and is virtually meaningless even as a rough qualitative estimate.

Hyperstatic concrete structures at fire /B/

The thermal and mechanical response of hyperstatic concrete structures under fire exposure conditions is studied both experimentally and theoretically. In the study representative fire processes, including the subsequent cooling phase, are considered and laboratory tests are accomplished under well-defined conditions. These tests are performed for a pure type of hyperstatic structure with regard to support conditions, viz., a reinforced concrete plate strip thermally exposed on one side and restrained against rotation at both ends, while axial displacement is free to take place.

The experimental investigation is the first one of its kind and the structural behaviour was furthermore followed up to the residual state after cooling with respect to residual stresses and deformations, residual load-carrying capacity and flexural stiffness.

The analytical predictions of thermal and mechanical behaviour comprise a heat flow analysis in the first step and a structural analysis in a second step, based on two separate computer programs.

The evaluation of the thermal response is carried out by a finite element computer program in which the moisture flow is disregarded. In the analysis, the influence of moisture is taken into account in a approximate way by making the thermal properties of concrete moisture dependent which strictly is functionally incorrect. Though the approximations made, the prediction of the temperature-time fields for the present application was in all cases in a good accordance with the measurements during the heating as well as during the subsequent cooling phase.

The theoretical analysis of the structural response to fire is carried out by a computer program "FIRES-RC" originally constructed at University of California, Berkeley. This program has been further improved by the author and the new development of more realistic behaviour models of the structural materials under transient temperature conditions is an essential new contribution in the program. The computer program is capable to evaluate the detailed structural behaviour of fire exposed reinforced concrete frames. In this study the application of the program is however limited to a hyperstatic structural member in accordance to the experimental investigation.

The calculations are referred to four different combinations of boundary conditions for the plate strip, viz.

(1) Complete rotational restraint at both ends and a free axial movement

(2) Simply support at both ends

(3) Simply support at both ends but restraint against axial movement

(4) Complete restraint against rotation as well as axial movement at both ends.

Some general conclusions of the study are

1. Material behaviour models based on experimental data, obtained at steady state conditions, applicated in the prediction of the structural response to fire of concrete structures result in unrealistic great thermal restraint forces and moments (if less than the yield moment) and sometimes in an erroneous collapse state.

2. The material behaviour models and the computer model give a good prediction of the mechanical behaviour and load-carrying capacity at fire of isostatic as well as hyperstatic reinforced concrete structures.

3. Thermal restraint forces never exceed 45 % of the load-carrying capacity at ambient conditions, in analyzed fire-exposed hyperstatic concrete plate strip, axially restrained.

4. From calculations and tests performed it seems to be justified to treat the thermal restraint forces and moments separated from those caused by an external load, as long as the yielding moment has not been reached at any cross-section. The sum of these components is approximately equal to the total forces and moments of the structure at fire.

Practical use of presented study for design purposes

The presented study gives an improved basis of a thorough, functional understanding of the fire response of hyperstatic concrete structures. This fact is owing mainly to the development of the new material behaviour model of concrete valid at transient temperature states which enables a reliable stress and strain analysis. The model is especially crucial for a theoretical study of, for instance hyperstatic structures and slender columns where an accurate evaluation of the deformations is necessary.

Reliable predictions of the thermal response and the mechanical behaviour of fire-exposed concrete structures, demonstrated in this study, improve the prospects for a realistic fire engineering design not only for the structure dealt with here but also for other types of concrete structures. The presented study may form a basis of and contribute to the development of such a rational design procedure presented for facilitating the practical application, for instance, in the form of a design manual, comprising simplified methods and systematized design diagrams and tables.

Need for further research

A development of an analytical design procedure, based on real fire exposure characteristics and ready for a general practical application to different types of reinforced and prestressed concrete structures, requires, from the present state of knowledge, comprehensive future research contributions concerning a series of important problems. Examples of such fundamental and anxious contributions are:

1. Development of analytical methods and connected computer programs for the simultaneous, interrelated transport mechanisms for heat and moisture. In such an analysis, the thermal properties of concrete are described by real, well-defined, physical quantities which are independent of the moisture content. Within the problem, a related important task is to develop methods for measuring the true enthalpy-temperature variation, including the latent heat from chemical reactions, for heating as well as for subsequent cooling.

2. Extension, quantitatively, of the mechanical behaviour model for concrete at transient, high-temperature conditions to other types of concrete than that one dealt with in /A/ - ordinary concrete with different mixtures and aggregates, lightweight aggregate concrete, aerated concrete. The extension requires the temperature variation of the thermal expansion, the strength and the ultimate strain being determined, in the first place from tests where specimens are heated to failure under sustained load. A parallel extension, generally, by a deduction of a more accurate theory for the mechanical behaviour during the subsequent cooling

phase has high degree of priority, too.

3. Complementary investigations of the mechanical behaviour properties at transient, high-temperature exposure for different reinforcing and prestressing steels, related to heating as well as subsequent cooling.

4. Development of analytical models and connected computer programs, verified in systematic decisive tests, for the deformation capacity, for instance the rotation capacity, at transient high-temperature conditions. This property is of crucial importance for the influence of restraint forces and moments on the load-carrying capacity of fire exposed, hyperstatic concrete structures and consequently for the possibilities of applying a limit state design in connection with fire. The current study and also other experimental investigations, reported previously, for instance by Gustaferro, then indicate the validity of an ultimate state approach for continuous beams and frames, but the problem needs further studies to be carried through.

5. Further experimental studies connected to a development of analytical models and computer programs with respect to other types of failure than in bending - shear, torsion, interaction, instability, second order influence. Within this extensive group of problems, the present state of knowledge is as a whole of an extremely virgin character, as concerns the structural behaviour and load-carrying capacity of concrete structures at elavated temperatures.

6. Further experimental and theoretical studies leading to an improved functional understanding of the spalling of concrete and its causes. In such studies, the joined mechanisms of transient heat and moisture transfer at elevated temperatures constitute a central concept.

7. More thorough studies on the residual load-carrying capacity, the residual bending stiffness and residual state of stress and deformation for fire-exposed structures. These residual characteristics are important for the reserviceability of a load-carrying

concrete structure after fire and the extent of the subsequent repair of the fire-damaged structure.

8. A general fire safety analysis of concrete structures, based on probabilistic concepts used in normal structural design, including a probabilistic determination of design load and design fire load density. A methodology of such a probabilistic analysis has been developed by Magnusson for fire-exposed steel structures. The procedure comprises a general systematized scheme for the identification and evaluation of the various sources and kinds of uncertainty in the differentiated, structural fire engineering design. Resultant safety levels can be expressed by a so called safety index, in which these uncertainties are included. For concrete structures there arise an additional problem viz. the risk of spalling which must be considered in such a methodology.

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Paper /A/ is a final paper from a joint research project between the author and Sven Thelandersson. The work on the project is carried out in close cooperation between the authors. In particular, paper /A/ has been outlined and written by the authors in close connection, though Yngve Anderberg has been mainly responsible for the performance of the tests and the theoretical analysis.