Committee Report : JCI- TC096FS

Technical Committee on Concrete Properties under High Temperature and Fire Resistance of Concrete Structures

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Abstract

This Research Committee, for three years from 2009 to 2011, conducted research on the latest experimental findings and analytical methods with regard to relations between concrete properties and load resistance/deformation properties of structures on fire, as well as literature research concerning fire resistance test methods, and inspections/diagnosis/measures of structures damaged by fire, and then summarized the present technical status of the design/construction/maintenance management of refractory concrete structures (including concrete products). In addition, the Committee made proposals such as "tentative proposal on diagnosis and repair/reinforcement plan for fire-damaged concrete structures", and identified future issues.

Keywords: fire resistant design, fire curve, fire response, fire damage diagnosis, repair/reinforcement, test method

1. Introduction

Concrete structures, a non-inflammable material, have been thought to be more resistant to fire than those built with wood or steel. In recent years, however, since structures have become bigger and higher, and/or more and more complicated, in some cases excessive losses have been incurred by fire in tunnels, highways, high-rise RC buildings, etc., and a system in which the behavior of concrete structures on fire can be evaluated in both civil engineering and construction is now needed. The Research Committee therefore set up a design/structure working group (WG1), an inspection diagnosis/repair reinforcement working group (WG2), and a material working group (WG3) shown in **Table 1**, and for three years from fiscal year 2009 to 2011, analyzed domestic and international research cases, and carried out research on systems/standards/laws and regulations with regard to fire, chemical/physical changes in concrete in a fire, and the effect of fire on various performances of concrete structures, etc.

Table 1: Committee members

Chairman	Takafumi NOGUCHI	The University of Tokyo
Vice-chairman	Tsuyoshi MARUYA	Taisei Corporation
WG1		
Leader	Toru KANDA	Nippon Civic Consulting Engineers Co., Ltd.
Secretary	Shintaro MICHIKOSHI	Taisei Corporation
	Yoshifumi OHMIYA	Tokyo University of Science
	Osamu KIYOMIYA	Waseda University
	Jun-ichi SUZUKI	Building Research Institute
	Yasushi TAKEI	Railway Technical Research Institute
	Kazunori HARADA	Kyoto University
	Takeo HIRASHIMA	Chiba University
	Masashi MORIKAWA	Central Japan Railway Company
WG2		
Leader	Kenichi ICHISE	Obayashi Corporation
Secretary	Shoji NOJIMA	Nippon Expressway Research Institute Co., Ltd.
	Masanori OKUBO	National Institute for Land and Infrastructure Management
	Kazuya KOGA	Tokyo University of Science
	Akihiro SAKAGUCHI	General Building Research Corporation of Japan
	Atsushi SHIMURA	Hanshin Expressway Management Technology Center
	Hiroshi DOBASHI	Metropolitan Expressway Co., Ltd.
	Kousuke NOMOTO	Maeda Corporation
WG3		
Leader	Kosuke FURUICHI	Kajima Corporation
Secretary	Takeshi MORITA	Shimizu Corporation
	Mitsuo OZAWA	Gifu University
	Masarou KOJIMA	Takenaka Corporation
	Miwa SASANUMA	Tokyo Electric Power Company
	Tooru TANIBE	Taiheiyo Materials Corporation
	Masatoshi TOKOYODA	Japan Testing Center for Construction Materials
	Hitoshi HAMASAKI	Building Research Institute

The aim was to develop fire-resistant design methods for concrete structures, and to establish fire damage diagnosis methods. Specifically, the following activities were carried out:

- ✓ Collecting views about fire resistance of concrete structures
- ✓ Examining fire resistance designs and construction methods for fire prevention in consideration of fire risks
- ✓ Proposing rational decision procedures for fire action to structures such as basement car parks, tunnels, and bridges

- ✓ Organizing data about the thermodeformational behavior of existing structures
- ✓ Performing case research on fire-resistant designs of concrete structures
- ✓ Collecting cases of fire damage inspections, diagnosis, evaluations and judgment methods, and organizing data about the present technical status
- ✓ Organizing data about present test methods for fire damage inspections/diagnosis
- ✓ Examining methods for evaluating the health of members/structures after fire
- ✓ Organizing data about methods for repair/reinforcement after fire
- ✓ Proposing "views on fire damage diagnosis of concrete structures"
- ✓ Conducting research on RILEM test methods for concrete under high temperature
- ✓ Examining test methods for concrete spalling
- ✓ Conducting research on the Dutch test method for fireproofing protection
- ✓ Conducting research on the physical properties of polymer cement mortar under high temperature
- ✓ Conducting research on the properties of high-strength steel bars under high temperature

2. Design/structure WG (WG 1)

2.1 Introduction

The response of concrete structures to fire is as follows: with increasing temperature, thermal expansion, high temperature degradation, and stress redistribution occur coupled with one another, which eventually results in destruction. This WG analyzed present data about fire action and fire response, and identified problems to accurately predict the behavior of various concrete structures on fire. It proposed procedures for analyzing fires and evaluating fire action with regard not only to fires in buildings, but also those in outdoor spaces such as road structures and railroad structures. It also collected the latest fire-resistant designs, and introduced useful information for professionals to make fire-resistant designs.

2.2 Fire action

For fire within buildings, methods of determining data and fire curves of flammable materials based on the fire-resistant verification method specified in the Building Standards Law were identified, and applied in design practice. While technical problems still remain as to adjacent or urban fire, the temperature and duration of outdoor fires are also specified. However, methods for buildings themselves cannot be applied to road structures such as tunnels and bridges, since the kinds of flammable materials and ventilation conditions are largely different between buildings and road structures, although large-scale fires have been increasing in the latter case. It is becoming more and more necessary to devise reasonable methods to evaluate such fires. Although WG 1 has examined fire protection measures by properly choosing from among overseas fire curves as shown in **Fig. 1**, there are many unclear points as to their scope, and thus there remains much room for examination.

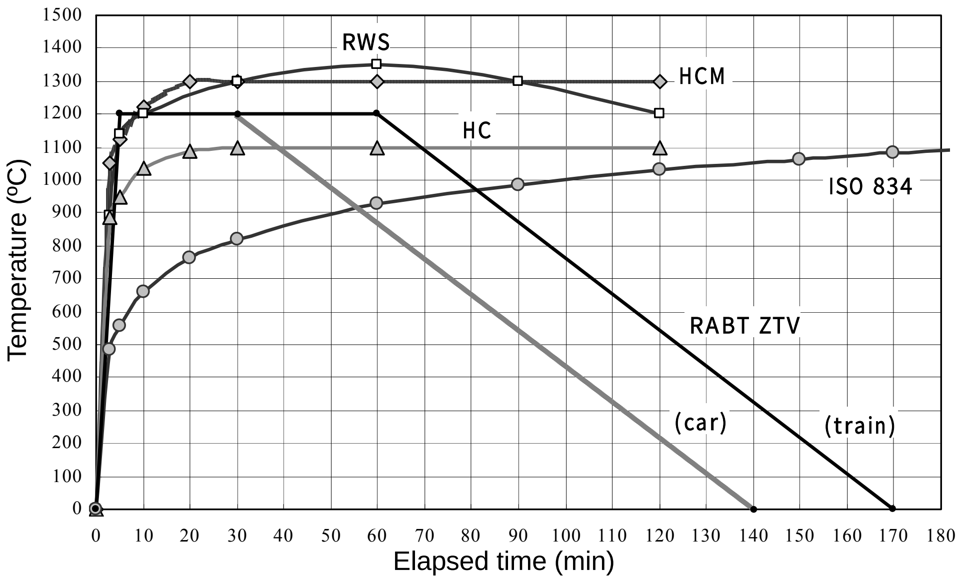


Fig.1: Various kinds of fire curves

A fire curve for a fire-resistant design corresponds to an input earthquake motion for an earthquake-resistant design, and if a fire curve is not determined, it is difficult to examine a fire-resistant design further. Under the present circumstances, although it is quite difficult to precisely determine a fire curve for a road structure, it is thought possible to rather reasonably establish a fire curve to the extent that it would cause no practical problems if a heat balance were determined as shown in **Fig. 2**. When thinking of cases where an increasing number of tunnels have been given fire protection measures, the only flammable materials are vehicles, and the fire curve is known since the amount of ventilation is controlled.

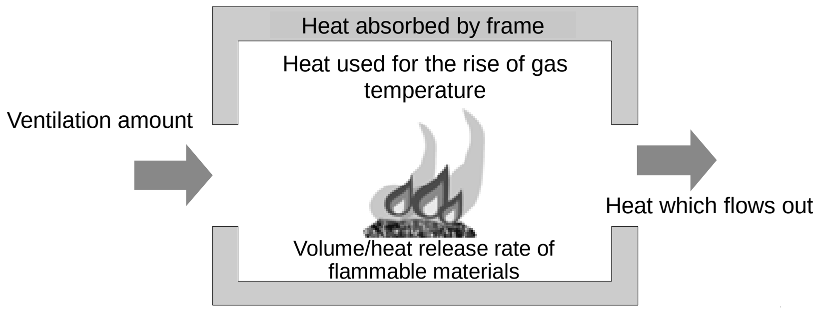


Fig. 2: Prerequisites for calculating fire curves

It is possible to assume the number and types of vehicles which are flammable by considering road standards, designed traffic volumes, and whether or not there are traffic regulations on hazardous material vehicles, etc. Also for heat release rates, actual measurement values found by combustion experiments using actual vehicles have been increasingly reported mainly in other countries. Based on these findings, the history of heat release rates was similar to the RABT curve shown in **Fig. 3**, and when identical vehicles were burned, the faster the wind speed and the larger the inner section, the lower the highest temperature was. Based on this, the prerequisites shown in **Fig. 2** are appropriate, and if data like those shown in **Fig. 4** are available, it seems possible to reasonably obtain fire curves for tunnels. In the case of railroad tunnels, WG 1 presented its views about the analysis of the JR Sekisyo Line Fire Accident, and the flame behavior model for vehicles.

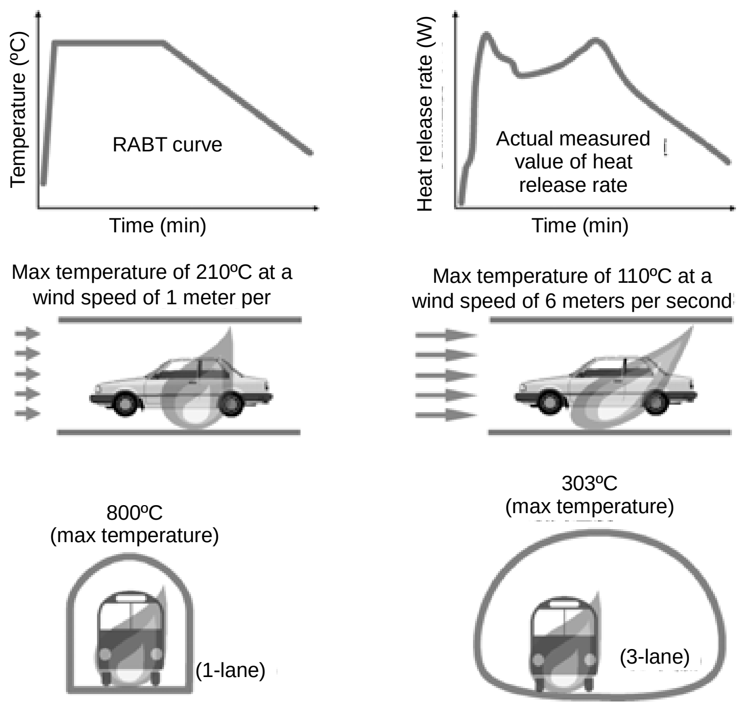


Fig. 3: Tendency of results of full-scale fire burning tests

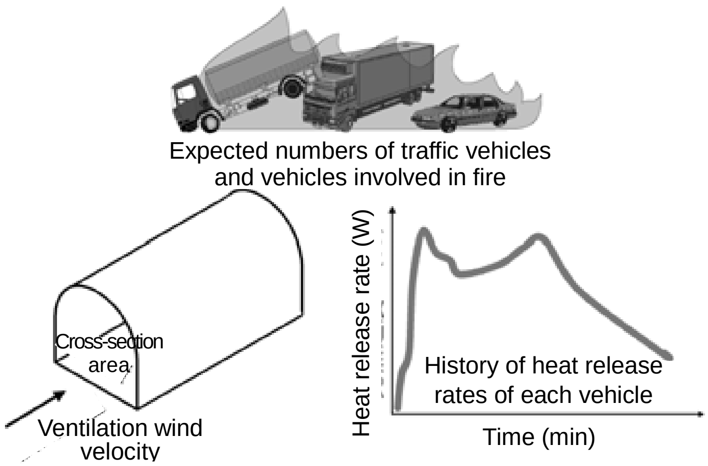


Fig. 4: Data required for determining fire curves for tunnels

It is thought that even in the case of a bridge fire, a fire curve can be proposed basically with the same approach. Just like the accident that occurred on the Metropolitan Expressway No. 5 Ikebukuro Line, a problem with regard to a bridge is a case where a fire breaks out under a bridge deck. In the case of a bridge fire, although ventilation is overwhelmingly larger compared with a tunnel fire, etc., since there is a ceiling and a floor, it seems that a bridge can be used as a spatial model with a very large proportion of opening as shown in **Fig. 5**.

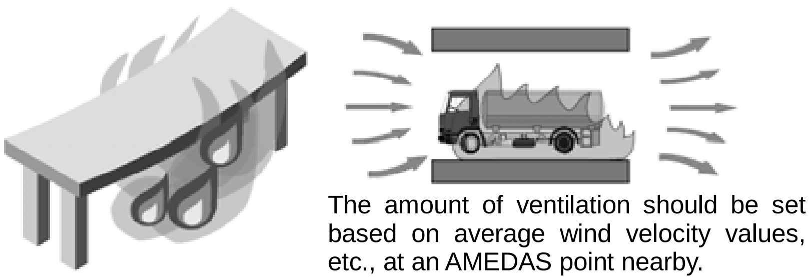


Fig. 5: Modeling of bridge fire

2.3 Fire response

WG 1 carried out research and analysis of methods which can reproduce member temperatures and deformational behaviors of concrete structures on fire with high accuracy. While collecting past cases of loading heating experiments and analyses, and introducing optimal analytical methods according to the structure/frame structure, WG 1 evaluated the physical properties necessary for analysis.

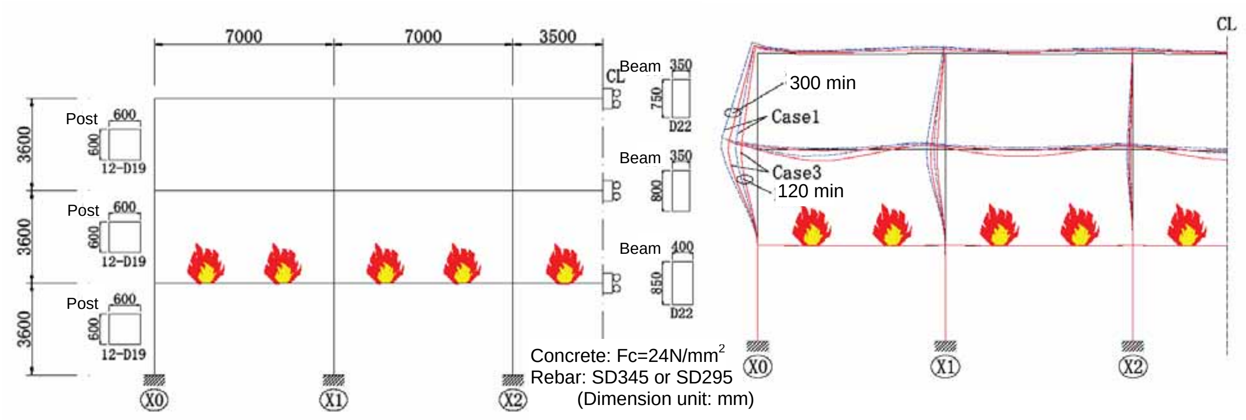


Fig. 6: Case 1: Load heating experiment and numerical analysis of RC frame structure

Fig. 6 shows a time history response analysis for 3-story office buildings (3x5 span). Considering the symmetrical property of frame structures, the left half is intended for analysis. In this case, assuming that the entire second floor is burning and the concrete surface temperature goes up according to the ISO834 standard fire temperature curve, the calculation was carried out until 5 hours later. The Eurocode model was used for stress-strain relations and thermal expansion distortion. The magnitude of transient strain was used as a parameter.

The more towards the outer side of a beam, the larger the capital horizontal displacement attributable to thermal expansion became, and the deflection of the beam leading to the side post became slightly larger even though the span was the same. Taking transient strain more into consideration resulted in a smaller capital horizontal displacement of the post and a larger deflection of the beam.

Needless to say, it is imperative that no system should collapse in an underground structure, and it is necessary to control deformation in a fire so that it does not affect the superstructure. **Fig. 7** shows a case of the heating experiment using actual cement and the numerical analysis considering the earth and water pressures of surrounding soil in order to predict the deformational behavior of a shield tunnel on fire. In this case, WG 1 carried out the RABT heating test while giving the design cross-sectional force to an actual-size test body. After confirming that experimental findings are reproducible by numerical analysis, WG 1 conducted a deformation analysis of the full face of a tunnel lining on fire. It was confirmed that the thermal deformation of the lining varies greatly depending on the presence or lack of fire-resistant measures.

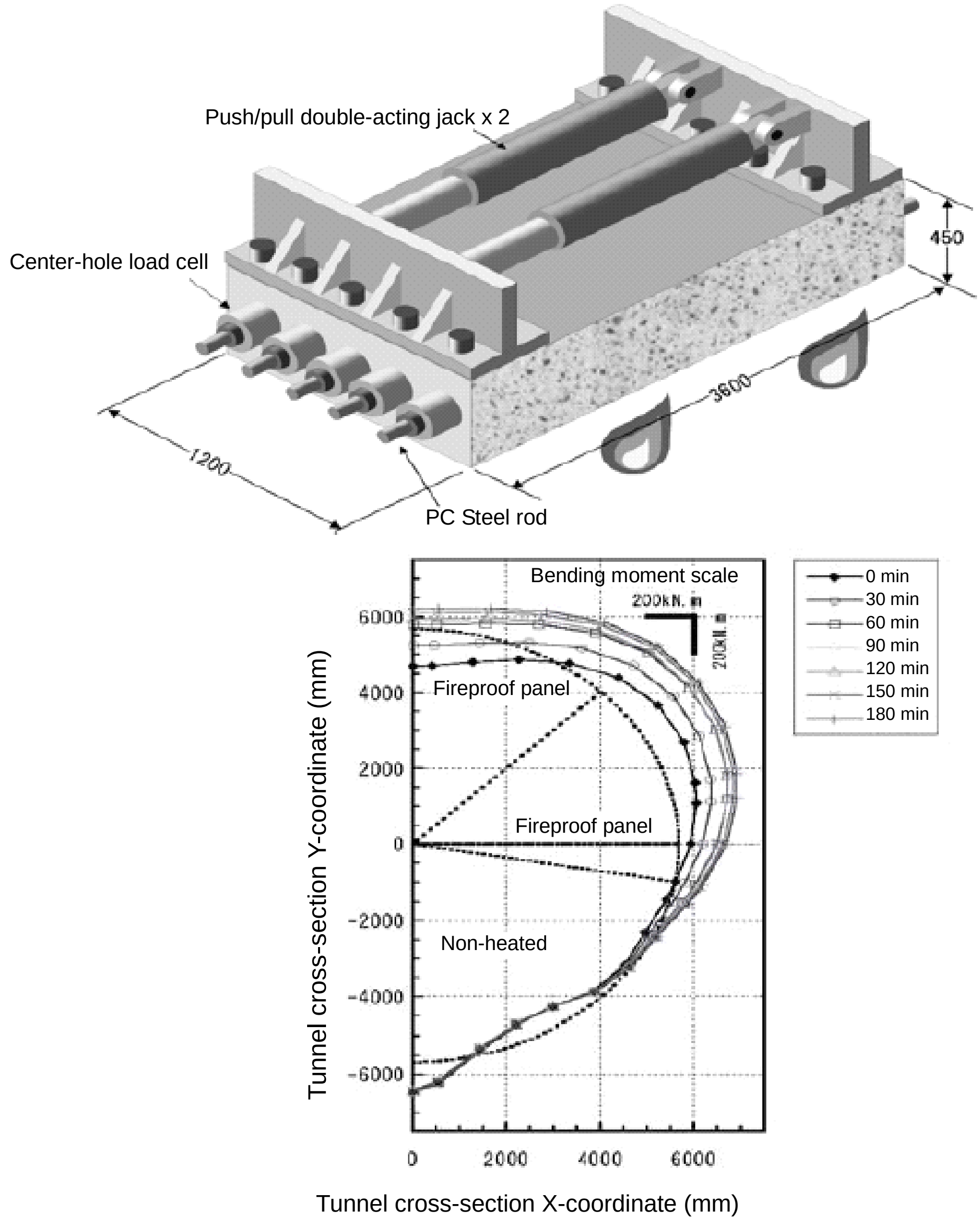


Fig. 7: Case 2: Heating experiment and numerical analysis of tunnel lining

2.4 Fire-resistant design case

With regard to buildings, WG 1 introduced spalling prevention measures by the addition of organic fiber, and views on fire-resistant designs in CFT. With regard to road structures, WG 1 summarized submerged tunneling methods and shield tunneling methods, as well as cases of fire-resistant measures using fire-resistive covering and organic fiber. Especially with regard to fire-resistive covering, WG 1 introduced a case of using a fire-resistive board with an interior functionality, which has recently become more widespread.

3. Inspection diagnosis/repair reinforcement WG (WG 2)

This WG mainly carried out literature research on repair/reinforcement as well as inspections/diagnosis of concrete structures which suffered from fire damage, and presented their recent findings. Specifically, after preparing a technical summary based on literature research on the establishment of health evaluation criteria, the clarification of judgment criteria for service, the selection of repair/reinforcement methods, and the development of simple on-site inspection methods, WG 2 prepared a "tentative proposal on plans for fire damage diagnosis and repair/reinforcement of concrete structures," a practical proposal for buildings and civil engineering structures.

3.1 Methods for inspection/diagnosis/evaluation/judgment after fire

(1) Collection of cases

WG 2 collected cases of fire damage inspections, diagnosis and evaluations from articles published in journals by relevant societies and associations. There are few cases published with regard to buildings. On the other hand, WG 2 was able to collect relatively many cases related to civil engineering structures. Many civil engineering structures are public properties, and then if socially notable fire damage occurred, the handling of such cases would be made public accordingly. For each case collected, WG 2 identified the inspection methods used, diagnostic outcomes and other noteworthy matters. In most cases, a visual inspection is carried out as for a primary inspection, and with regard to implementation of a secondary inspection which determines the grade of fire damage, there were some differences between building and civil structure inspections.

(2) Present status of technology as to inspection/diagnosis after fire

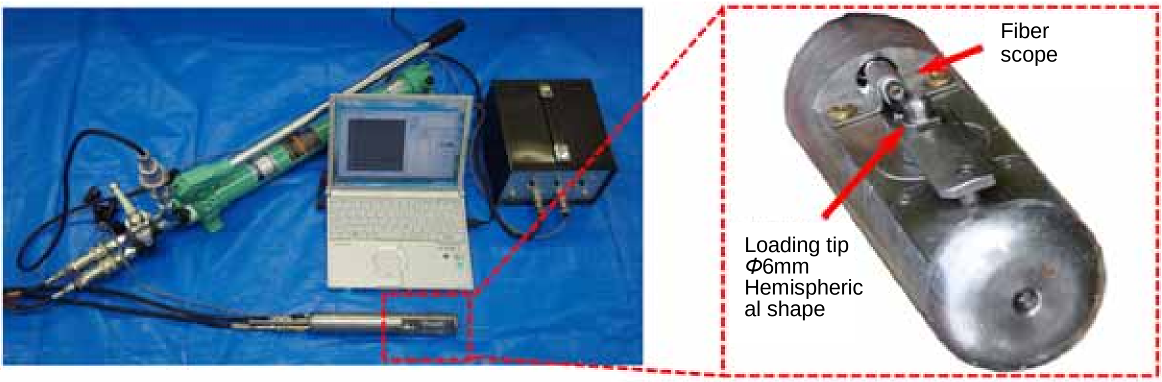
WG 2 collected proposals for fire damage inspection methods, diagnosis methods and minimally destructive/nondestructive inspection methods. Research on nondestructive inspection methods is in progress, and analytical methods using small size cores by the minimally destructive method, which permit a detailed diagnosis, have been proposed.

(3) Notable test methods concerning inspection/diagnosis

In fire damage diagnosis, test methods are desired which permit estimation of the heating temperature in the depth direction. However, at present, there is no choice but to rely on chemical analyses such as the UV spectrum method. In the process of collecting cases, a part loading aperture test[1)], a colorimetric analysis of concrete[2)], and a method based on drill resistance[3)] were mainly proposed to estimate, fairly easily, the heating temperature or intensity distribution in the depth direction.

For the part loading aperture test, a small device for a part loading aperture test of 40 mm diameter and 270 mm length, as shown in **Fig. 8**, is inserted into an aperture drilled in a core of 42 mm diameter to estimate the concrete strength by a load-penetration relationship, after loading a φ6 mm tip part as if to push it out against the sides of the concrete aperture. For example, it is possible to measure the physical properties of an area near the concrete surface for each 1 cm depth, and to determine its change in detail. However, there were no reliable records for fire-damaged concrete until now. This committee examined the applicability of the part loading aperture test by using normally heated concrete specimens. As a result, it was confirmed that this test method is applicable as a method for estimating the strength in the depth direction.

The colorimetric analysis of concrete inspects the depth of damage caused by heat based on the change of color of the side surface in a core aperture. The method based on drill resistance estimates the remaining strength in the depth direction based on the work per unit depth necessary when drilling an aperture. Since all of these methods evaluate each layer from the heated concreted surface, research and development for extending applicability in the future is desired.



Test device: Φ40mm, 270mm in length

Fig. 8: Device for part loading test in aperture

(4) Problems relating to the present fire damage inspection/diagnosis methods

WG 2 identified methods for inspection, diagnosis, evaluation and judgment after fire, and cited the following problems:

(i) Method for surface measurement of fire damage: discoloration used to estimate the heating temperature may vary depending on aggregate used;

(ii) Measurement in the depth direction of fire damage: there is no simple judgment method at a heating temperature of 200 ºC that affects Young's modulus; and

(iii) Calibration value: it is necessary to prepare various calibration values for concrete.

3.2 Proposals on methods for identifying and selecting technologies regarding repair material/reinforcement methods for concrete structures damaged by fire

WG 2 carried out research on cases where measures were taken after fire, classified structures into buildings, civil engineering structures (bridges), and civil engineering structures (tunnels), and identified trends in present protection measures.

Repair materials and reinforcement methods seem to be selected after thorough examination by a fire damage diagnostic engineer, a structural design engineer and a contractor based on the intention of the owner, supervisor and user of a structure damaged by fire. By examining guidelines, etc., protective measures can be roughly divided into as follows:

(i) Repair (top surface concrete): surface treatment methods, grouting/filling methods;
(ii) Repair (cover concrete): coating method; and
(iii) Reinforcement: steel plate/FRP wrapping methods, bonding methods, thickness increasing methods, or replacement of members

3.3 Evaluation methods for health condition of members and structures after fire

(1) Judgment of serviceability immediately after fire

The judgment of serviceability immediately after a fire greatly differs between buildings which mainly tend to be used by individuals and companies, and civil engineering structures which tend to be used for the public.

Buildings are judged based on the "Guidelines (Proposal)/Interpretation of Methods for Fire Damage Diagnosis and Repair/Reinforcement of Buildings"[4)]. That is, with regard to fire damage diagnosis, a fire damage inspection (preliminary inspection, primary inspection, and secondary inspection, if necessary, based on the results of the primary inspection), and a fire damage diagnosis (judgment of the degree of fire damage/catastrophe based on inspection results) are carried out, and measures are considered according to the diagnostic results. In addition, with regard to buildings damaged by an earthquake, the “Manual for Emergency Judgment of Safety of Damaged Buildings"[5)] shows a method for judging the usability of such buildings until their permanent rehabilitation.

In the case of civil engineering structures, since there are no general judgment criteria, many cases are diagnosed individually. With regard to highway bridges, the "Inspection Manual (Proposal) for Bridges Damaged by Fire"[6)] may be used, which shows the flow of emergency measures after carrying out a comprehensive judgment according to an urgent inspection, and taking measures such as traffic controls.

(2) Judgment of health after repair/reinforcement

With regard to buildings, health evaluation is rarely performed after repair/reinforcement. However, although there are only a few cases, it may be carried out in order to compare with the vibration and loading tests done in the secondary inspection.

With regard to civil engineering structures, there are cases where the effect of measures was confirmed by a loading experiment to judge whether to put the structure into service after taking measures.

3.4 Tentative proposal on fire damage diagnosis, and plans for repair/reinforcement of concrete structures

Based on the results of research/tests relating to inspections/diagnosis and repair/reinforcement of concrete structures damaged by fire, the committee completed a tentative proposal on fire damage diagnosis and plans for repair/reinforcement of concrete structures, targeted at buildings and civil engineering structures made of non-reinforced or reinforced concrete (including steel-framed concrete). The composition of the tentative proposal is as follows: Chapter **1** "General Rules," Chapter **2** "Views of Fire Damage Inspection/Fire Damage Diagnosis and Repair/Reinforcement," Chapter **3** "Buildings," Chapter **4** "Civil Engineering Structures," and Chapter **5** "Test Items." Although the committee tried to unify descriptions for buildings and civil engineering structures as much as possible, Chapter **3** and Chapter **4** were provided separately for the following reason.

For buildings, after preliminary and primary inspections of fire damage are performed, the necessity of further inspection and repair/reinforcement is determined, and then a secondary inspection is carried out. On the other hand, for civil engineering structures, an urgent inspection to judge whether to stop train services or vehicle traffic is carried out, measures such as traffic regulation or emergency rehabilitation are taken, and then primary/secondary inspections are carried out. Therefore, the committee considered it difficult to unify the description, since buildings and civil engineering structures differ in terms of the positioning of emergency measures and inspections.

Table 1 shows an outline of the tentative proposal.

Table 1: Tentative proposal on fire damage diagnosis and plans for repair/reinforcement of concrete structures

(1) General rules

These specify the purpose of the tentative proposal, the scope of application and the definition of terms. The purpose is to show matters to be considered in the fire damage inspection/diagnosis of concrete structures damaged by fire, and the plan for repair/reinforcement; to contribute to the proper maintenance management of concrete structures; and to apply these provisions to buildings made of non-reinforced or reinforced concrete (including steel-framed concrete), and civil engineering structures such as bridges and tunnels. The terms are defined to unify those of buildings and civil engineering structures as much as possible.

(2) Views of fire damage inspection/fire damage diagnosis, and repair/reinforcement

The purpose of a fire damage inspection and a fire damage diagnosis is to obtain basic data for judging the possible risk of collapse of bridges and tunnels damaged by fire; whether to stop train services or third party traffic; the necessity of emergency measures or the possibility of reuse of buildings; and if such buildings are to be reused, examining and selecting repair/reinforcement methods. A fire damage inspection is divided into three stages, that is, a preliminary or urgent inspection, a primary inspection, and a secondary inspection. In a fire damage diagnosis, the degree of fire damage/catastrophe is judged based on the result of the inspection.

The purpose of repair/reinforcement is to realize recovery of fire-damaged structures up to the goal set for the safety of such structures, public safety, fire resistance, durability, usability, serviceability and other necessary performance.

(3) Buildings

This deals with planning of the inspection, diagnosis, and repair/reinforcement of buildings damaged by fire. A fire damage inspection consists of a preliminary inspection, a primary inspection and a secondary inspection, and a fire damage diagnosis is to be performed based on the result of the fire damage inspection. Repair/reinforcement is to be implemented after setting a recovery goal and a repair/reinforcement range, and selecting a repair/reinforcement construction method.

(4) Civil engineering structures

This deals with planning of the inspection, diagnosis, and repair/reinforcement of civil engineering structures damaged by fire. However, PC structures are excluded from the scope of application because of a lack of knowledge. In a fire damage inspection procedure, at first an urgent inspection is conducted, and whether or not prompt emergency measures are necessary is stated. Then, a primary inspection, and if needed, a secondary inspection are carried out, and a repair/reinforcement plan is drawn up.

(5) Test items

This describes the test methods used in primary and secondary inspections. In primary inspections, test methods are used that can easily be performed on the spot. In secondary inspections, a dynamic test, a material analysis and other tests are conducted in order to inspect the fire damage in more detail.

4. Material WG (WG 3)

WG 3 collected information through literature search in the FS of fiscal year 2009, in order to grasp the present state of high-temperature property data (including data after cooling) as regards the fire resistance performance of concrete structures, and of construction materials such as concrete, steel materials, fire-resistive covering and repair materials, in connection with repair/reinforcement. As a result, as shown in the following (1) to (4), the present state of knowledge and problems were identified, and WG 3 conducted activities with a view to presenting underlying data for contributing to future domestic research and development. An outline of the research/examination result is given in **4.2** to **4.6** below.

4.1 Present state and problems

(1) Data on high-temperature properties of concrete and steel materials

With regard to concrete, it is understood that although many data have been collected, it is difficult to systematically compare or organize such data in interpreting them, due to the fact that test methods have not yet been unified. In order to solve such a problem in the future, WG 3 believes that unification of test methods would be required. Then, with regard to concrete, WG 3 mainly carried out research on the details of a series of test methods for high-temperature concrete, proposed by RILEM (International Union of Laboratories and Experts in Construction Materials, Systems and Structures), and created data contributing to a proposal on standard test methods.

With regard to steel materials, there are also many data available, and standard test methods for materials are defined by JIS. Hence, while systematically understanding the presence/lack of current data focusing on steel grades, etc., GW 3 collected information focusing on reinforced joints and post-installed anchors which are rarely subject to examination.

(2) Explosive spalling of concrete

There are many research/development results in relation to the application of high-strength concrete in Japan. Meanwhile, various experimental/analytical studies have been carried out in foreign countries too, and in recent years, workshops have been held regularly. Many precious research results have been reported from such workshops, and WG 3 summarized an outline of these results.

(3) Fire-resistive covering

Fire-resistant measures for road tunnels, etc., have been examined and applied mainly in Europe, and such measures have become a good model for vehicle fires, etc., in road tunnels in Japan in recent years. In Europe, especially in the Netherlands, which has many underwater tunnels, pioneering research/development has been carried out, and the standard test method for tunnel fire-resistant measures such as fire-resistive covering was recently revised. On the other hand, Japan has no standard fire-resistant performance test/evaluation method for road tunnels, etc. For this reason, while studying fire-resistive covering construction methods for present buildings/road tunnels, etc., GW 3 summarized an outline of the Dutch standard test method, which might help propose a prospective standard test method for Japan.

(4) Repair materials

In order to reuse a concrete structure damaged by fire, a diagnosis for judging the possibility of reuse, and repair/reinforcement with a view to reuse, are needed. For inspection/diagnosis and repair/reinforcement due to fire, research, examinations and proposals have been made by WG 2, a subcommittee of this committee. On the other hand, WG 3 focused on polymer cement mortar as a repair material. Although polymer cement mortar, in terms of its workability and adhesiveness, is promising as a repair material, its application to a structure that requires fire resistance is yet to be justified because its high-temperature properties have not been thoroughly clarified. For this reason, a thorough examination as to whether polymer cement mortar is fire-resistant has been carried out domestically in recent years. The committee therefore decided to collect information about these latest examination results.

4.2 Material properties of concrete

(1) Outline

Although concrete is generally seen as a fire-resistant material, its dynamic properties such as strength and elasticity deteriorate under high temperature or in a fire, and after a history of high temperature. Also, deformation (strain) like thermal expansion, contraction, etc., occurs with changing temperature, and stress (thermal stress) resulting from this occurs. On the other hand, in the case of a concrete member damaged by fire, since concrete does not conduct heat easily, a relatively large temperature gradient occurs between the heated surface whose temperature may reach around 1,000 ºC and the deep inner part. This temperature gradient causes the thermal stress mentioned above, and affects the behavior of a structure on fire. Therefore, in order to create a fire-resistant design for a concrete structure, it is necessary to quantitatively grasp the following properties of concrete, for which the committee completed an outline in its report.

<u>Thermal properties</u>

Density, specific heat, heat conductivity, moisture movement, latent heat and sensible heat, coefficient of heat transfer on heated surface

<u>Mechanical properties</u>

Compressive strength, attachment strength, tensile strength (bending strength and strength in shear), stress-strain relationship, elastic modulus, Poisson's ratio, thermal strain, transient creep, steady-state creep

(2) Research on research field

WG 3 carried out research on what data are currently reported as to the material properties of concrete under high temperature. The literature quoted by the Architectural Institute of Japan's fire resistance guidebook for structural materials[7)] and the report by the Japan Concrete Institute's Research Committee on Fire Safety for Concrete Structures[8)], both of which deal with the properties of concrete under high temperature, was mainly the subject of this research. The results of the research were evaluated under experimental conditions based on the amount and the richness of research data. Based on this result, WG 3 organized future tasks, such as what kind of research data should be enhanced in future.

(3) Test methods

As a result of examination of the dynamic test method for concrete under high temperature suggested by RILEM, 10 kinds of test methods related to stress-strain relationship, compressive strength, tensile strength, elastic modulus, thermal strain, transient creep, steady-state creep, contraction, reaction stress, and stress relaxation were proposed. Although every test method is specified in detail according to each dynamic property, the descriptions as to the estimated status of concrete, materials/blending, and formwork/stamping/curing/keeping, etc., involved in making specimens have much in common. In this text of the committee's report, an outline of what is described in Part 1. RILEM test methods (Introduction) is given, and each test method (Parts 2 to 11) is described in the appendix.

4.3 Material properties of steel

Based on the three references (reference 7) to 9)) in the literature as main sources of information, the presence or lack of data such as stress-strain relationship, elastic modulus, yield strength, tensile strength, breaking elongation, creep property, heat conductivity/specific heat/linear expansion coefficient, etc., was studied according to each steel type (steel material, cable, bolt, etc.), and specified in the committee's report. As a result of data classification, the following problems became clear: the strain rate during the test greatly affects the result of the high temperature strength test; with regard to general steel materials, there are few data on steel plate, steel pipe and heat-treated steel; and there are few data on fire-resistant steel, stainless steel, PC and joints.

Although the committee tried to collect information on the fire resistance of reinforced joints and post-installed anchors, which are important elements for constituting reinforced concrete structures, in reality, there are few data available.

4.4 Explosive spalling of concrete

Discussions relating to resistance to structural fires and concrete explosive spalling have been active in foreign countries. For instance, the 1st International Conference on Concrete Explosive Spalling[10)] was held in Leipzig, Germany in September, 2009; Structures on Fire 2010[11)] was held in Michigan, USA in 2010; and the 2nd International Conference on Concrete Explosive Spalling[12)] was held in Delft, the Netherlands in October, 2011. WG 3 prepared an outline of the latest information, including information on concrete explosive spalling published at these international conferences, methods for measuring steam pressure and thermal stress which are supposed to cause explosive spalling, methods for monitoring explosive spalling, analytical examination of explosive spalling, explosive spalling prevention measures, etc.

4.5 Fire-resistive covering

The fire-resistive covering construction method has been applied to many buildings. On the other hand, as far as fire-resistive covering for civil engineering structures is concerned, cement-based or alumina/silica/calcia-based spray-type fire-resistive covering materials, calcium silicate-based or alumina-silica ceramic-based board-type fire-resistive covering materials, and other blanket-type fire-resistive covering materials are applied domestically.

With regard to fire-resistant test methods, in 1986, TNO (Fire Research Center of Building and Construction Research) published the "BI-86-69: Tunnel Fire Resistance Test Procedure," a test method for concrete slab made of fire-resistive covering material which is to be tested according to the fire curve specified by RWS (Rijkswaterstaat of the Netherlands). In 1998, RWS and TNO jointly prepared a more detailed test method, "1998-CVB-R1161 (revised edition 1): Tunnel Fire Resistance - Part I: Fire Resistance Test Procedure." Then, RWS and Efektis Netherlands (former TNO Fire Research Center) prepared the latest fire resistance test method for tunnel lining by taking advantage of ten or more years' experience with fire resistance tests in accordance with the procedure of this 1998-CVB-R1161 (revised edition 1). This test method is divided into the "Spalling Test" for checking the explosive spalling prevention effect on concrete by such measures as fire-resistive covering systems (spraying mortar, etc.) and addition of synthetic fibers (polypropylene fiber, etc.), and the "Thermal Insulation Test" to evaluate the heat insulation properties of and fixing methods for fire-resistive covering systems. The "Spalling Test" is further subdivided into the fire-resistive covering system construction method, and the explosive spalling prevention-type concrete construction method.

4.6 Repair materials

Materials for filling absent parts, such as polymer cement mortar and epoxy resin mortar, and surface coating materials for concrete surfaces, are used as materials for repairing RC structures. Among them, epoxy resin mortar and surface coating materials are mainly organic, and burn or disappears when subjected to high temperature or fire. On the other hand, polymer cement mortar is a material in which organic polymer is usually mixed in mortar, and although it shows high temperature physical properties similar to that of concrete, some difference is seen due to the effect of the polymer. WG 3 therefore carried out research on and collected past research data regarding physical properties, dynamic properties (compressive strength, Young's modulus, and attachment strength), burning properties, and explosive spalling behavior of polymer cement mortar under high temperature (including post-cooling).

With regard to the evaluation of explosive spalling resistance, there is no standardized simple test method, and a test method for explosive spalling resistance which can be carried out relatively simply as a screening test in choosing repair materials and developing materials is desired. WG 3 thus examined simple test methods for explosive spalling resistance of polymer cement mortar.

5. Conclusions

In order to verify the required performance of concrete structures on fire, it is necessary to estimate the behavior in a fire with great accuracy. In this context, WG 1 analyzed present data and abstracted problems as to fire action and fire response. With regard to fire action, although there are few problems relating to buildings, there exist no clear criteria or guidelines relating to road structures such as tunnels and bridges, and thus WG 1 indicated how to estimate the fire action for these. From now on, it is required to verify accuracy and adequacy.

With regard to fire response, one problem is that the transient strain value of concrete greatly affects the result of a behavior analysis. From now on, it is necessary to study how to set the value appropriately.

WG 1 also introduced the latest analysis cases and present techniques which may help make a fire-resistant design. Especially with regard to structures such as roads and railroads, even under the present conditions where the development of guidelines/specifications, master specifications, etc. is delayed, and the committee has worked to achieve the goal of providing useful information for professionals who make fire-resistant designs, it is difficult to say that the goal could be fully achieved. We hope that in future, guidelines/specifications, master specifications, etc., will be provided, and fire-resistant designs according to the required performance can be made.

On the other hand, the committee summarized the latest technologies as to inspections/diagnosis of concrete structures damaged by fire and repair/reinforcement, based on literature searches and discussions. This was possible because some fire damage cases were published in academic journals, etc. Cases of buildings where publication is highly likely to lead to disputes are especially difficult to find. The publication of cases is considered to greatly contribute to the improvement of future diagnostic techniques and countermeasures, and a mechanism to publish cases will have to be established in future.

For inspection techniques, it is desirable to develop techniques that enable easier diagnosis on site.

We would be delighted if you could apply the tentative proposal to actual fire damage cases, provide your own views, and draw on it as a source of information when preparing future guidelines (proposals) etc.

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