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Structural Concrete

Journal of the *fib*

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One of Netherland's most important north to south corridors is the A50 motorway and a part of it the Waal Bridge near Ewijk with a main span of 270 m. Build between 1971 and 1976, it is one of the longest bridge structures in the Netherlands. The Rijkswaterstaat, the executive arm of the Dutch Ministry of Infrastructure and the Environment, has decided to widen the A50 motorway between Ewijk and Valburg in both directions from two to four lanes each over a distance of 7 km. The entire project was carried out within the scope of a Design-Build contract. The consortium responsible for its execution and design is Waalkoppel, a consortium consisting of Mobilis, Van Gelder B.V. and DYWIDAG Bau GmbH. (see page A5 f)

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Fire resistance performance of steel composite hollow RC column with inner tube under ISO 834 standard fire

An internally confined hollow RC (ICH RC) column offers strong and durable confinement owing to the reinforcement provided by the inner tube. The strength and ductility of the column are enhanced because of the continuous confining stress provided by the inner tube. The excellent structural performance of ICH RC columns makes them particularly suitable for applications in high-rise buildings. However, if a high-rise building is damaged by fire, it will collapse without fire resistance performance. Also, lack of evacuation measures endangers human life. Thus, to predict the status of structures in fires, their behaviour should be evaluated in terms of fire time. In this study, the fire resistance performance of an ICH RC column was analysed during an ISO 834 standard fire and with certain initial conditions. Furthermore, the effects of hollow ratio, thickness of inner tube and thickness of cover concrete on the fire resistance performance were analysed. The results could be used for designing fire-resistant ICH RC columns.

Keywords: fire resistance, composite column, concrete, ISO 834, Eurocode

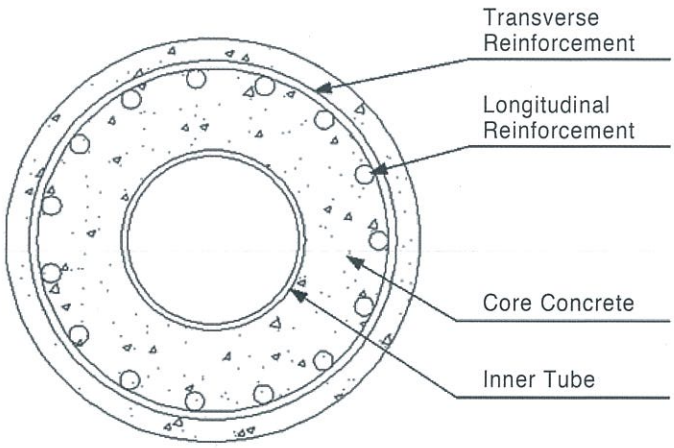

Fig. 1. Section through circular ICH RC column [1]

1 Introduction

Hollow RC columns are used as economical design elements because they use little material and are lightweight. However, they have poor ductility owing to brittle failure on the inner face of the column. The brittle failure of a hollow RC column originates from the lack of confinement of the core concrete because, generally, the core concrete of a hollow RC column is confined by the outer transverse reinforcement only or both the outer and the inner transverse reinforcement. To prevent this brittle failure, *Han* et al. [1] used an inner tube to reinforce the inner face of a hollow RC column, as shown in Fig. 1. This column is known as an internally confined hollow RC (ICH RC) column. It offers strong and durable confinement because of the reinforcement provided by the inner tube. The column's strength and ductility are enhanced because of the continuous confining stress provided by the inner tube. A non-linear concrete model and the compressive performance were analysed in an experimental study on an ICH RC column [1, 2]. In the study, the yielding and buckling failure conditions of the inner tube were considered as well.

The excellent structural performance of ICH RC columns makes them particularly suitable for use in high-rise buildings. However, if a high-rise building is damaged by fire, it will collapse without fire resistance performance. Also, lack of evacuation measures endangers human life [3]. Thus, for predicting the status of structures in fires, their behaviour should be evaluated in terms of fire time. In this study, the behaviour of ICH RC columns was analysed under the ISO 834 [4] standard fire. A heat transfer analysis was performed for predicting the temperature distribution due to the conduction of fire heat according to fire time. The ICH RC column's behaviour was characterized based on its temperature distribution.

2 Evaluation method for the fire resistance performance of an ICH RC column

2.1 Material properties

ICH RC columns consist of concrete, steel tube, transverse reinforcement and longitudinal reinforcement. To investigate column behaviour, we require material properties along with temperature. These properties can be divided into two groups: thermal material properties in terms of conduction of fire heat, and structural material properties in terms of change in material strength. The thermal material properties considered for investigating the conduc-

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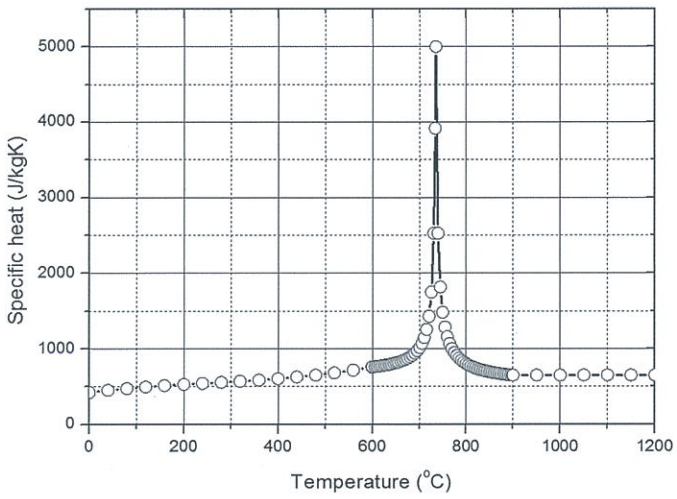
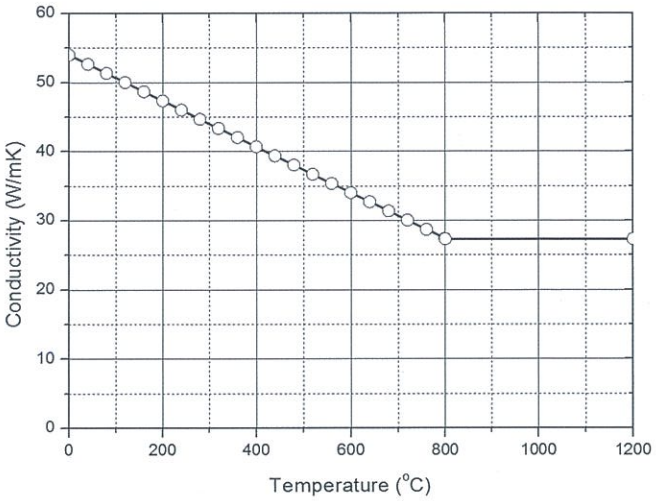
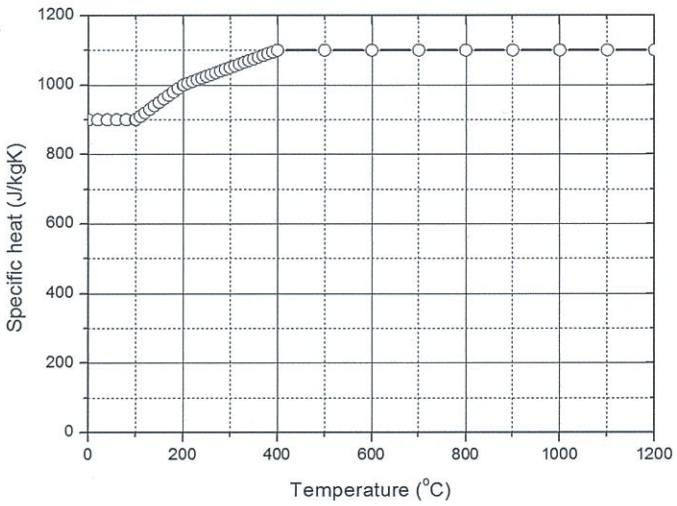


(a) Specific heat of steel

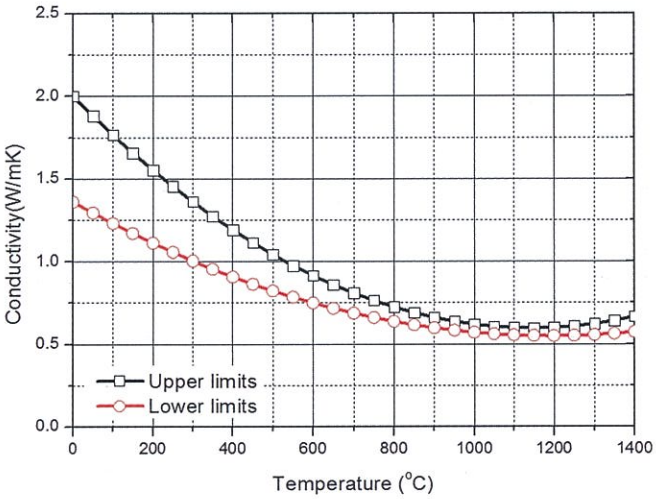


(b) Conductivity of steel

Fig. 2. Properties of steel according to Eurocode 3 [6]

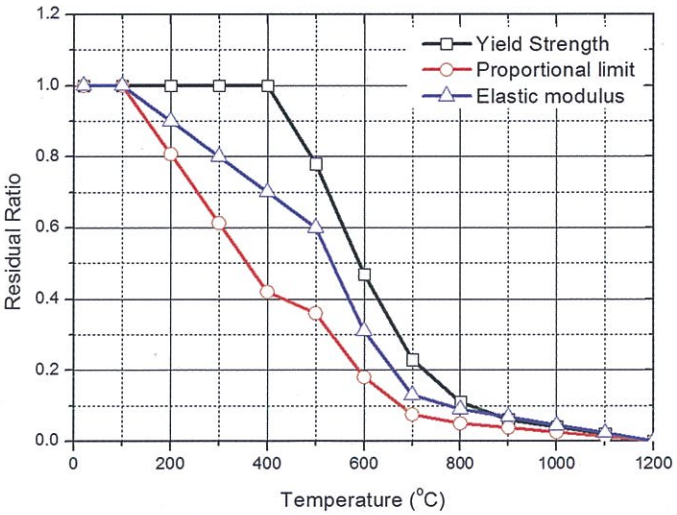


(a) Specific heat of concrete

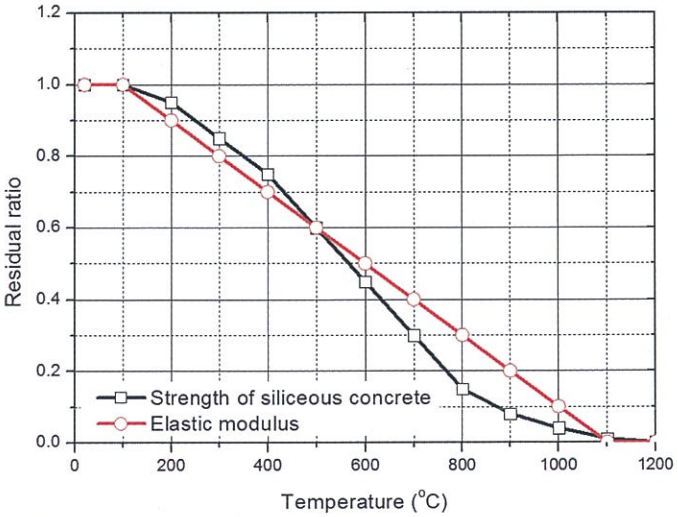


(b) Conductivity of concrete

Fig. 3. Properties of concrete according to Eurocode 2 [5]



(a) Steel properties in Eurocode 3 [6] and CEB code [7]



(b) Concrete properties in Eurocode 2 [6]

Fig. 4. Material properties in terms of temperature

tion of fire heat are representative of specific heat and conductivity. Eurocodes 2 [5] and 3 [6] list the material properties of steel and concrete respectively. Thermal material properties as shown in Figs. 2 and 3 apply for heat transfer analysis. Conductivity of concrete used the upper limit condition.

Structural material properties that depend on a change in temperature are the ultimate strength, yield strength, elastic modulus and compressive strength of concrete and steel. They are specified in Eurocodes 2 [5] and 3 [6] and in CEB code [7], as shown in Fig. 4.

2.2 Method of analysis for an ICH RC column

To predict the behaviour of an ICH RC column, a column analysis model is suggested in this study based on the *Han* et al. [1, 2] concrete model. This analysis tool is capable of axial load–bending moment interaction analyses. It uses section analysis, accounting for equilibrium, strain compatibility and material stress–strain curves, and adoptes the layer-by-layer technique for numerical integration of stresses (*Kilpatrick* and *Ranagan* [8]). The analyses are conducted for two conditions including a) unconfined

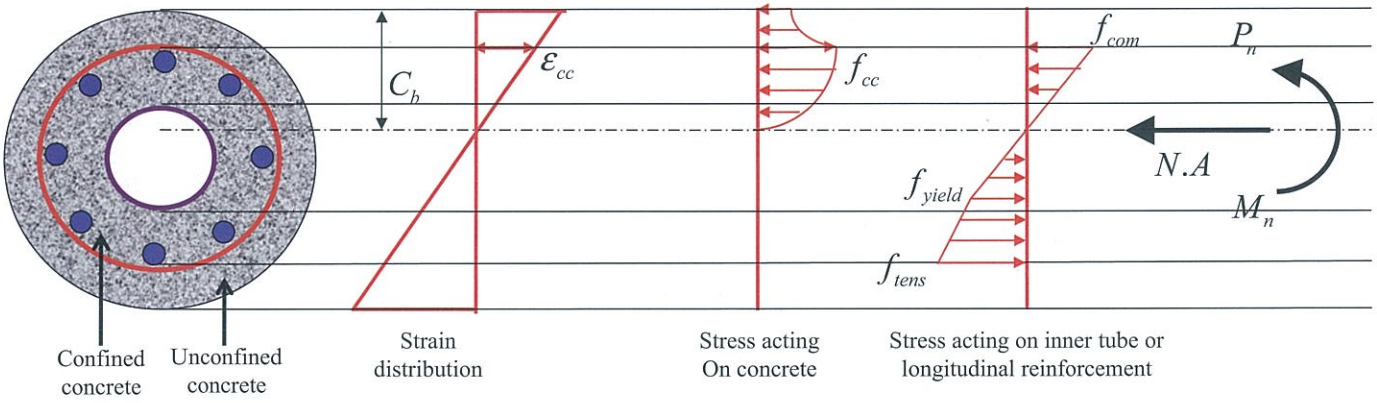


Fig. 5a. Section analysis using strain compatibility and layer-by-layer approach [2]

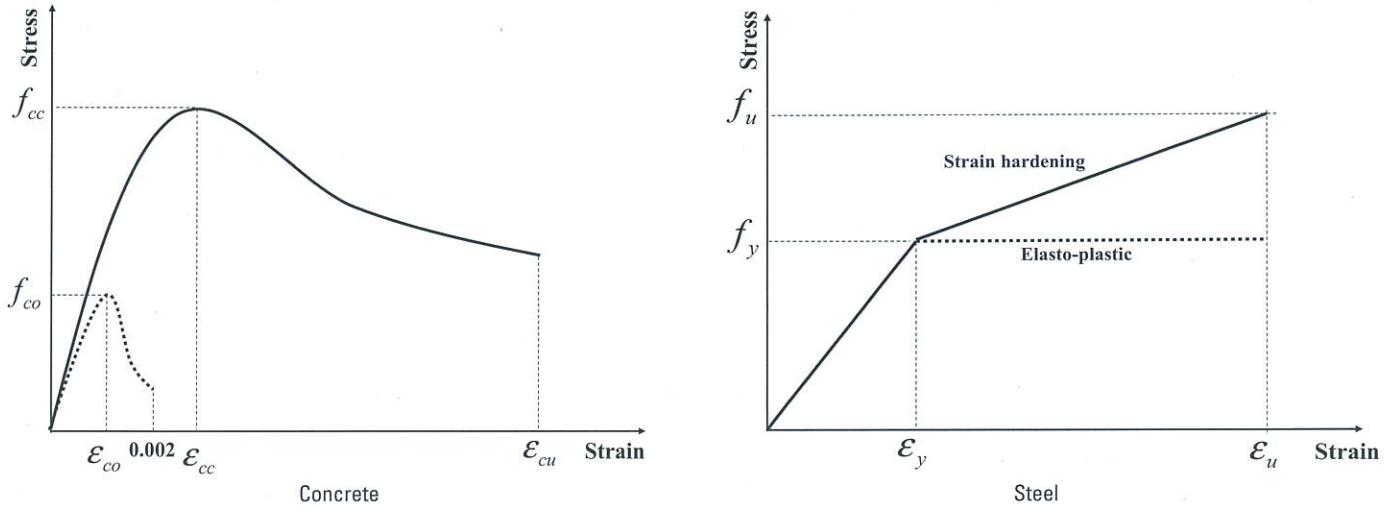


Fig. 5b. Idealized stress-strain curves [2]

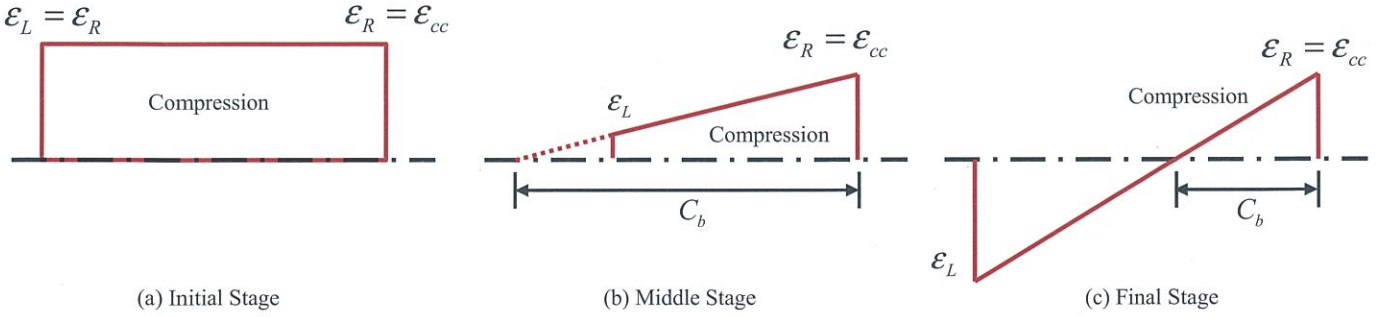


Fig. 5c. Stages of strain distribution [2]

concrete stress-strain curve and elasto-plastic steel behaviour and b) confined concrete stress-strain curve and accounting for strain hardening of the steel. Fig. 5a shows the idealized section, Fig. 5b the stress-strain curves adopted for concrete and steel. The analysis is performed at the stage of strain distribution as shown in Fig. 5c. The stresses acting on the concrete, longitudinal reinforcement and inner tube are calculated for each stage of strain distribution. By summating them, the axial load and the moment are calculated for each stage of the strain distribution; P_j and M_j are given by Eqs. (1) and (2) respectively:

$$P_j = P_j^{CC} + P_j^{CV} + P_j^R + P_j^T \quad (1)$$

$$M_j = M_j^{CC} + M_j^{CV} + M_j^R + M_j^T \quad (2)$$

where:

P_j axial load acting at jth stage of strain contribution
P_j^{CC} axial load acting on core concrete at jth stage of strain contribution
P_j^{CV} axial load acting on cover concrete at jth stage of strain contribution
P_j^R axial load acting on longitudinal reinforcement at jth stage of strain contribution
P_j^T axial load acting on inner tube at jth stage of strain contribution
M_j moment at jth stage of strain contribution
M_j^{CC} moment acting on core concrete at jth stage of strain contribution
M_j^{CV} moment acting on cover concrete at jth stage of strain contribution
M_j^R moment acting on longitudinal reinforcement at jth stage of strain contribution
M_j^T moment acting on inner tube at jth stage of strain contribution

The calculation procedure for the axial force-bending moment interaction for investigating the fire resistance performance of ICH RC column is shown in Fig. 6. After deducting the material properties in the ICH RC column

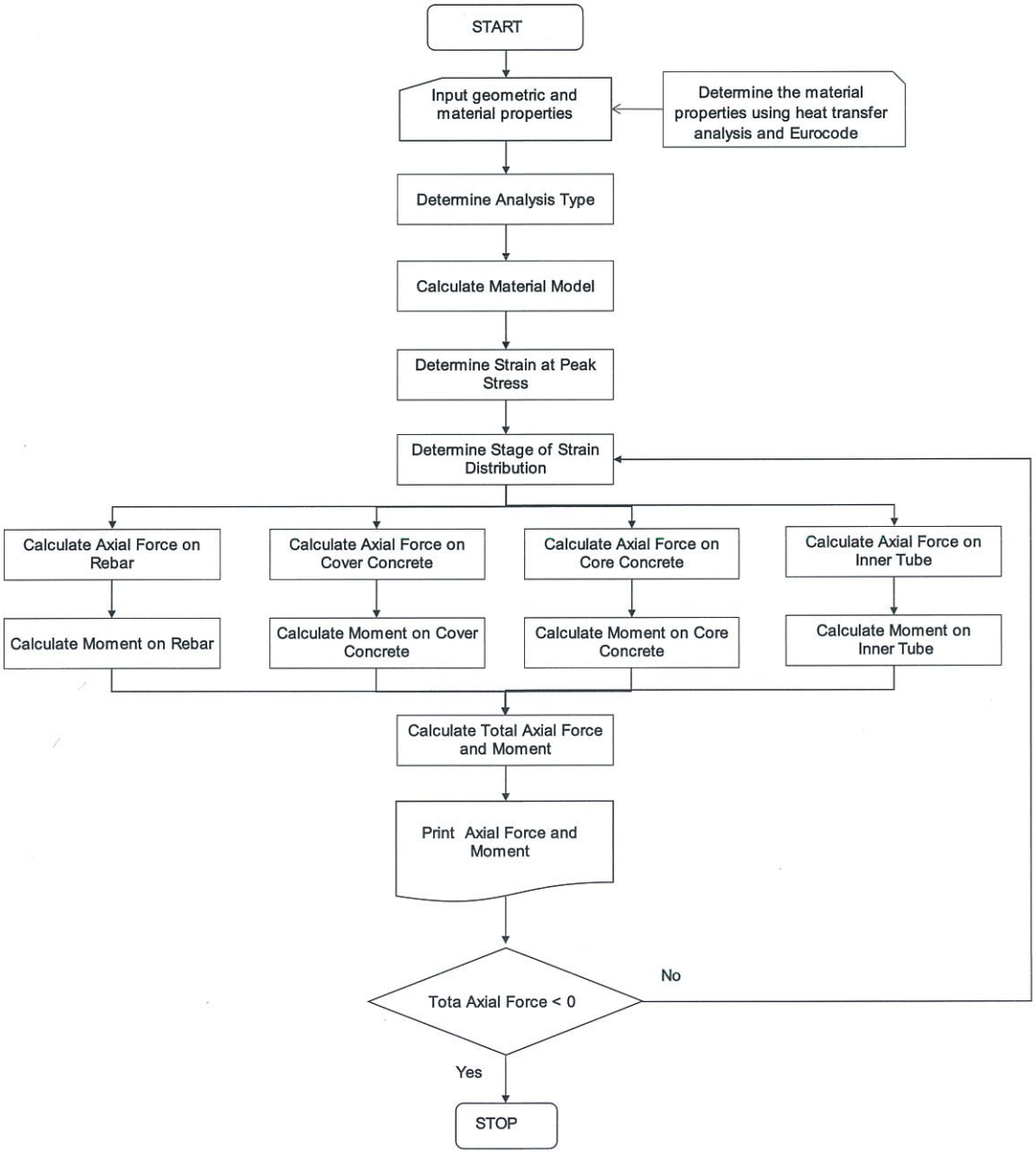


Fig. 6. Calculation procedure for axial load-bending moment interaction analyses [2]

using heat transfer analysis and the Eurocode, the material model and strain at peak stress are calculated. Interaction between axial force and bending moment can be calculated using the method suggested by *Han* et al. [2].

2.3 Heat transfer analysis and verification for application

In this study, a heat transfer analysis was performed in ABAQUS [9] to investigate the conduction of heat in terms of fire time after the onset of a fire. The basic energy balance for heat transfer analysis uses the theory of *Green* and *Naghdi* [9], expressed as Eq. (3). It is assumed that thermal and mechanical problems are uncoupled in the sense that $U = U(\theta)$ only.

$$\int_V \rho \dot{U} dV = \int_s q ds + \int_V r dV \tag{3}$$

where:

V volume of solid material of surface area S
ρ density of the material
$\dot{U}$ material time rate of internal energy
q heat flux per unit area of the body flowing into the body
r external heat supplied to the body per unit volume
θ temperature of the material

(q and r do not depend on the strain or displacement of the body)

DC2D4, a four-node linear heat transfer element, is used for representing steel and concrete. Furthermore, the thermal material properties for heat transfer analysis in a fire are the same as those described in the previous section. The average furnace temperature, measured using the thermocouples specified in the cotton pad test, is monitored and controlled such that it follows the relationship given by Eq. (4). This thermal load is applied uniformly to the column surface.

$$T = 345\log_{10}(8t + 1) + 20 \tag{4}$$

where T denotes the average furnace temperature in °C and t the time in minutes.

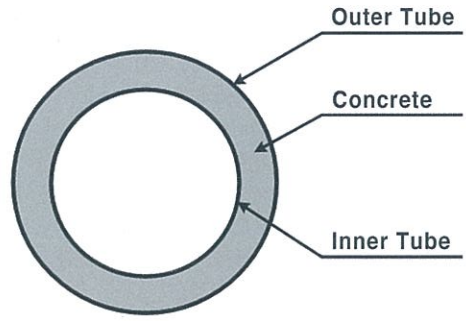


Fig. 7. Section through DSCT column [10]

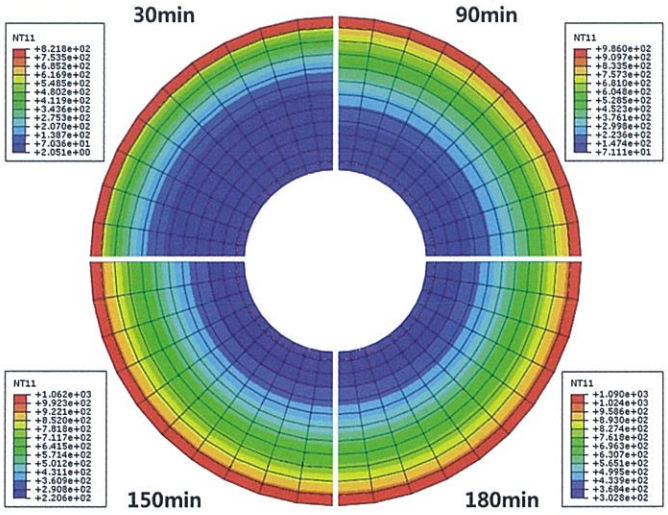
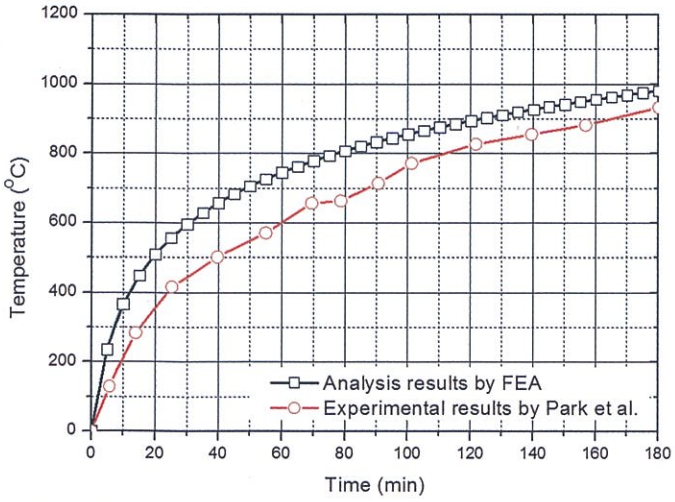


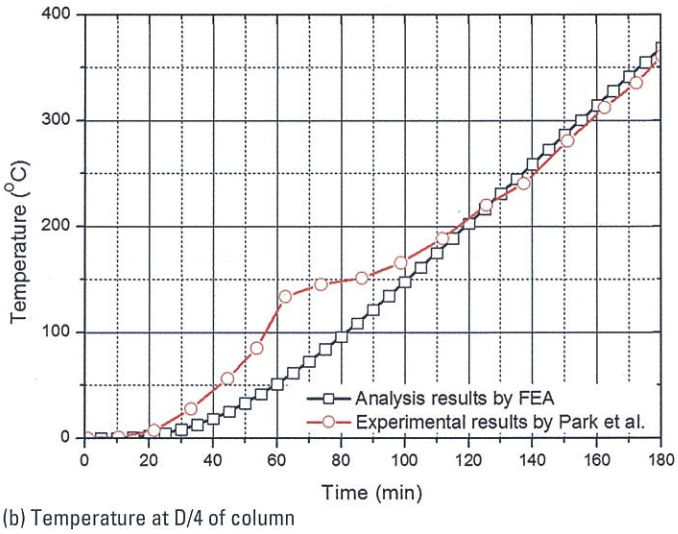
Fig. 8. Heat transfer analysis results of DSCT column

Table 1. Dimensions of DSCT column for verifying analysis method [9]

Diameter of column (mm)	406.4
Thickness of outer tube (mm)	9
Thickness of inner tube (mm)	7.1
Diameter of hollow section (mm)	150



(a) Temperature on outer concrete face



(b) Temperature at D/4 of column

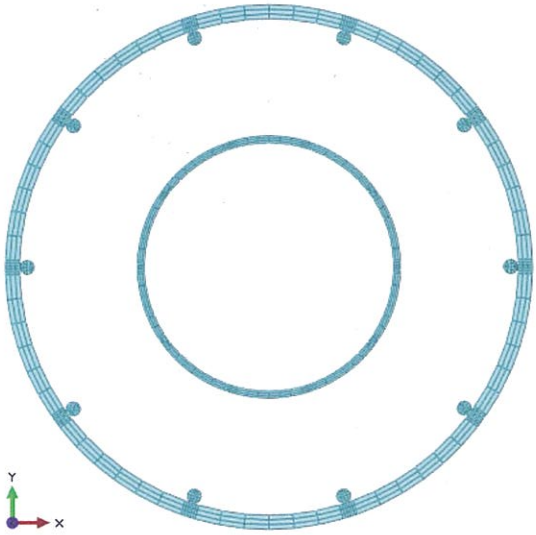
Fig. 9. Temperature of DSCT column

This heat transfer analysis method should be verified before applying it to the ICH RC column. In this paper, the analysis method is verified indirectly using another type of column as summarized and shown in Table 1 and Fig. 7 respectively because an experimental study of an ICH RC column in a fire has not yet been conducted. The dimensions of the double-skin composite tubular (DSCT) column, including those of the outer tube, concrete and inner tube, are listed in Table 1. The fire test was performed under an ISO 834 standard fire by *Park* et al. [10].

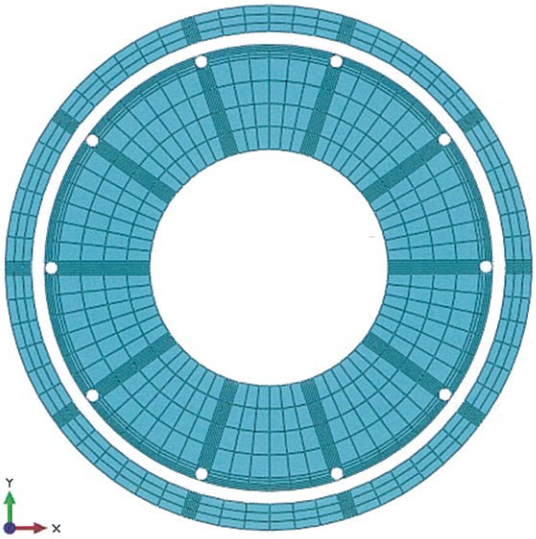
The heat transfer analysis is performed using the suggested thermal material properties and the DSCT column dimensions listed in Table 1. Fig. 8 shows the temperature distribution in the column during fire time at 30 min intervals. Fire heat is conducted to the hollow face from the surface of the outer tube. Figs. 9a and 9b show a comparison of the temperature changes at the outer surface of the concrete and D/4 of the diameter, as obtained in the heat transfer analysis performed in this study. The figures indicate that as time passes, the temperatures at outer concrete surface and D/4 of column diameter increase gradually, and the tendency for a temperature rise as obtained through heat transfer analysis is similar to that obtained experimentally [10]. The comparison results show that the analysis method is reasonable; thus, it can be used for investigating the conduction of fire heat in ICH RC columns comprising concrete, inner tube and steel reinforcement.

3 Fire resistance of ICH RC column

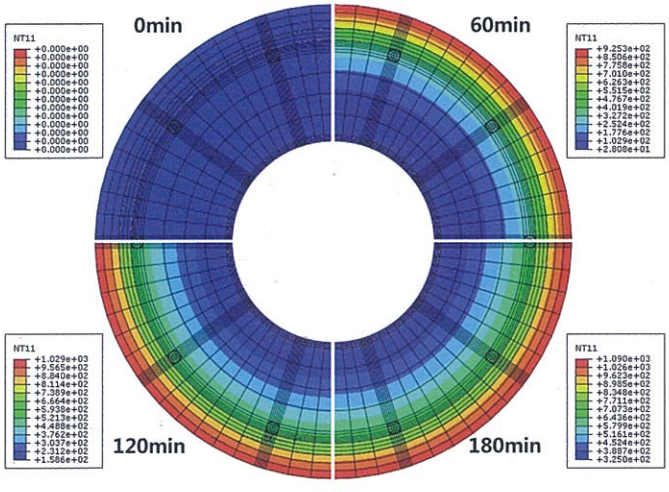
In this section, the heat transfer analysis of an ICH RC column under the ISO 834 standard fire [4] is performed using the FEA method verified in the previous section. Changes to the structural properties of the ICH RC column's component elements are derived based on the temperatures obtained from the heat transfer analysis. The compression and moment performance of the ICH RC column in terms of fire time are investigated. In addition, parametric studies are performed by selecting main parameters such as hollow ratio, depth of cover concrete and thickness of inner tube.



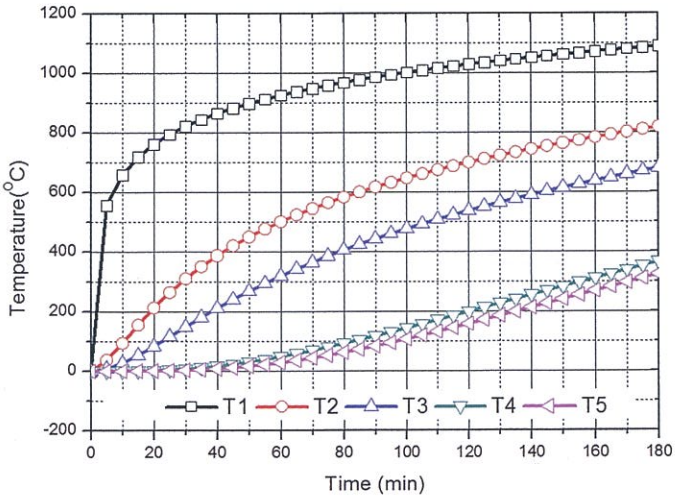
(a) Modelling of transverse reinforcement, longitudinal reinforcement and inner tube



(b) Modelling of cover concrete and core concrete



(c) Temperature distribution in ICH RC column in terms of fire time



(d) Temperature at each location

Fig. 10. Modelling of and temperature distribution in ICH RC column

3.1 Heat transfer analysis and behaviour of ICH RC column under ISO 834 standard fire

Table 2 lists the dimensions of the ICH RC column used for the heat transfer analysis. The diameter of the column is 400 mm, its hollow ratio is 0.5 and the thickness of the inner tube is 5 mm. Here, the hollow ratio is the ratio of the outer diameter of the transverse reinforcement to the inner diameter of the concrete. The thermal material properties given in section 2.1 are used for the heat transfer analysis. The type of element used for representing concrete, reinforcement and inner tube in the heat transfer analysis is DC2D4, a four-node, linear, solid element. Furthermore, ISO 834 standard fire [4] was applied as the thermal load on the surface of the ICH RC column.

All components are modelled individually. Fig. 10a shows the modelling of transverse reinforcement, longitudinal reinforcement and inner tube. Concrete is modelled as shown Fig. 10b. Fig. 10c shows the temperature distribution in the ICH RC column in terms of fire time at 60 min intervals. Fire heat is conducted to the inside of the ICH RC column with fire exposure time. Here, T1 denotes the surface of the cover concrete, T2 and T3 the transverse and longitudinal reinforcement respectively, T4 the concrete centre and T5 the inner tube. The change in temperature at each location is as shown in Fig. 10d. As the conductivity of concrete is very low, the cover concrete and core concrete delay fire heat conduction to the inside of the column. Therefore, the temperature at the centre of the core concrete is similar to the temperature of the inner tube, as shown in Fig. 10d.

Next, the structural behaviour of the ICH RC column under the ISO 834 standard fire is evaluated using structural material properties in terms of temperature, as shown in Fig. 4. Temperature by fire time is based on the results of the heat transfer analysis, and the structural material properties of the ICH RC column at room temperature are listed Table 3. These are standard values.

Tables 4–7 show the changes in the structural material properties of the ICH RC column components during a

Table 2. Dimensions of ICH RC column

Diameter of column (mm)	400
Thickness of cover concrete (mm)	20
Diameter of transverse reinforcement (mm)	10
Diameter of longitudinal reinforcement (mm)	10
Number of longitudinal reinforcing bars	10
Outer diameter of concrete (mm)	340
Inner diameter of concrete (mm)	180
Thickness of inner tube (mm)	5

Table 3. Material properties of ICH RC column at room temperature

Compressive strength of concrete (MPa)	30
Yield strength of steel reinforcement (MPa)	400
Elastic modulus of steel reinforcement (MPa)	200 000
Yield strength of steel tube (MPa)	320
Elastic modulus of steel tube (MPa)	210 000

Table 4. Material properties of longitudinal reinforcement based on fire time

Time (min)	Average yield strength (MPa)	Average ultimate strength (MPa)	Average elastic modulus (MPa)
0	400.00	500.00	200 000.00
30	400.00	500.00	190 416.70
60	400.00	481.81	156 362.20
90	364.02	364.02	131 821.60
120	270.68	270.68	100 670.63
150	181.29	181.29	59 484.50
180	122.55	122.55	37 457.72

Table 5. Material properties of transverse reinforcement based on fire time

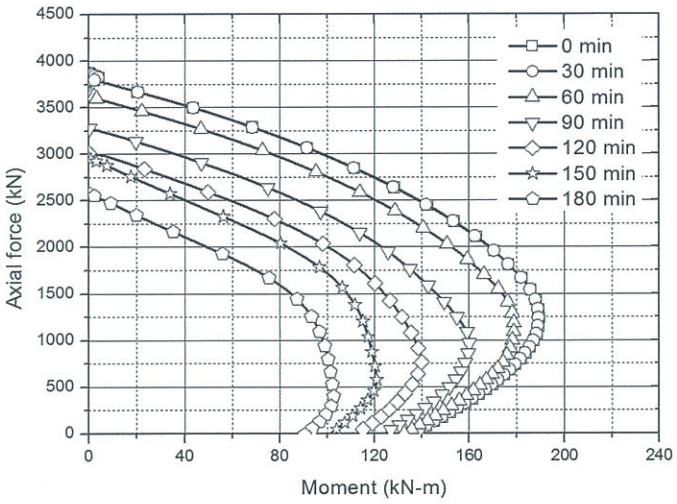
Time (min)	Average yield strength (MPa)	Average ultimate strength (MPa)	Average elastic modulus (MPa)
0	400.00	500.00	200 000.00
30	400.00	490.55	158 109.20
60	311.88	311.88	119 944.32
90	173.39	173.39	56 522.60
120	95.10	95.10	27 163.88
150	63.28	63.28	21 214.12
180	41.75	41.75	17 493.64

Table 6. Material properties of core concrete based on fire time

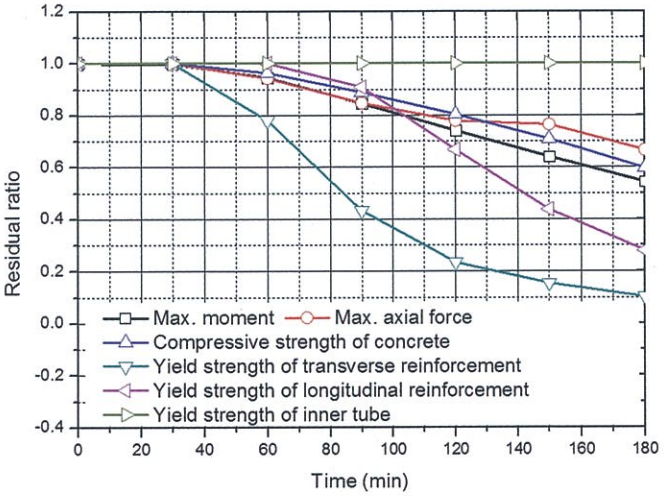
Time (min)	Average compressive strength (MPa)	Average elastic modulus (MPa)
0	30.00	28 577
30	30.00	28 577
60	29.08	28 577
90	27.20	28 072
120	24.72	25 735
150	22.24	23 314
180	18.83	20 949

Table 7. Material properties of inner tube based on fire time

Time (min)	Average yield strength (MPa)	Average ultimate strength (MPa)	Average elastic modulus (MPa)
0	320.00	400.00	210 000.00
30	320.00	400.00	210 000.00
60	320.00	400.00	210 000.00
90	320.00	400.00	210 000.00
120	320.00	400.00	197 685.81
150	320.00	400.00	180 293.09
180	320.00	380.02	162 755.36



(a) P-M interaction diagram for section



(b) Residual strength ratio in ICH RC column components

Fig. 11. Behaviour of ICH RC column based on fire time

fire. The material properties of steel and concrete based on fire exposure times were set as shown in Fig. 4.

Table 4 lists the material properties of the longitudinal reinforcement based on fire exposure time. Close to 90 min, the average yield strength of the longitudinal reinforcement begins to decline. It drops from 500 to 122 MPa at about 180 min. Furthermore, the average ultimate strength and average elastic modulus reach 122.52 and 37 457.72 MPa respectively.

The change rates of the material properties of the transverse reinforcement are larger than those for the longitudinal reinforcement, as shown in Fig. 4, because the transverse reinforcement is located outside the longitudinal reinforcement. At 180 min, the average yield and ultimate strength are both 41.75 MPa.

Table 6 shows the changes in the average compressive strength and average elastic modulus of the core concrete. Here, the average compressive strength of the core concrete decreased gradually from 30 to 18.83 MPa over the fire exposure time of 180 min. Material properties of the inner tube exhibit few decreasing rates because it is located inside the core concrete. Furthermore, the temperature of the inner tube was about 300 °C at 180 min. Table 7 lists the structural material properties of the inner tube by fire time. Only the average elastic modulus changes because it is located inside the core concrete, which delays the conduction of fire heat.

The performance of the ICH RC column is evaluated using changes to the structural material properties of the components, which are listed in Tables 4–7. The P-M interaction diagram of the ICH RC column, shown in Fig. 11a, is drawn for 30 min intervals. Axial and moment performance decreases as fire exposure time passes. The residual strength, axial strength and moment performance of the ICH RC column are compared in Fig. 11b. The change rates of the maximum moment and maximum axial performance show similar tendencies to the change rate of the core concrete's compressive strength.

3.2 Parametric studies

In this section, the fire resistance performance of the ICH RC column is investigated through parametric studies considering hollow ratio, thickness of cover concrete and thickness of inner tube. The fire resistance of the ICH RC column is evaluated through parametric studies based on the method suggested in the preceding section.

3.2.1 Hollow ratio

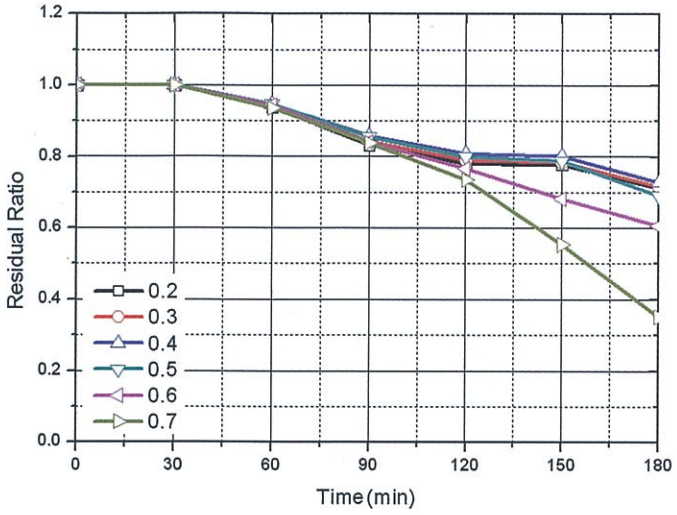
Table 8 lists the dimensions of the analysis models in terms of hollow ratio, i.e. ratio of core concrete outer and inner diameters. The effect of the hollow ratio is investi-

Table 8. Dimensions of analysis models by hollow ratio

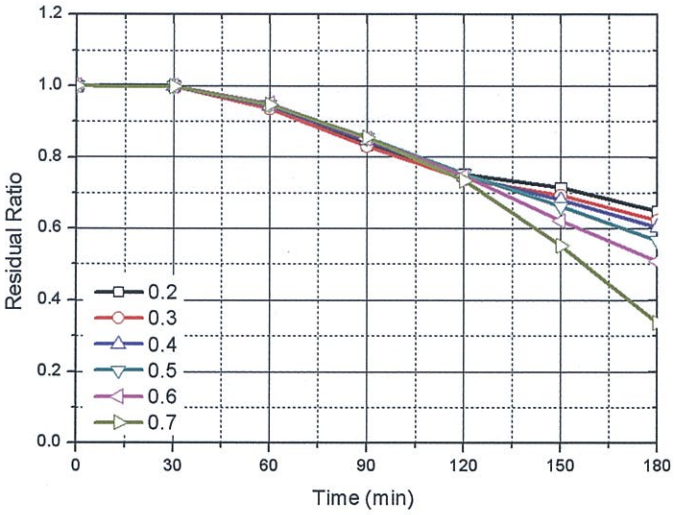
Hollow ratio	0.2	0.3	0.4	0.5	0.6	0.7
Diameter of hollow section (mm)	62	98	134	170	206	242
Thickness of cover concrete (mm)	20					
Diameter of transverse reinforcement (mm)	10					
Thickness of inner tube (mm)	5					
Diameter of longitudinal reinforcement (mm)	10					
Number of longitudinal reinforcing bars	10					
Diameter of column (mm)	400					

gated by varying it from 0.2 to 0.7, whereas the other dimensions of the analysis models are maintained at their original values.

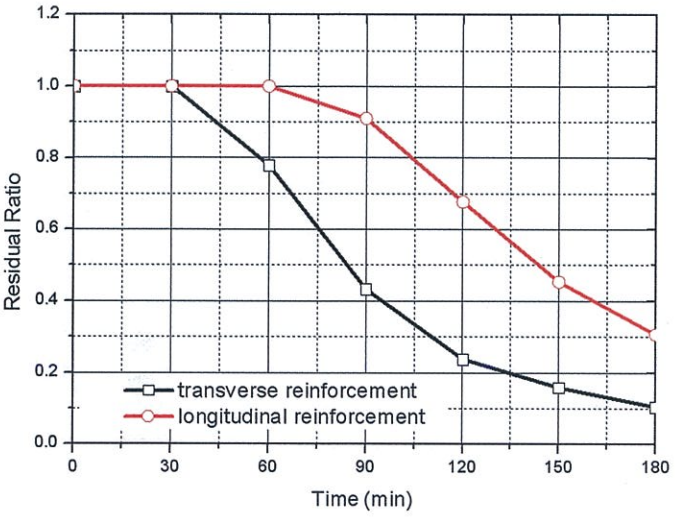
Figs. 12a and b show the residual maximum moment ratio and residual maximum axial force respectively. The hollow ratio is changed from 0.2 to 0.7, which degrades



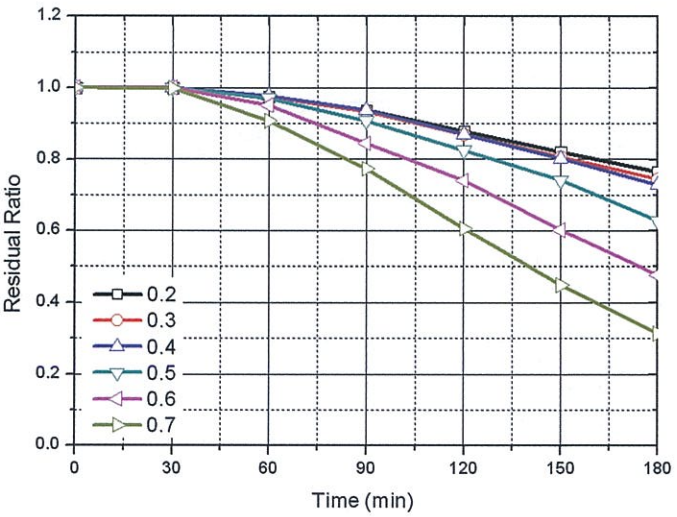
(a) Residual maximum moment ratio



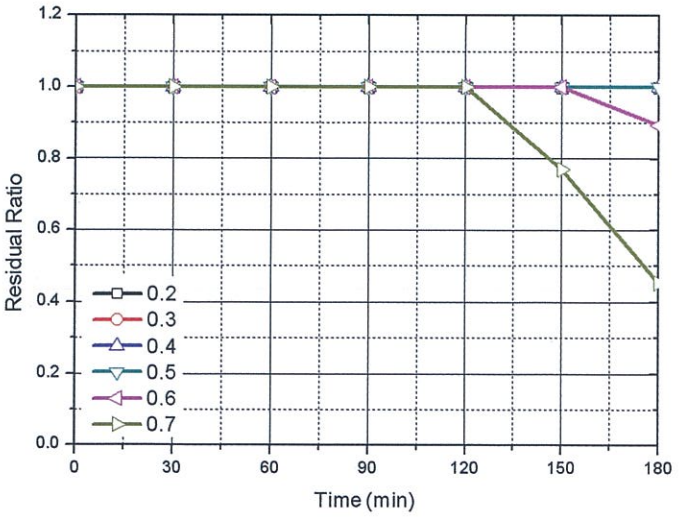
(b) Residual maximum axial force ratio



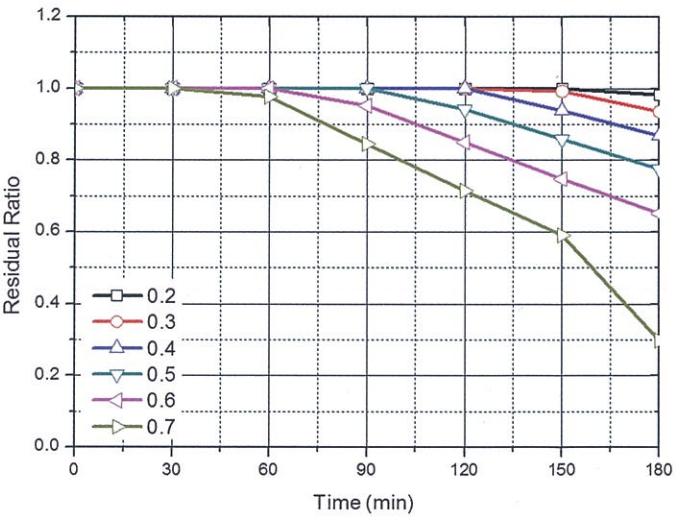
(c) Residual yield strength ratio of transverse and longitudinal reinforcement



(d) Residual compressive strength ratio of core concrete



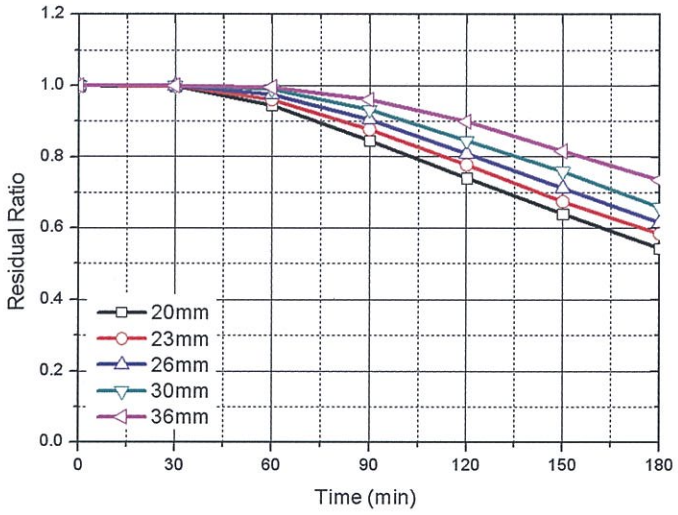
(e) Residual yield strength ratio of inner tube



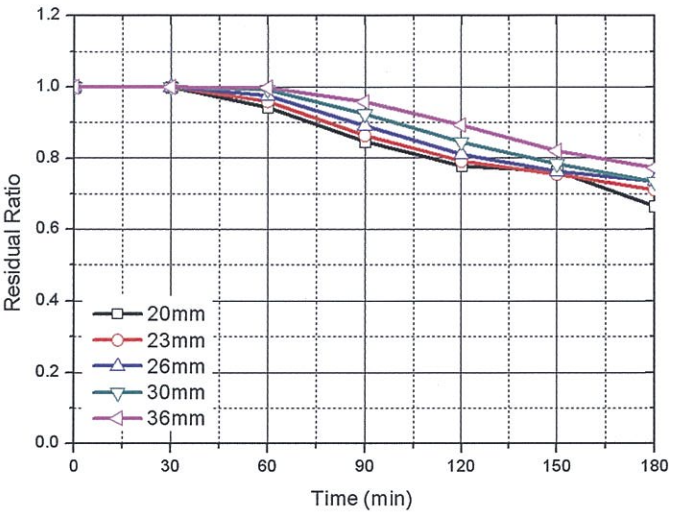
(f) Residual elastic modulus ratio of inner tube

Fig. 12. Residual strength ratio of ICH RC column by hollow ratio

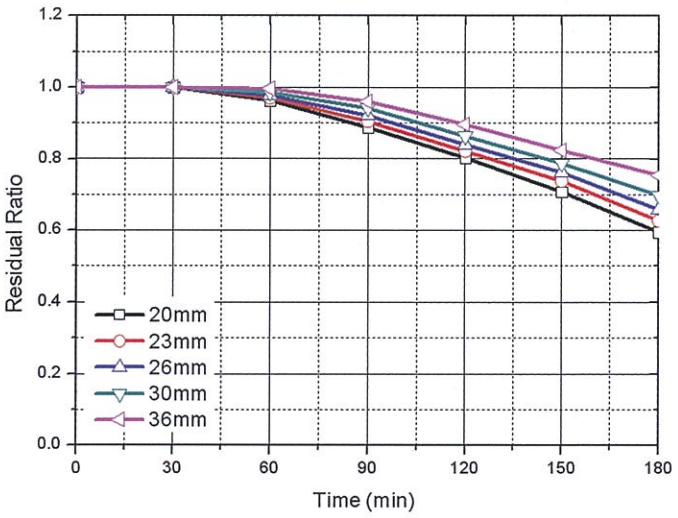
column performance. This behaviour of the ICH RC column is ascribed to the effect of the core concrete. The tendency of the core concrete's residual compressive strength ratio is similar to those of the residual moment and the axial force ratio, as shown in Fig. 12d. Damage to the ICH RC column due to fire increases as the hollow ratio in-



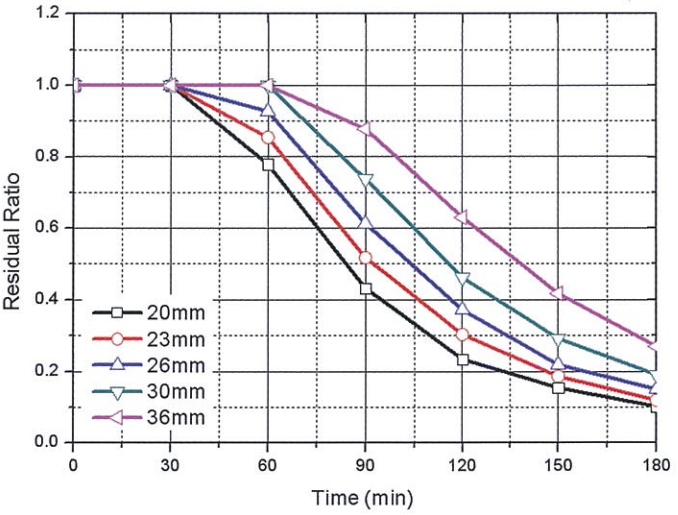
(a) Residual maximum moment ratio



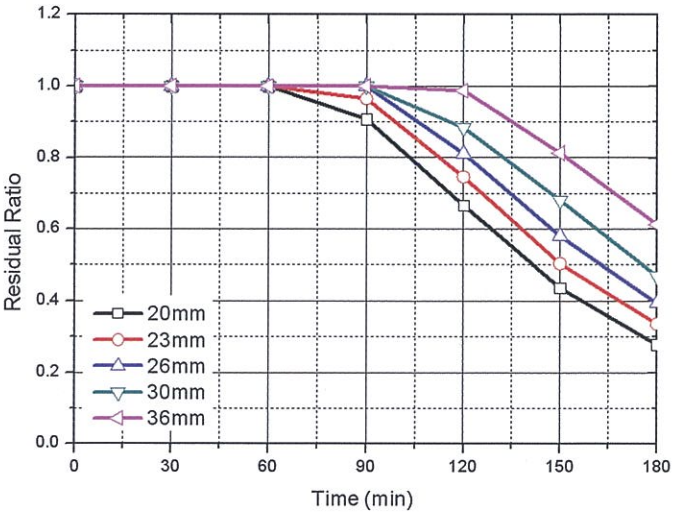
(b) Residual maximum axial force ratio



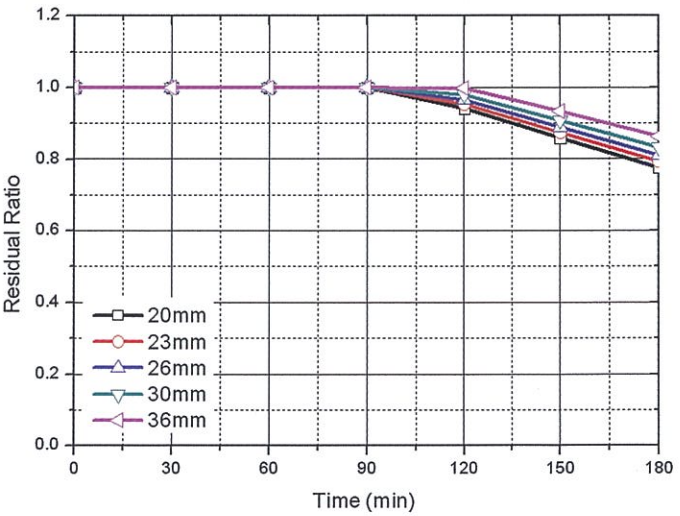
(c) Residual compressive strength ratio of core concrete



(d) Residual yield strength ratio of transverse reinforcement



(e) Residual yield strength ratio of longitudinal reinforcement



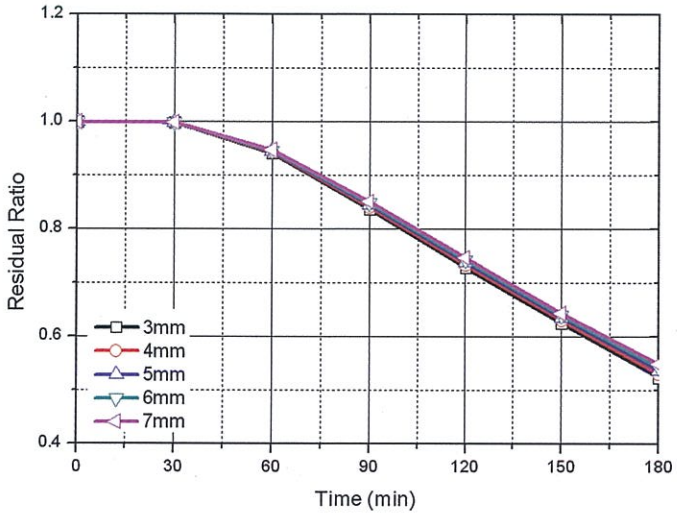
(f) Residual elastic modulus ratio of inner tube

Fig. 13. Residual strength ratio of ICH RC column by thickness of cover concrete

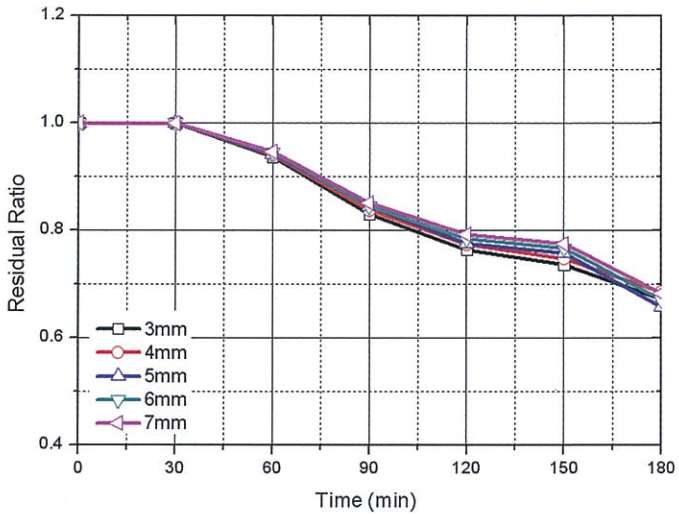
creases because the thickness of the core concrete decreases. In addition, the residual yield strength ratio of the transverse and longitudinal reinforcement decreases, as shown in Fig. 12c. The residual ratio of all the models is identical because only the inner diameter of the core concrete is changed. Additionally, the yield strength of the inner tube does not decrease despite its temperature reaching 300 °C owing to the fire.

Table 9. Dimensions of analysis models based on cover concrete thickness

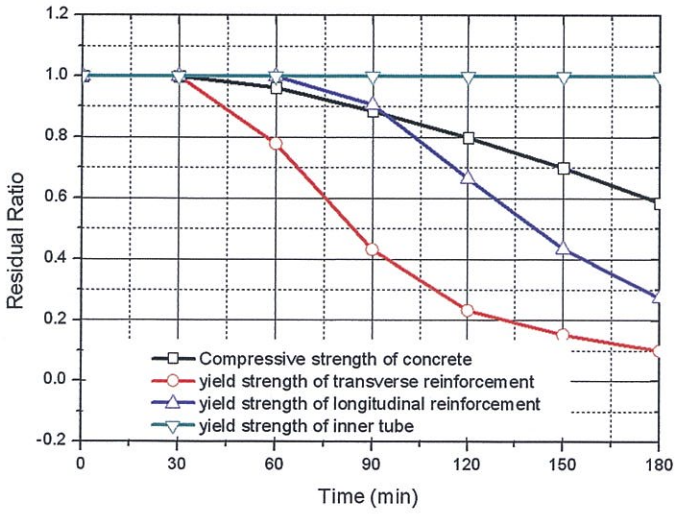
Thickness of cover concrete (mm)	20	23	26	30	36	20
Hollow ratio	0.5					
Diameter of transverse reinforcement (mm)	10					
Thickness of inner tube (mm)	5					
Diameter of longitudinal reinforcement (mm)	10					
Number of longitudinal reinforcing bars	10					
Diameter of column (mm)	400					
Diameter of hollow section (mm)	170					



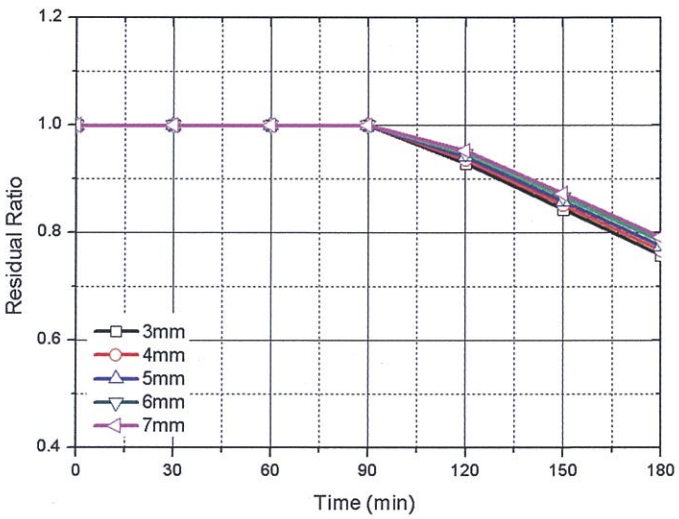
(a) Residual maximum moment ratio



(b) Residual maximum axial force ratio



(c) Comparison of residual strength ratio



(d) Residual elastic modulus ratio of inner tube

Fig. 14. Residual strength ratio of ICH RC column by thickness of inner tube

Table 10. Dimensions of analysis models based on inner tube thickness

Thickness of inner tube (mm)	3	4	5	6	7
Diameter of hollow section (mm)	164	168	170	172	174
Hollow ratio	0.5				
Diameter of transverse reinforcement (mm)	20				
Thickness of cover concrete (mm)	10				
Diameter of longitudinal reinforcement (mm)	10				
Number of longitudinal reinforcing bars	10				
Diameter of column (mm)	400				

3.2.2 Thickness of cover concrete

Next, the thickness of the cover concrete is varied for investigating the fire resistance of the ICH RC column, as summarized in Table 9. It is changed from 20 to 36 mm, whereas the other dimensions of the models are maintained at their original values.

Figs. 13a and b show, respectively, the residual moments and the axial force of the ICH RC column. The damage rate of the ICH RC column decreases as the thickness of the cover concrete increases. The cover concrete delays the conduction of fire heat. As shown in Figs. 13d and e, the transverse and longitudinal reinforcement reach a high temperature and their yield strength decreases rapidly because they are located outside the column, unlike the cover concrete. If the confining effect of the transverse reinforcement on the concrete is considered, the strength of the confined concrete would decrease rapidly because reduction of the yield strength of the transverse reinforcement. In addition, the elastic modulus of the inner tube decreases slowly after 90 min.

3.2.3 Thickness of inner tube

Table 10 lists the dimensions of the analysis models in terms of the inner tube thickness, which is changed from 3 to 7 mm in steps of 1 mm. Other dimensions of the analysis models are maintained at their original values.

As shown in Fig. 14, the rate of decrease of the residual strength falls as the thickness of the inner tube is increased from 3 to 7 mm. However, the yield strength of the inner tube does not decrease, as shown in Fig. 14c. This improvement in performance is an effect of increasing the inner tube thickness.

4 Summary and conclusions

In this study, the fire resistance performance of an ICH RC column was investigated using an analytical Eurocode method. In addition, the effects of changing hollow ratio, thickness of inner tube and thickness of cover concrete on fire resistance performance were analysed. The following conclusions can be drawn:

(1) As the hollow ratio is increased, so the fire resistance performance improves. This behaviour of the ICH RC column is ascribed to the effect of the core concrete. The residual compressive strength ratio of the core concrete has a tendency similar to those of the residual moment and the axial force ratio. Damage to an ICH RC column by fire increases as the hollow ratio increases, which is ascribed to a decrease in core concrete thickness.
(2) The damage rate of an ICH RC column decreases as the cover concrete thickness increases because the cover concrete retards the conduction of fire heat. Therefore, the fire resistance performance of an ICH RC column can be improved by increasing the cover concrete thickness.
(3) The fire resistance performance of an ICH RC column suffers as the thickness of the inner tube is decreased. The reduced performance is a result of decreasing the inner tube thickness.

Acknowledgments

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