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An experimental study on fire resistance of medical modular block

Hyung-Jun Kim[1a], Jae-Sung Lee[2b], Heung-Youl Kim[3c], Bong-ho Cho[*4], Yunping Xi[5d] and Ki-hyuck Kwon[6e]

[1] Fire Safety Research Center, Korea Institute of Construction Technology, 64, Mado-ro 182beon-gil, Mado-myeon, Hwaseong-si, Gyeonggi-do, 445-861, Republic of Korea
[2] Department of Architectural Engineering, Hannam University, 70, Hannam-ro, Daedeok-gu, Daejeon 306-818, Republic of Korea
[3] Fire Safety Research Center, Korea Institute of Construction Technology, 64, Mado-ro 182beon-gil, Mado-myeon, Hwaseong-si, Gyeonggi-do 445-861, Republic of Korea
[4] Department of Architectural Engineering, Ajou University, 206, World cup-ro, Yeongtong-gu, Suwon-si, Gyeonggi-do, 443-749, Republic of Korea
[5] Department of Civil, Environmental, and Architectural Engineering, University of Colorado, 1800 Grant Street, Suite 800, USA
[6] Department of Architecture Engineering, University of Seoul, Seoul city, Republic of Korea

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Abstract. Fire performance and fire safety of high-rise buildings have become major concerns after the disasters of World Trade Center in the U.S. in 2001 and Windsor tower in Spain in 2005. Performance based design (PBD) approaches have been considered as a better method for fire resistance design of structures because it is capable of incorporating test results of most recent fire resistance technologies. However, there is a difficulty to evaluate fireproof performance of large structures, which have multiple structural members such as columns, slabs, and walls. The difficulty is mainly due to the limitation in the testing equipment, such as size of furnace that can be used to carry out fire tests with existing criteria like ISO 834, BS 476, and KS F 2257. In the present research, a large scale calorie meter (10 MW) was used to conduct three full scale fire tests on medical modular blocks. Average fire load of 13.99 kg/m² was used in the first test. In the second test, the weighting coefficient of 3.5 (the fire load of 50 kg/ m²) was used to simulate the worst fire scenario. The flashover of the medical modular block occurred at 62 minutes in the first test and 12 minutes in the second test. The heat resistance capacity of the external wall, the temperatures and deformations of the structural members satisfied the requirements of fire resistance performance of 90 minutes burning period. The total heat loads and the heat values for each test are calculated by theoretical equations. The duration of burning was predicted. The predicted results were compared with the test results, and they agree quite well.

Keywords: full-scale fire test; modular block; fire load; fire resistance

*Corresponding author, Professor, Ph.D., E-mail: bhcho@ajou.ac.kr
[a] Researcher, E-mail: kimfestival@kict.re.kr
[b] Professor, Ph.D., E-mail: jaesung@hnu.kr
[c] Fellow Researcher, Ph.D., E-mail: hykim@kict.re.kr
[d] Professor, E-mail: yunping@colorado.edu
[e] Professor, E-mail: khkwan@uos.ac.kr

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1. Introduction

The research on fire safety of buildings was started in Europe in the mid-1600s and was focused on developing evaluation criteria and technologies related to structural members under various types of fire (Wald *et al*. 2009). Numerous full-scale fire tests were conducted, such as Churchill fire test conducted in England in 1986 (Lawson *et al*. 1997), Broadgate fire test in England in 1991 (Steel Construction Industry Forum 1991), Collin street fire test in Australia in 1992 (Thomas *et al*. 1992), and William street fire test in Australia in 1994 (Proe and Bennetts 1994). In these fire tests, dynamic behaviors of the building fires were analyzed. One of the dynamic behaviors is the change in the loading path that is an important phenomenon occurring during building fire in which a non-load-bearing wall becomes a load-bearing wall (Park *et al*. 2010). BRE (Building Research Establishment) in Cardington conducted seven full-scale fire tests with eight-story buildings (45 m × 21 m) to develop technologies to improve fire resistance of the structure (Wald *et al*. 2006). The primary goal of the design methods is to ensure that the fire resistance rating of the structures satisfies the requirement of national building codes (Lee *et al*. 2008).

The fire design methods for buildings in South Korea were developed based on the result of standard fire tests for various structural members. These design methods are not only uneconomic but also inefficient because the fire protections provided by the design methods are only conducted by the specific protection methods defined for each member without application of the performance-based design (PBD) method. The fire design methods based on the results of standard fire tests for structural members did not consider the new improvement in fire safety technologies, which are considered in the Performance-based design method (Sun *et al*. 2012). Therefore, many countries considered the PBD criterion as a more efficient and economic fire safety design criterion for buildings (Department of Building Housing 2011). For example, in New Zealand, an ‘Acceptable Solution’ was recommended in order to conduct the fire safety design using a performance-based code (BIA 1992). The “acceptable solution” was actually referenced to the guidelines developed in several countries, such as Australia (ABCB 1996), Sweden (SBBHP 1994), England (HMSO 1985), and USA (IFCI 2000).

The basic process for a PBD method is shown in Fig. 1, in which the following items must be considered.

- Minimum required thickness and shape of structure members based on the period of fire
- Load bearing performance of the structure and various structure members
- Minimum covering thickness of concrete and condition for arranging the re-bar
- Minimum passive fire protection of steel members

To conduct a performance-based fire resistance design for a building, a fire scenario should be selected first, which is primarily the fire load (fire severity) and fire period depending on the purpose and the current status of the building. Based on the selected fire severity, the period of the fire can be calculated and the time to maintain the fire resistance performance of the structure can be predicted using available experimental data or a theoretical equation (Iqbal and Harichandran 2011). The procedure of PBD methods can be summarized as three phases.

Determination of the fire scenario

Determination of the fire scenario is the most important stage to evaluate the fire resistance performance of the structure. The fire scenario is affected by the fire source, the fire load, the period of the fire and so on. If the inflammables in the target building are defined, and the mass,

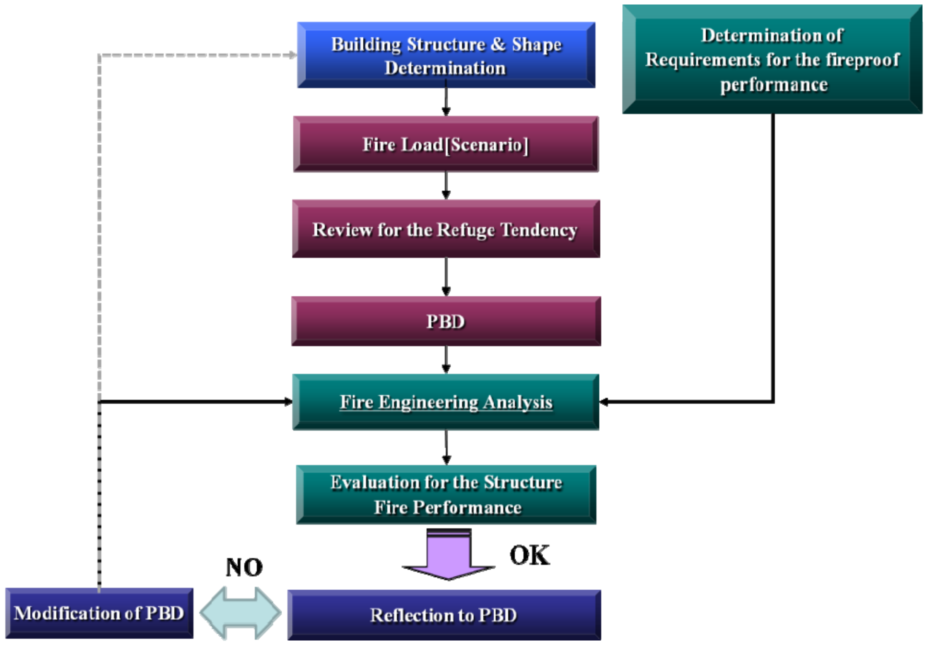


Fig. 1 Design strategy for performance-based fire protection of a structure

the calorie, the maximum amount of emitted heat, and the time of the growing fire are prescribed, the performance fire scenario can be yielded by calculating the period of the fire (Buchanan 2001a). Unless there is objectivity in the assumptions made for a fire scenario, the results for the fireproof performance are not reliable.

Determination of the fire load and prediction of flashover

The fire load by the inflammables in the building varies according to the purpose of the building. In order to apply a PBD method, the coefficients for inflammables are used. Using the coefficients, the worst fire scenario can be assumed. The time for flashover should be predicted in order to apply the maximum time to refuge related to building collapse. For the prediction, the condition of ventilation such as the size of the opening and the period of fire should be determined with the fire source. The flashover can be defined objectively using conventional equations (Buchanan 2001a).

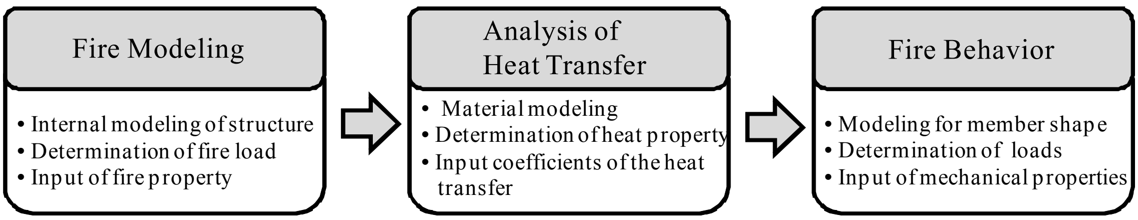


Fig. 2 Numeric analysis process of the fire resistance performance

Evaluation for the fire resistance performance of structures

To conduct a PBD, a numeric analysis or an experimental study should be conducted. Fig. 2 shows the process of numeric analysis for fire resistance performance of structures.

The mathematical equations for calculating the fire resistance performance of steel structure members can be obtained by using section shape coefficients that are related to the fire exposure conditions of the members. (Buchanan 2001a).

Since the mid-1980s, BRE (Building Research Establishment) in England, SP (Science Partner) in Sweden, and BRI (Building Research Institute) in Japan have adopted a performance-based approach as the fire safety evaluation method. Since then, PBD method has been considered as a more important method especially for high-rise buildings and large span structures. In South Korea, PBD method has not been incorporated in fire design code, and thus, there has been a pressing need to improve fire design codes on the basis of PBD. In order to do so, full-scale fire tests must be performed to provide sufficient results for PBD of various fire protection technologies (Carden and Itani 2007). Large-scale fire tests have not been conducted due mainly to the financial limitation and availability of test equipment in South Korea. One of the purposes of this study is to evaluate the fire resistance of a four-story modular building (called modular block) under a natural fire condition by using PBD. The modular block is a steel structure with a length of 6.7 m, width 3.75 m and height 3.6 m. Another purpose of the study is to evaluate the effectiveness of the fire protection materials used in the modular block. The uniformly distributed loads on the upper floor of the modular block were the dead load of three floors (279.7 kN) and a live load (136.9 kN). To ventilate the smoke from the large scale test under the natural fire condition using woods, a large scale calorimeter (10 MW) was used.

2. Fire tests of the modular block

In South Korea, the building fire codes present specific fire protection requirements according to building usage at member level such as beam, column and slab without consideration of PBD. This fire test using various codes can be considered as a valuable study to introduce PBD code in South Korea. The codes of SNIP 21-01-97, GOST 30247.0, GOST 30247.1, BNP 233-96 and ISO 834-1 were referred to the test set-up and were used to evaluate the fire resistance of the modular block. The target fire performance time of the modular block to be used in a hospital building is 90 minutes under the evaluation criteria as shown in Table 5.

Two fire tests were conducted under the natural fire condition. The first test was conducted to evaluate the fire resistance performance of the modular block under the fire load with 1.0 of fire load coefficient (Kim *et al*. 2009a). The second test assuming the worst fire scenario with 3.5 of the fire load coefficient was performed to compare with the results of the first test.

The conditions of fire source were adjusted as shown in Fig. 3. The performance-based evaluation was conducted through the determination of the fire scenario, the prediction of the flashover related to the fire load, and the analysis of the experimental results.

2.1 Fire resistance materials and geometry of the modular block

The modular block (length 6.7 m, width 3.75 m and height 3.6 m, Window: L X H = 1.78 m × 1.8 m) used in the experimental study is a unit module of prefabricated hospital building. The unit

Table 1 Structural profile of members

Classification	Sections	Material	Yield strength (MPa)	Ultimate strength (MPa)
Floor long beam	MCO200 × 120 × 6T[1)]	SPA-H (KS D 3542)	380	510
Floor short beam	MCO200 × 120 × 6T1)	SPA-H (KS D 3542)	380	510
Floor joist	Rect.Pipe 150 × 100 × 4.5T	SS400 (KS D 3503)	278	362
Joist (Long Wall)	Rect.Pipe 75 × 75 × 4.5T	SS400 (KS D 3503)	278	362
Joist (Short Wall)	Rect.Pipe 75 × 75 × 6T	SS400 (KS D 3503)	278	362
Ceiling long beam	Rect.Pipe 150 × 75 × 4.5T	SS400 (KS D 3503)	278	362
Ceiling short beam	Rect.Pipe 150 × 75 × 4.5T	SS400 (KS D 3503)	278	362
Ceiling Joist	Rect.Pipe 125 × 40 × 3.2T	SS400 (KS D 3503)	278	362
Brace	Plate 100 × 6T	SS400 (KS D 3503)	278	362
Corner Column	Rect.Pipe 150 × 75 × 6T	SS400 (KS D 3503)	278	362

[1)] MCO is a new shape for beam of modular block developed by RIST. Section shape is shown in Fig. 4(b) and Reference (Lee *et al*. 2008)

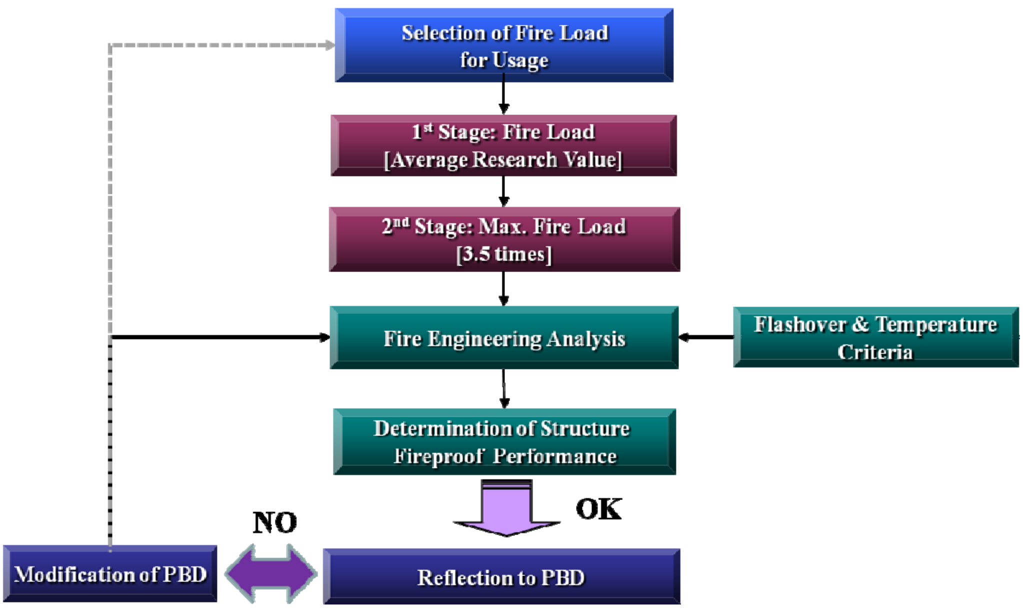
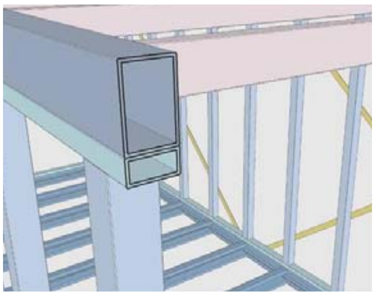
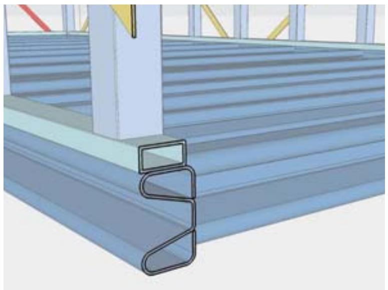


Fig. 3 PBD procedure for the modular block

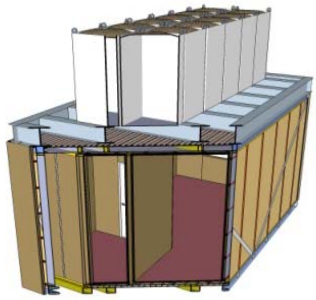


(a) Section of ceiling slab



(b) Section of bottom slab

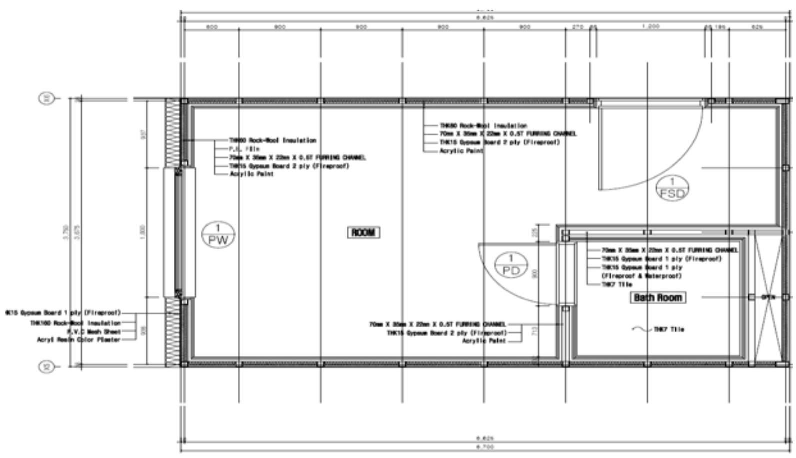
(c) Section detail



(d) Section detail of entrance

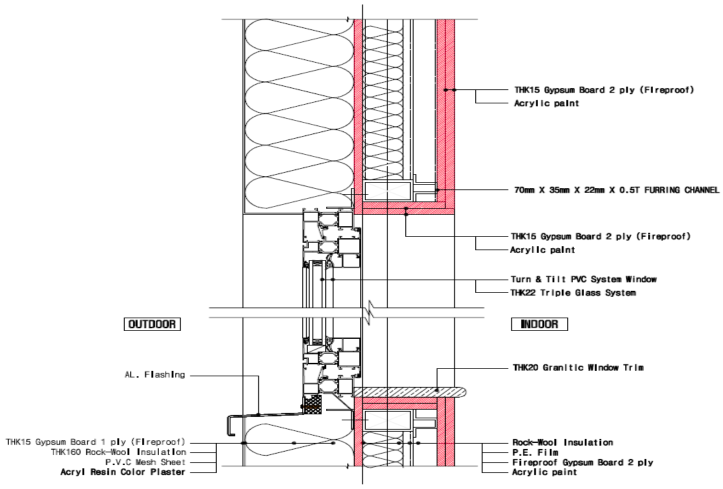
Fig. 4 Detailed drawing of the modular block

module is composed of a restroom and a patient room. Three dimensional details of the unit are shown in Fig. 4. To secure the fire resistance performance of the square steel columns and the beams, fireproof plaster boards were attached. The thickness of the boards is 30 mm (15 mm × 2 layers) for the wall, and 37.5 mm (12.5 mm × 3 layers) for the ceiling as indicated in Fig. 5.



(a) Plan of the modular block

Fig. 5 Continued



(b) Section detail of the modular block

Fig. 5 Plane and section of the modular block

Table 2 Properties of the fire protection materials

Classification	Location	Density (kg/m³)	Thermal conductivity (kcal/mh°C)	Specific heat (kcal/kg°C)	Percentage of water content (%)
Fireproof plaster board (15 mm)	Wall, Ceiling	824	0.19	0.56	Less than 3
Fireproof plaster board (12.5 mm)	Ceiling				
Rock-wool (60mm)	Floor	100	0.044	0.2	Less than 4
	Wall, Ceiling	200			
	Floor	400			
Cement board (20 mm)	Floor	1500	0.25	3.5	Less than 7

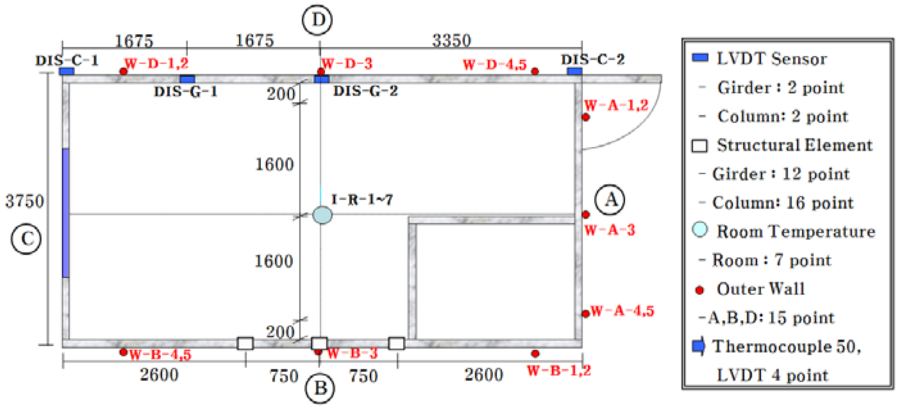
Table 2 shows the properties of the fire protection materials used for the medical modular block. To achieve the most economical efficiency, the thickness of the fireproof board was determined based on the results of a finite element analysis and an experimental study for the modular beam (Kim *et al*. 2009b).

2.2 Instrumentation

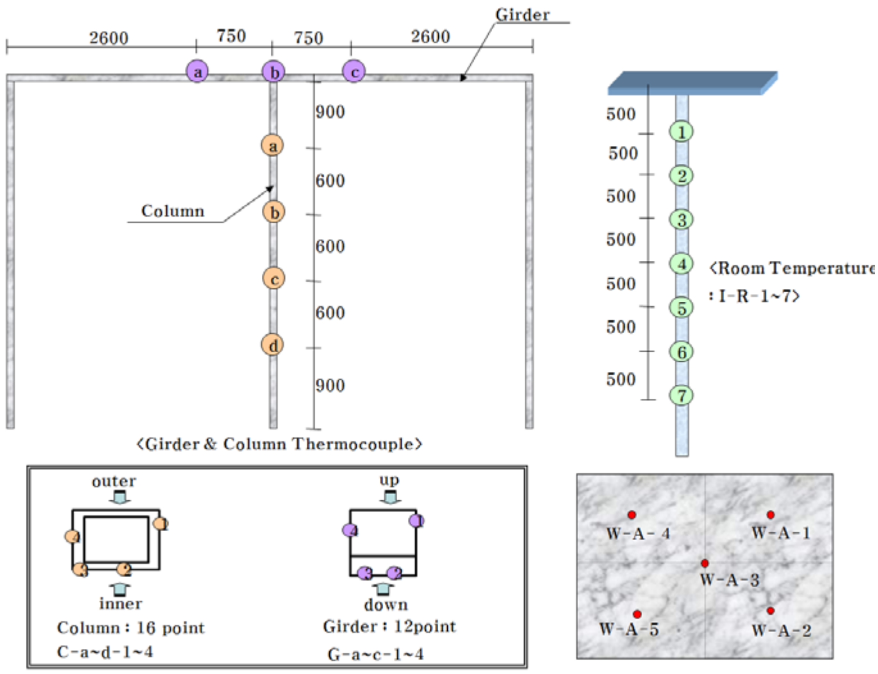
Two experiments were conducted. In the first test, 59 K-thermocouples were installed to evaluate the fire resistance performance of the modular block under the fire load with 1.0 of fire load coefficient. In the second test assuming the worst fire scenario with 3.5 of the fire load coefficient, 64 K-thermocouples including thermocouples attached on the internal walls were installed to evaluate the fire behavior of the modular block.

The measured data include temperature distributions in the room, temperatures and displacements of structural members, and temperatures of the internal and external wall.

In the first experiment, seven thermocouples were installed at an interval of 500 mm downward from the ceiling using a vertical bar at the center of the room to measure the internal room temperature as shown in Figs. 6(a) and (b). In the second experiment, the temperature in the room was measured with five thermocouples at 1.5 m downward from the ceiling. In order to measure the temperature changes of the structural members, three thermocouples were installed at the right

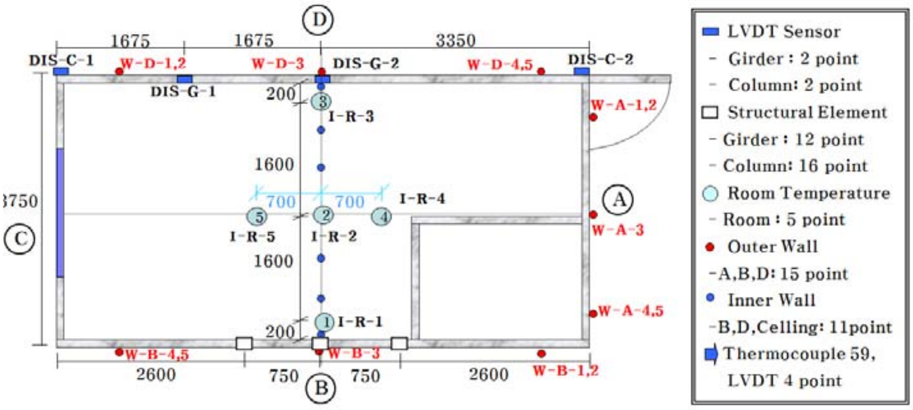


(a) Locations of installed sensors (Plan)

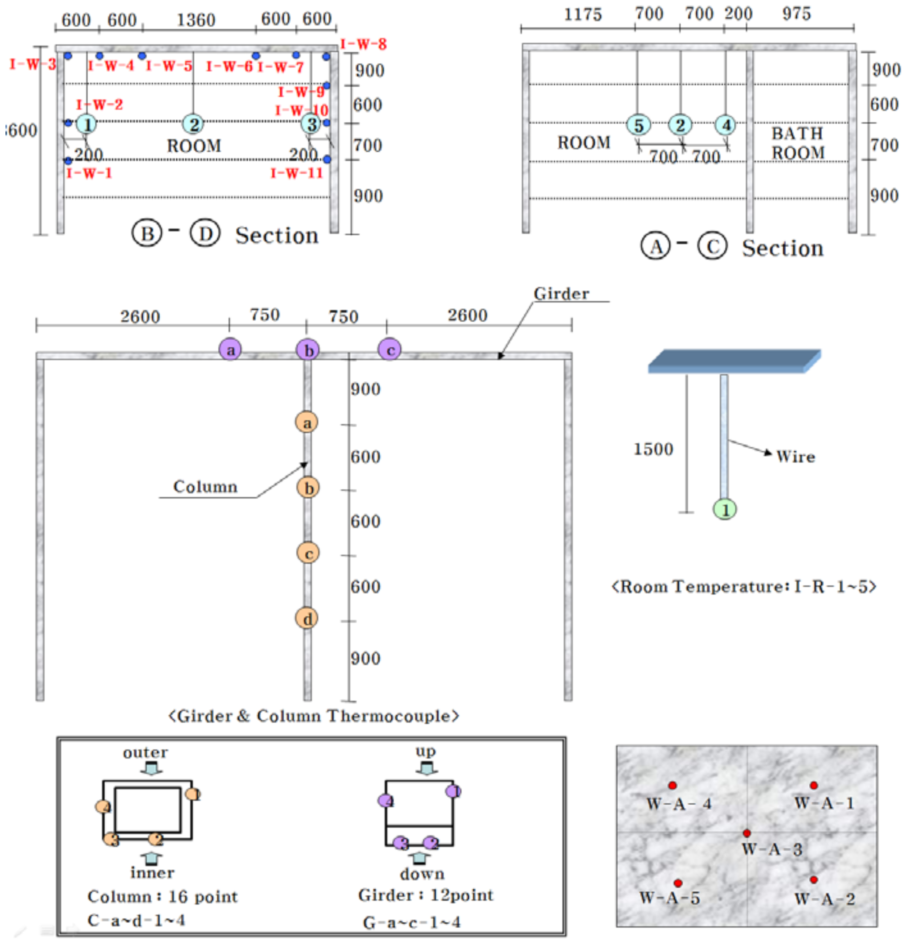


(b) Locations of sensors (Girder, Column and Room)

Fig. 6 Details of installed thermocouples and LVDT (First test)



(a) Locations of installed sensors (Plan)



(b) Locations of sensors (Girder, Column and Room)

Fig. 7 Details of installed thermocouples and LVDTs (Second test)

(a) Installations of the LVDTs

(b) Thermocouples installed on the external wall

Fig. 8 Installations of LVDTs (Girder/Column) and thermocouples (External wall)

and left side of 750 mm from the center and at the center of the girder. For the column, four thermocouples were installed as shown in Figs. 6(b) and 7(b). The displacements of the girder and column were measured using LVDTs (Linear Variable Differential Transformer). Four LVDTs were installed to measure displacements of the girder and the end two columns using jig as shown in Fig. 8(a).

2.3 Fire loads

Since the fire load varies by the material properties of the inflammables, the unit calorific value of the inflammable was calculated on the basis of ISO 5660-1. The inflammable used in this study was pine tree. The required water content of the wood should be less than 15% by NPB-233-96. The water content of the pine tree was 11.38% by KS F 2199 (Korean Industrial Standard F 2199). The amount of the wood crib per unit area was calculated using Eq. (1).

$$q_o = k_c \cdot G_i \cdot h_a = k_c \cdot \frac{\sum G_i \cdot H_i}{h_o \cdot A} = k_c \cdot \frac{\sum Q_i}{h_o \cdot A} \tag{1}$$

where, k_c: Weighting coefficient (3.57)
h_a: Caloric value per unit weight of the fire source (MJ/kg)
q_o: Fire load (kg/m²)
h_o: Unit caloric value of wood (4,381 kcal/kg)
G_i: amount of inflammable wood (kg)
H_i: Unit caloric value of the inflammable (2,015 kcal/0.46 kg)
A: Bottom area of the fired space (25.125 m²)
ΣQ_i: Total caloric value of the inflammables in the fire section (kcal)

In the first test, the fire load was the combined load (14.08 kg/m²) of the average dead fire load (5.76 kg/m²) and the average live fire load (8.32 kg/m²), which were determined from the investigations of 21 hospitals in Seoul, South Korea (Korea Institute of Construction Technology

Table 3 Test variables of the natural fire test

Test	Weighting coefficient (kc)	Fire load (kg/ m²)	Total caloric value (Kcal)	Window condition	Measuring of temperature
First	1	13.99	1,539.916	Closed	Beam, Column, Outside and inside of wall
Second	3.5	50	5,643.075	1/3 Open	Beam, Column, Outside and inside of wall

(a) Ignition point of wood cribs (b) Location of wood cribs [First test] (b) Location of wood cribs [Second test]

Fig. 9 Wood cribs location and ignition point in the modular block [Second Test]

Fig. 10 Loading and large scale calorimeter

2004). In the second test, the weighting coefficient of 3.5 was used to make sure that the worst fire scenario can be reached in the tests. Table 3 is to summarize the weighting coefficients, fire loads and total caloric values used in the two experiments. Fig. 9 shows the arranged wood cribs for the fire test. The fire was ignited by two rolled gauze as an ignition source.

2.4 Dead load and live load

The mechanical loads of the modular block were considered to be a four-story hospital building. Thus, the applied total load on the upper floor was 417 kN considering the dead load of three floors (279.7 kN) and the live load (136.9 kN). This load was applied uniformly using sand bags in

Table 4 Designation of thermocouples and LVDTs

Definitions	Examples
Girder (G), Column (C), Wall (W)	ex) G – A(a) – 1: G: Girder, C:Column, W:Wall A: Location of the thermocouple (surface of wall: A~D, Location: a~d) 1: No. of the thermocouple
Thermocouples to measure room temperatures (I)	ex) I –R- 1 I: Thermocouple in the room R:Room, W:Wall 1: Location of the thermocouple
Displacements (DIS)	ex) DIS – C – 1 DIS: Displacement C: Column, G: Girder 1: No. of the LVDT

Table 5 Performance criteria

Heat resistance criteria (°C)						Deformation criteria (mm)	
Column		Girder		Ext. wall		Girder	Column
(ISO 834, KS F 2257-1)				(GOST30247)		(GOST30247)	(ISO 834, KS F 2257-1)
Ave.	Max.	Ave.	Max.	Ave.	Max.	L/20 (Bending)	h/100 (Axial)
538	649	538	649	140 + ambient temperature	180 + ambient temperature	335	36

* L: the length of the girder, h: the height of the column

the vessels as shown Fig. 10. The large scale calorimeter of 10 MW was used to collect the smoke and the hazard gas generated by the fire.

2.5 Evaluation criteria

Table 4 shows the designations of the installed thermocouples and LVDTs. The locations of the sensors can be easily found using the designations and Fig. 7.

The fire resistance performance of the structure was evaluated with KS F 2257, ISO 834, and GOST 30247.1-94. The evaluation includes the heat resistance capability of the walls, the limiting temperature of the structural members, and the load bearing capacity of the structural members. Table 5 shows the performance criteria.

3. Test results

The fire resistance performance of the modular block was evaluated by the measured displacements, temperatures of the structural members and the heat resistance capabilities of the walls.

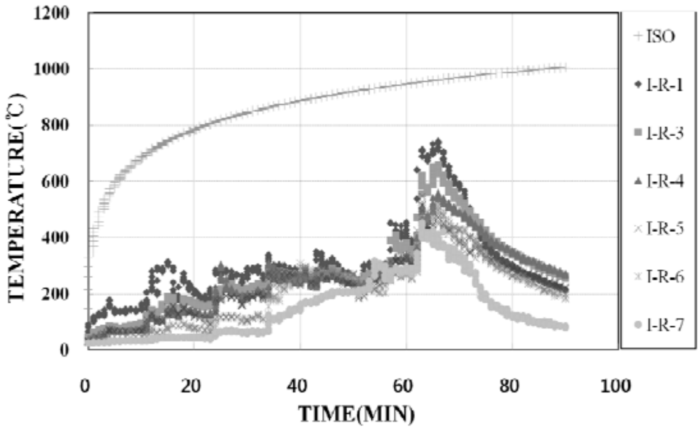


Fig. 11 Interior temperatures of the first test

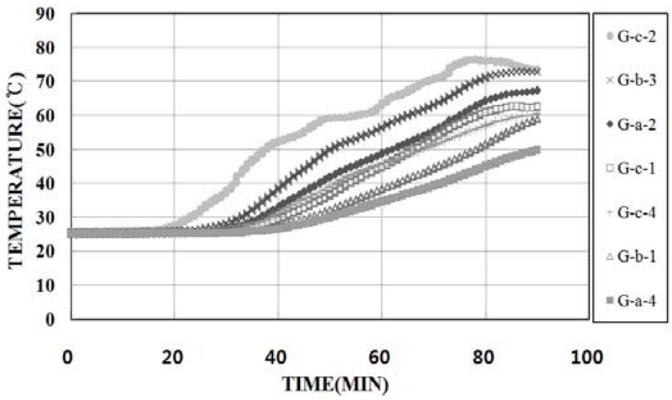


Fig. 12 Temperature changes of the girder according to the time (1st test)

3.1 Results of the first test

3.1.1 Interior temperatures

The test was conducted for 90 minutes and the temperature for the ceiling part I-R-1 (Fig. 6 (b)) attained by the maximum of 742°C at 66 minutes after the ignition. The temperature at 90 minutes was 255°C. Fig. 11 shows the result for the interior temperature. It showed that the measured temperatures are lower than the temperature of the ISO standard fire curve used to evaluate the fire resistance performance of the buildings.

3.1.2 Temperatures of the structural members

With the increase of temperature, the maximum temperature of the girder G-c-2 showed to be 76°C at 79 min. after the ignition which was 13 minutes behind the time of the maximum interior temperature as shown in Fig. 12. It means that the time to reach the maximum temperature in the girder can be delayed 13 minutes by an increase of the heat resistance capability of the girder with the fire resistance board. The temperature increased more rapidly in the direction of the window in the part C of Fig. 6(a) because the fire went out through the window.

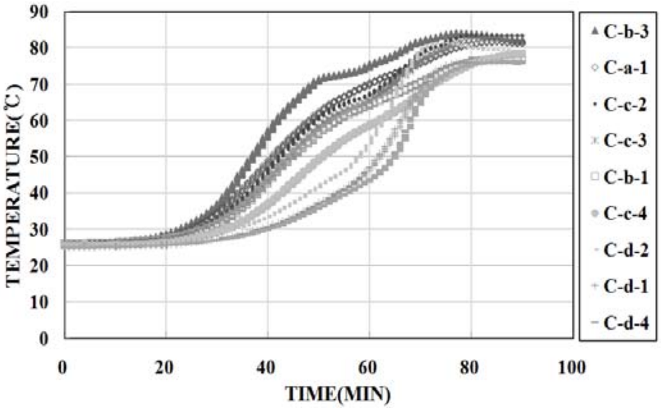
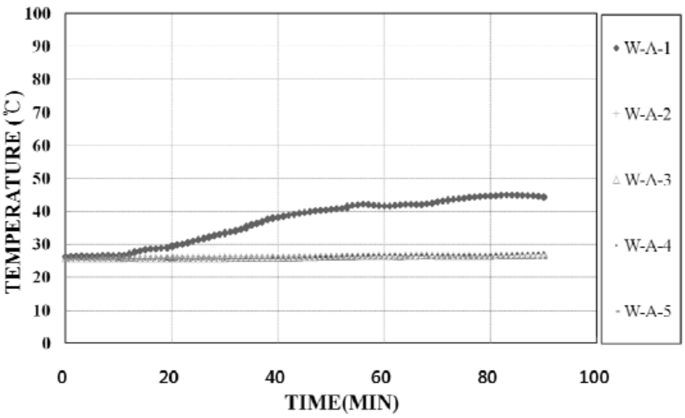


Fig. 13 Temperature changes of the column according to the time (1st test)

In case of the column, the maximum temperature was 84°C as shown in the part C of Fig. 6(a) because the fire went out through the window. The temperature of the upper portion of the column is only a few degrees higher than the temperature of the girder. Thus, the fire resistance performance for the ceilings and the upper parts of structural members can be particularly improved by the fire resistance board.

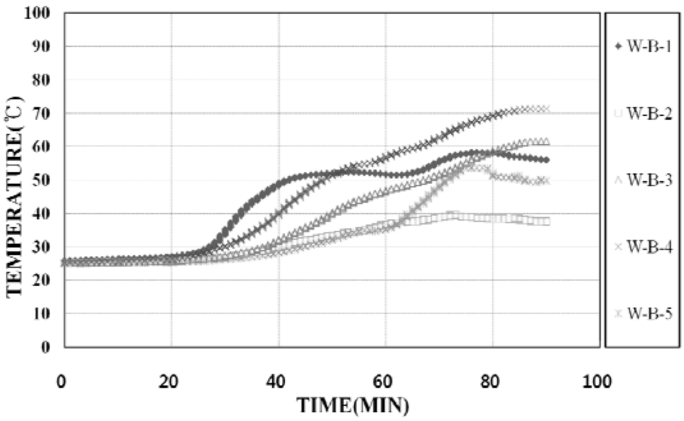
3.1.3 Heat resistance capability of the walls (external surfaces)

The temperatures in the wall were measured to evaluate the heat resistance capacity of the external surfaces of the wall and the fire resistance of the plaster board. The maximum temperature of the external surface of the wall was 83°C. The highest temperatures measured on the walls of the external surface B and D were W-B-4 and W-D-1 respectively as shown in Fig. 14, which are the upper parts of the walls near the window. This is due to the fire through the window.

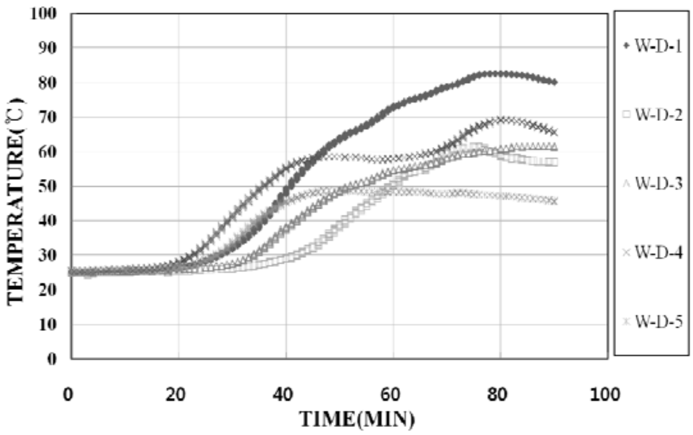


(a) Temperature changes of the wall (external surfaces A)

Fig. 14 Continued



(b) Temperature changes of the wall (external surfaces B)



(c) Temperature changes of the wall (external surfaces D)

Fig. 14 Temperature changes of the wall (external surfaces) according to the time (1st test)

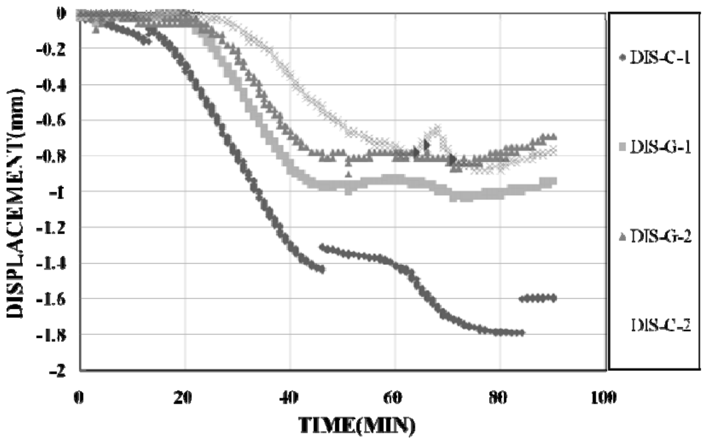


Fig. 15 Displacements of the girders and the columns according to time (1st test)

3.1.4 Deformations of girders and columns

The displacements of the columns and the girders were measured and they are maximum 1.8 mm for columns and maximum 1.1 mm for girders as shown in Fig. 15. This is because the temperatures of the structural members were only 85°C shown in Fig. 15. This relatively low temperature is resulted from the fire resistance plaster boards and the ceramic wools installed for the columns and the girders.

3.2 Results of the second test

Assuming the worst fire scenario, the second test was conducted by applying the fire load of 50 kg/m² considering 3.5 of weighting coefficient to the regular fire load for the hospitals. In the second test, the measured data included the internal surface temperatures of the walls.

3.2.1 Interior temperatures

At the location I-2, the center of the modular block, the maximum temperature of 1170°C was measured 34 minutes after ignition as shown in Fig. 16. The locations of the sensors were determined by GOST-30247-94 (CNISK *et al*. 1996). The maximum temperature was higher and reached earlier than that of the first test. In the first test, the maximum temperature was 742°C at 66 minutes after ignition. It is concluded that these resulted from two causes.

The first is that fire load in this experiment is greater by 3.5 times than that in the first experiment, and the second is that ventilation condition is different. Actually, in the 2nd experiment, fire expansion was faster than in the 1st experiment (closed) since it was performed with 1/3 of windows and doors open.

Temperature is higher near the ceiling by the rising fire which is similar to the result from the first test.

3.2.2 Temperatures of the structural members

The temperature increased by 181°C in 90 minutes at G-b-2, which is at the bottom surface of the middle of the girder as shown in Fig. 17. The maximum temperature was reached in such a long time because it takes time for the fire to spread from the entrance of the block to surrounding areas in the block and also because the heat transfer through the fire resistance boards. From Fig. 16,

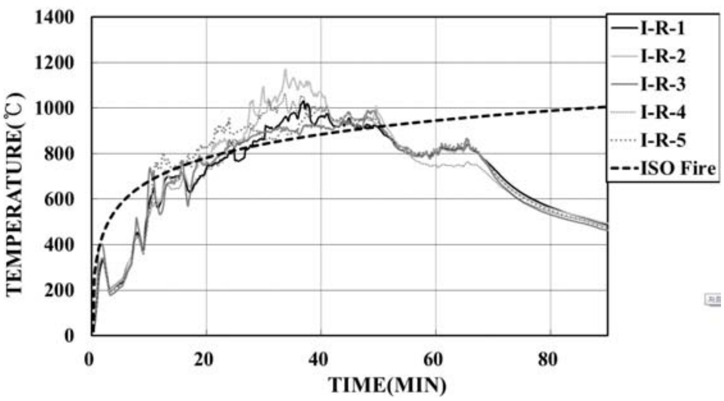
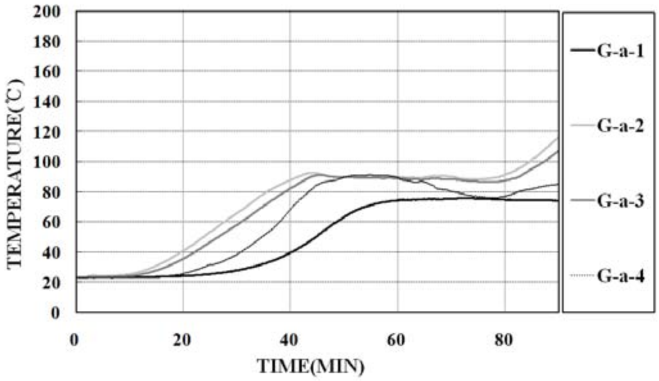
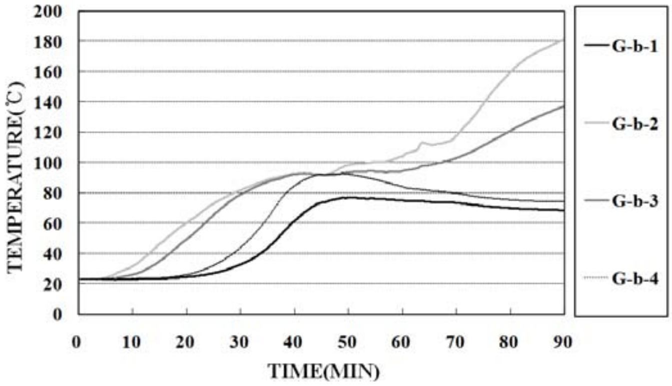


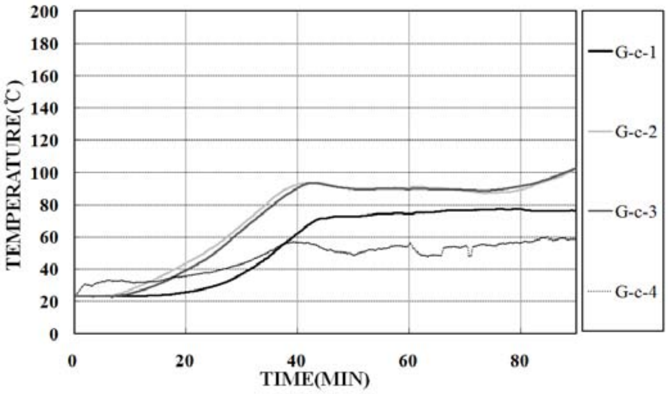
Fig. 16 Room temperatures (2nd test)



(a) Temperature changes on the girder (Part – a: 750 mm distance of center)



(b) Temperature changes on the girder (Part – b: center)

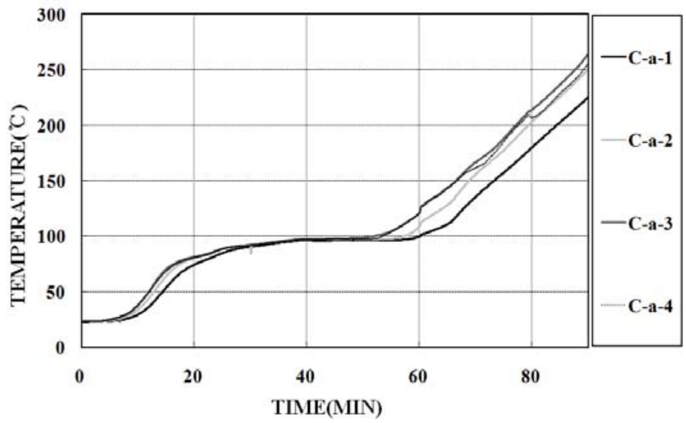


(c) Temperature changes on the girder (Part – c: 750 mm distance of center)

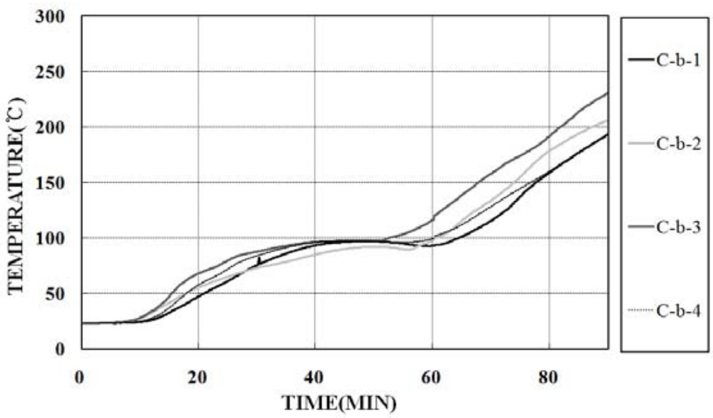
Fig. 17 Temperature changes of the girder according to the time (2nd test)

one can see that the maximum interior temperature was reached after 34 minutes, and the interior temperature started to decrease afterward. However, the temperatures of the structural members were not decreased but either increased or kept constant for a while and then started to rise. This is an indication that the heat resistance of the fireproof boards is quite effective to reduce the maximum temperature of the structural members and to slow down the heating rate of the fire.

As for the temperature in the columns, the temperatures at C-a-3 and C-c-4 increased by 264°C in 90 minutes. The temperature differences by the height and the locations in the columns were not remarkable as shown in Fig. 18. There is a common feature that can be observed in Fig. 18, at about 10 minutes, the time for the flashover (will be discussed later), the temperatures of the girders and the columns increased remarkably due to the incoming oxygen from broken window. Then, the temperature increases leisurely. This result can be explained with the combined effect of heat and mass transfer related to dehydration of the fireproof board. When exposed to fire attack, the free water and the chemically bound water in fireproof board are gradually driven off at temperatures above 100°C. The evaporation of the water consumes large amount of heat and thus slows down the heat transfer process and results in the temperature plateau at 100°C on the unexposed surface of the construction (Kwon 2002). At about 60 minutes, this process may be completed and the temperature increased rapidly again.

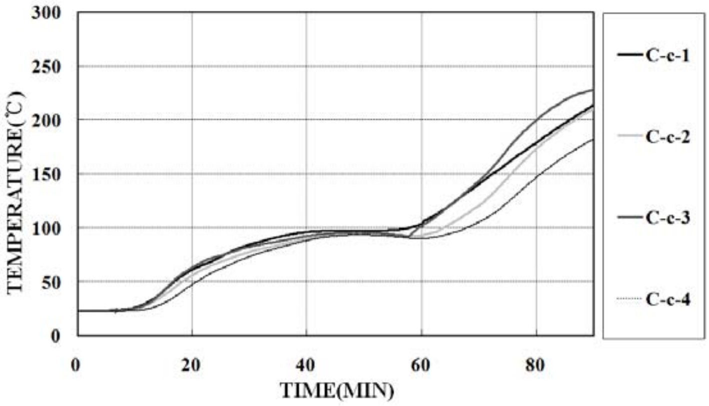


(a) Temperature changes of the column (Part – a: 900 mm distance of ceiling)

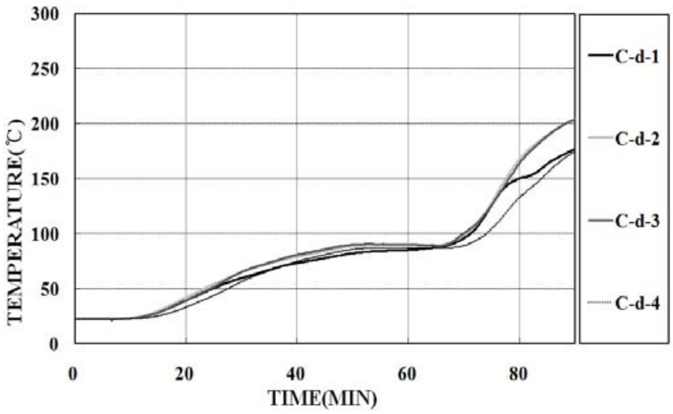


(b) Temperature changes of the column (Part – b: 1,500 mm distance of ceiling)

Fig. 18 Continued



(c) Temperature changes of the column (Part – c: 2,100 mm distance of ceiling)



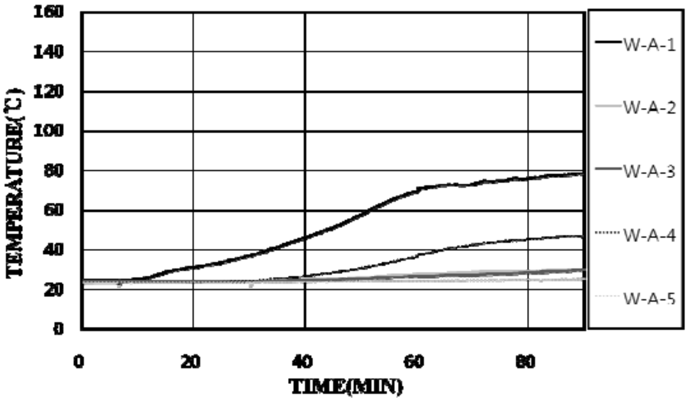
(d) Temperature changes of the column (Part – d: 2,700 mm distance of ceiling)

Fig. 18 Temperature changes of the column according to the time (2nd test)

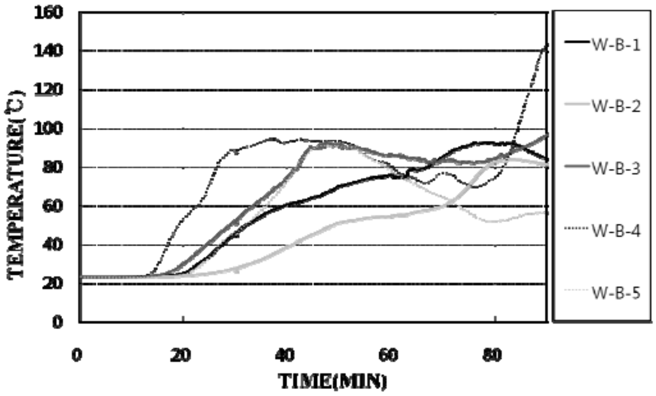
3.2.3 Heat resistance capability of the walls (internal and external surfaces)

The temperature changes of the wall were delayed for 15 minutes on average, because of heat resistance of the fireproof board and the ceramic wool. At 80 minutes after the ignition, the temperature at W-B-4, which is the upper part of the walls near the window, rapidly increased in the second test as shown in Fig. 19. The result showed that the fire protections around the walls adjacent to the openings are very effective and should be considered in the fire protection of a medical modular building.

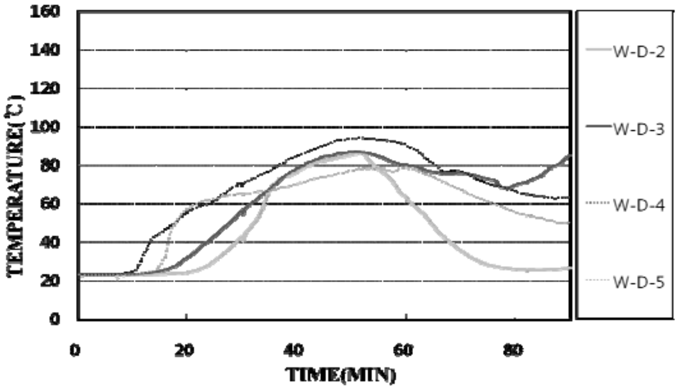
At 44 minutes after the ignition, the temperature of I-W-3 located 900 mm from the ceiling increased by 1368°C, see Fig. 20. To analyze the properties of the heat transfer of the internal wall, thermocouples were installed as shown in Fig. 7(b). The maximum temperature occurred first at the upper part of the wall due to the rising fire and then the heat was transferred toward the lower part of the wall. As for the ceiling, the maximum temperature was 1368°C at 43 minutes on the I-W-4. The data from I-W-5 around 40 min. is unreliable as compared with the temperature data from the other locations shown in Fig. 21. This result provides useful information in fire protections of a medical modular building in the future.



(a) Temperature changes of the wall (External surface A)



(b) Temperature changes of the wall (External surface B)



(c) Temperature changes of the wall (External surface D)

Fig. 19 Temperature changes of the wall (external surfaces) according to time (2nd test)

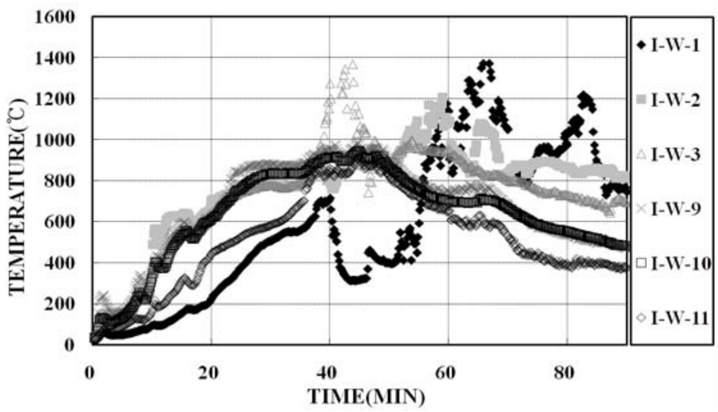


Fig. 20 Temperature changes of the wall (internal surfaces) according to time (2nd test)

3.2.4 Deformation of girders and columns

To evaluate the fire resistance performance of the structural members, the deformations of the girders and the columns were measured. The maximum axial deformation of the column C-1 located at the entrance was 5.56 mm, which is three times of the maximum deformation 1.8mm measured in the first test as shown in Fig. 15. The deformation of 5.56 mm is within the critical limit (Korean agency for technology and Standards 2005), which is summarized in Table 4, for fire resistance performance after 90 minutes of fire. For the column C-2 located near the window, 3.07 mm of deformation occurred after 58 minutes. The axial deformation of C-2 was partially recovered after the maximum deformation at 60 minute. It may be related to the change of the loading path with the continuous axial deformation of C-1. In the case of the girders, the maximum deflection of 4.78 mm occurred at about 90 minutes in G-1. The deformation values satisfy the evaluation criteria shown in Table 4.

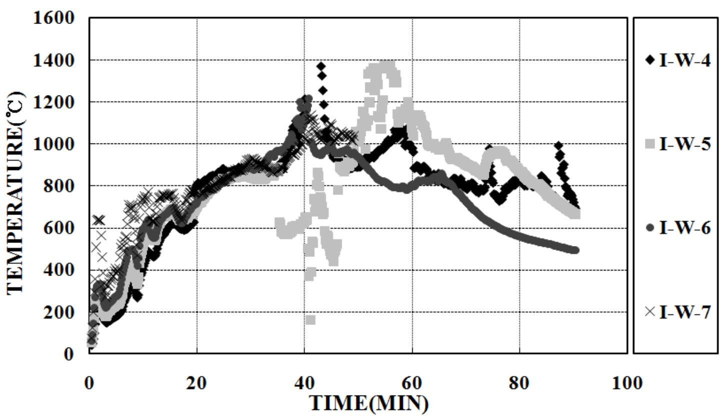


Fig. 21 Temperature changes of the internal ceiling (2nd test)

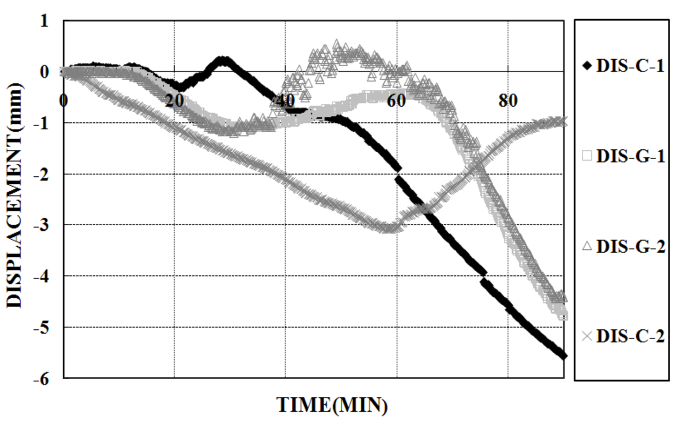


Fig. 22 Displacements of the columns and the girders

4. Fire engineering analysis

In the PBD, the inflammables in the structure are considered as the fuel source. Then, the fire load is determined by predicting the fire severity in the structure, and the temperatures in the structural members are predicted based on the fire severity, and finally, the internal force of the members is evaluated through the test.

4.1 Determination of the flashover and prediction of the fire period

The criteria to determine if a flashover occurs are the temperature in the upper layer in the internal space of the building (600°C), the level of radiation per unit area of the floor (20 kW/m²), and the time in which all heated surfaces by radiation from the flames burns rapidly (Buchanan 2001b). For the medical modular block, the time for the flashover was analyzed and the results are shown in Table 6. The analyses were done on the basis of the temperature at the upper part of structure. In the first test, flashover occurred within three minutes after the window was broken and the fire going through the window. In the second test, the flashover occurred about 50 minutes earlier than in the first test.


(a) 1st test (59 minutes)


(b) 2nd test (10 minutes)

Fig. 23 Fire outgoing of widow before the flashover

Table 6 Determination of the flashover and prediction of the burning time

Test	Fire going out of window	Occurrence of F.O.	HRR (MW)	Duration of burning (min)	HRR at F.O
1	59 min	62 min	7.214	15	2.59 (MW)
2	10 min	12 min	7.396	53	

By “Thomas’s flashover criterion” (Kwon 2005) the heat release rate of the medical modular block can be predicted. The duration of burning of the total inflammables was inferred on the basis of the heat release rate (HRR in Table 5). The results were summarized in Table 5. The duration of burning is based on the inflow time of the outside air through the window. In the first test, the maximum interior temperature occurred seven minutes after the fire going out of the window, which is 66 minutes after ignition as shown in Fig. 11. Thus, the predicted duration of burning using ‘Eurocode Formula (EN 1991-1-2, 2002) is 15 minutes, which is quite reliable comparing with the test data. The duration of burning for the first test can be calculated as follows

$$w(\text{window width}) = 1.78\ \text{m},\quad A_v(\text{window area}) = 1.8\ \text{m} \times 1.78\ \text{m}$$

$$A_t(\text{total internal surface area}) = 2\left[A_f + H(L_f + W_f)\right] = 125.490\ \text{m}^2$$

$$h_a(\text{calorific value of wood fuel}) = 18.342\ \text{MJ/kg}$$

$$M(\text{mass of fuel}) = 352\ \text{kg}$$

$$\dot{m}(\text{ventilation controlled burning rate}) = 0.092 A_v\sqrt{h}(\text{kg/sec}) = 0.39327\ \text{kg/sec}$$

$$Q_v(\text{heat release rate}) = \dot{m} \times h_a = 7.2135\ \text{MW}$$

$$t_b(\text{duration of burning}) = M / \dot{m}(\text{sec}) = 894.81(\text{sec}) = 15\ \text{min}$$

$$Q_{fo}(\text{Thomas' Flash over correlation}) = 0.078 A_t + 0.378 A_{v\sqrt{h}} = 2.59\ \text{MW}$$

$$Q_v > Q_{fo}: \text{flashover occurs.}$$

where, A_f: floor area(m²)
H: height of fire cell (m)
W_f: width of fire cell (m)
h: window height (m)

In the second test, the maximum temperature of the internal wall occurred at 66 minutes as shown in the Fig. 20. The predicted duration of burning in second test using above calculation method was estimated to be in 53 minutes as shown in Table 5.

4.2 Calculations of fire exposure time and equivalent rate of heat release

Under the fire, the strength of structural members rapidly decreases due to the exposure to high temperature. The fire exposure time of the structure can be estimated by calculating the duration of the burning period. As a result of the calculation, in the first test, the duration of the burning period was over 30 minutes (Buchanan 2001b). In the second test, the calculated time was 110 minute as shown in Table 7. The calculated times are the durations of the fire in the structure according to the fire load. The constant heat value 3.576 MW was obtained by dividing the total burning load by the durations of the burning period.

Table 7 Burning period of the structure by the burning load of the inflammables

Test	Fire load (kg/m²)	Total fuel load (MJ)	Equivalent rate of heat release	Average fire severity time
1	13.99	6455	3.576 MW	30 min
2	50	23627		110 min

Table 8 Heat resistance capabilities for the walls of the medical modular block

External wall	A (°C)		B (°C)		D (°C)	
	Ave.	Max.	Ave.	Max.	Ave.	Max.
Standard	165	205	165	205	165	205
1st test	73	84	64	77	-	-
2nd test	42	78.4	92.3	143	67.6	94.3

4.3 Evaluation of fire resistance performance of the medical modular block

4.3.1 Heat resistance capability of the wall

Table 8 summarizes the heat resistance capabilities of the walls under the fire scenarios. As mentioned in Sections 3.1.3 and 3.2.3, the temperatures of the upper parts of the walls near the window, rapidly increased. The reason is that the walls were attacked by the flame going through the window. The walls satisfied the fire resistance performance of 90 minutes by the temperature criteria in GOST 30247-94 (CNISK *et al*. 1996). However, the walls with openings are needed to be reinforced by passive or active fire resistance systems.

4.3.2 Fire resistance performance of the structural members

In order to evaluate the fire resistance performance of the structural members, the temperature changes over time were measured. The result by ISO 834 and KS F 2257-1 satisfied the fire resistance performance of 90 minutes in the tests (see Table 9).

4.3.3 Displacements of the structural members

The deformations of the structural members were measured to evaluate the decrease of the load bearing performance of the structure with increasing temperature and fire duration (Dwaikat and Kodur 2011). The test results showed that the deformations of the structural members completely satisfied the deformation criteria (Korean agency for technology and Standards 2005). In fact, the measured deformations were very small compared with the required values as shown in Table 10.

Table 9 Fire resistance performance for temperature of the structural members

Parts	Girder (°C)		Column (°C)	
	Ave.	Max.	Ave.	Max.
Evaluation Criteria (ISO 834 & KS F 2257-1)	538	649	538	649
1st test	73	84	64	77
2nd test	99	182.2	214.6	266.6

Table 10 Deformations of the girders and columns

Parts	Girder (mm)	Column (mm)
	L/20	h/100
Standard	335	36
1st test	1.1	1.8
2nd test	4.78	5.59

* L: the length of the girder, h: the height of the column

Initial Phase – Smoke

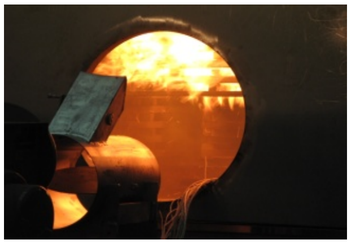
Growing Phase

Spreading Phase

After termination

(a) 1st test

Initial Phase



Growing Phase

Spreading Phase

After termination

(b) 2nd test

Fig. 24 Test photos

The results mean that the strength and stiffness of the structural steel were not decreased significantly because the maximum temperatures in the structural members of the 1st test and the 2nd test were within 100°C and 270°C, respectively.

5. Conclusions

1. Two full scale fire tests using various codes such as SNIP 21-01-97, GOST 30247.0, GOST 30247.1, BNP 233-96 and ISO 834-1 were conducted by considering a four-story hospital building under the natural fire scenarios. In the first and second test, the weighting coefficients were 1.0 and 3.5, respectively.
2. In the first test, flashover occurred at 62 minute and the flashover in the second test occurred about 50 minutes earlier than in the first test. The duration of burning of the total inflammables was inferred on the basis of the heat release rate. In the first and second test, the predicted durations of burning were estimated in 15 minute and 53 minutes, respectively. These results show that fire load and ventilation condition are critical factors in the determination of fire resistance performance of building.
3. In the second test, the maximum interior temperature was reached after 34 minutes, and the interior temperature started to decrease afterward. However, the temperatures of the structural members were not decreased but either increased or kept constant for a while and then started to rise. This result can be explained with the combined effect of heat and mass transfer related to dehydration of the fireproof board. When exposed to fire attack, the free water and the chemically bound water in fireproof board are gradually driven off at temperatures above 100°C. This slows down the heat transfer process and results in the temperature plateau at 100°C on the unexposed surface of the construction.
4. In the second test, at 80 minutes after the ignition, the temperature at W-B-4, which is the upper part of the walls near the window, rapidly increased, the same occurred in the first test. These results show that the fire protections around the walls adjacent to the openings are very important in a medical modular building.

The maximum axial deformation in the second test of the column C-1 located at the entrance was 5.56 mm, which is three times of the maximum deformation 1.8 mm measured in the first test. For the column C-2 located near the window, 3.07 mm of deformation occurred after 58 minutes. The axial deformation of C-2 was partially recovered after the maximum deformation at 60 minute. It may be related to the change of the loading path with the continuous axial deformation of C-1. In the case of the girders, the maximum deflection of 4.78 mm occurred at about 90 minutes in G-1. The deformation values satisfy the evaluation criteria.

Acknowledgements

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