TECHNICAL REPORT

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Fire safety engineering — Performance of structures in fire —

Part 4:
Example of a fifteen-storey steel-framed office building

Ingénierie de la sécurité incendie — Performance des structures en situation d'incendie —

Partie 4: Exemple d'un immeuble de bureaux en structure acier de quinze étages

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by Technical Committee ISO/TC 92, *Fire safety*, Subcommittee SC 4, *Fire safety engineering.*

Introduction

This document is an example of the application of ISO 24679-1, prepared in the format of ISO 24679-1. It includes only those subclauses of ISO 24679-1 that describe the steps of the methodology for assessing the performance of structures in fire. It preserves the numbering of subclauses in ISO 24679-1 and so omits numbered subclauses for which there is no text or information relevant to this example.

This example is intended to illustrate the implementation of the steps of the fire resistance assessment, as defined in ISO 24679-1. Only steps that are considered to be relevant to this example are well-detailed in this document. The technical contents are based on the performance based verification methods for fire resistance in the Building Standards Law of Japan, but were slightly modified for simplicity and compatibility with ISO 24679-1.

Fire safety engineering — Performance of structures in fire —

Part 4:
Example of a fifteen-storey steel-framed office building

1 Scope

This document provides a fire engineering application relative to the fire resistance assessment of a fifteen-storey steel framed building following the methodology given in ISO 24679-1. This document describes the adopted process which follows the same step by step procedure as that provided in ISO 24679-1. The annexes of this document present the detailed assessment results obtained for the most severe fire scenarios on the basis of the outcome of this specific fire safety engineering procedure for the building.

The fire safety engineering applied in this example to the office building with respect to its fire resistance considers specific design fire scenarios as well as the corresponding fire development. It takes into account fully-developed compartment fires. In realistic situations, activation of fire suppression systems and/or intervention of fire brigade are expected, but their beneficial effects are not taken into account. It should be noted that these severe fire scenarios have been selected for fire resistance purposes.

Global structural behaviour is not explicitly considered, but implicitly included in the calculation formulae. Since the building of the example is located in a seismic region, principal structural elements are rigidly connected to each other. Load redistribution from heated elements to cold surrounding elements exists, but it's not taken into account in the design calculations. By this approach, design is conservative, while the process of safety checking is greatly simplified and clear. As a result, all the calculations were carried out by explicit algebraic formulae.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 13943, *Fire safety — Vocabulary*

ISO 23932, *Fire safety engineering — General principles*

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3   Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 13943 and ISO 23932 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

3.1
design heat release of a room
amount of heat to be released in a room including movable fire load, fixed fire load and heat transferred from adjacent rooms

Note 1 to entry: It is expressed in MJ.

3.2
equivalent fire duration time
duration of heating by a standard fire as specified in ISO 834-1 that gives equivalent thermal effect on structural elements with a real fire

Note 1 to entry: It is expressed in min.

3.3
fixed fuel load density
heat of combustion of materials fixed to room, such as interior finish materials, equipment and so on, per unit floor area of fire room

Note 1 to entry: It is expressed in MJ/m^2.

3.4
heat penetration factor
ratio of heat penetrated from adjacent rooms to the room in consideration

Note 1 to entry: It is dimensionless.

3.5
movable fuel load density
heat of combustion of movable room contents such as furniture, commodities and so on per unit floor area of fire room

Note 1 to entry: It is expressed in MJ/m^2.

3.6
total heat release of a room
amount of heat possible to be released in a room including movable and fixed fire load

Note 1 to entry: It is expressed in MJ.

4   Symbols

For the purposes of this document, the following symbols are used.

A_r room floor area (m^2)

A_f surface area of interior lining material (m^2)

f_a heat penetration factor

f_y nominal yield strength of steel at normal temperature (MPa)

G permanent load

K kinematic load

q_l movable fire load density (MJ/m^2)

Q_f heat of combustion of interior lining materials per unit area (MJ/m^2)

Q_r design heat release of a room (MJ)

Q live or variable load

t time (min)

t_A approved fire resistance time of a construction element (min)

t_f fire duration time (min)

t_{eq} equivalent fire duration as replaced with a fire as specified in ISO 834-1 (min)

T_B limiting temperature for overall buckling (°C)

T_{Bcr} limiting temperature for bending failure of a beam (°C)

T_{cr} critical temperature of steel element (°C)

T_{DP} limiting temperature for excessive deformation (°C)

T_{JT} limiting temperature for joint failure (°C)

T_{LB} limiting temperature for local buckling (°C)

$T_{s.max}$ maximum steel temperature under design fire action (°C)

T_f fire temperature in a room (K)

T_0 initial temperature (K)

α fire temperature rise coefficient (K/min$^{1/6}$)

5 Design strategy for fire safety of structures

The built environment of this example is a medium-rise office building. Due to its use, the building is separated into multiple compartments by floors and walls to accommodate tenant office functions. As the combustible contents are distributed densely, fire is likely to spread over whole compartment. As a result, a fully-developed compartment fire is expected in each room of the building.

The structural elements are composed of steel and are protected against fire. To prevent failure of the structural elements and joints, the thickness of fire protection had been defined in order to limit their temperatures below their critical temperatures during the fully-developed fire in each compartment.

6 Quantification of the performance of structures in fire

6.1 General

The various steps of the design process considered in the conducted fire safety engineering study are detailed in 6.2 to 6.9.

6.2   Step 1: Scope of the project for fire safety of structures

6.2.1   Built environment characteristics

The built environment is a steel framed 15-storey office building. The gross floor area is 8 236 m² and the building height is 68,5 m. See Annex A for building drawings. According to the regulations, the building must be constructed by fire-resistive constructions. In the prescriptive code,[10] columns must be three hours fire-rated construction on the first floor, two hours on the second to eleventh floors and one hour on the floors above. The building is separated horizontally by compartment floors at all levels. Vertical shafts such as stairs, elevators and service shaft are surrounded by one hour-rated fire resistance walls.

The floor plan is shown in Figure 1. The office area is split into two rooms, XX01 and XX02. Symbol XX denotes floor number. For example, 1502 denotes room number 2 on floor 15. The two office rooms are separated by an EI60 wall as determined by ISO 834-8. In addition, the office area is divided into two rooms by a non-fire-rated wall made of regular gypsum board. The doors between office rooms and corridor are fire-rated E60 to prevent fire spread between office area and corridor.

The building structure is a rigid moment-resistant steel frame. Specification of members such as columns, beams and floor slabs are listed in Annex A. The columns, beams and girders are protected against fire by a 25 mm sprayed rock wool cementitious mixture.

— Span of primary beams: 13,6 m;

— Span of secondary beams: 6,4 m;

— Spacing of columns: 6,4 m in direction of primary beams and 13,6 m in direction of secondary beams.

The applied load of design on the floors is taken as follows:

— live load: 2,9 kN/m² (based on building code requirement);

— self-weight of floor: 3,65 kN/m².

In this document, only the results of construction elements in office rooms number: 201, 202, 1501 and 1502 are demonstrated.

The external walls are fire-rated for more than one hour. However, windows are not fire-resistant. The floors are composite constructions of concrete slabs and steel beams. The composite slabs are made of normal weight concrete and profiled steel sheets with reinforcing bars.
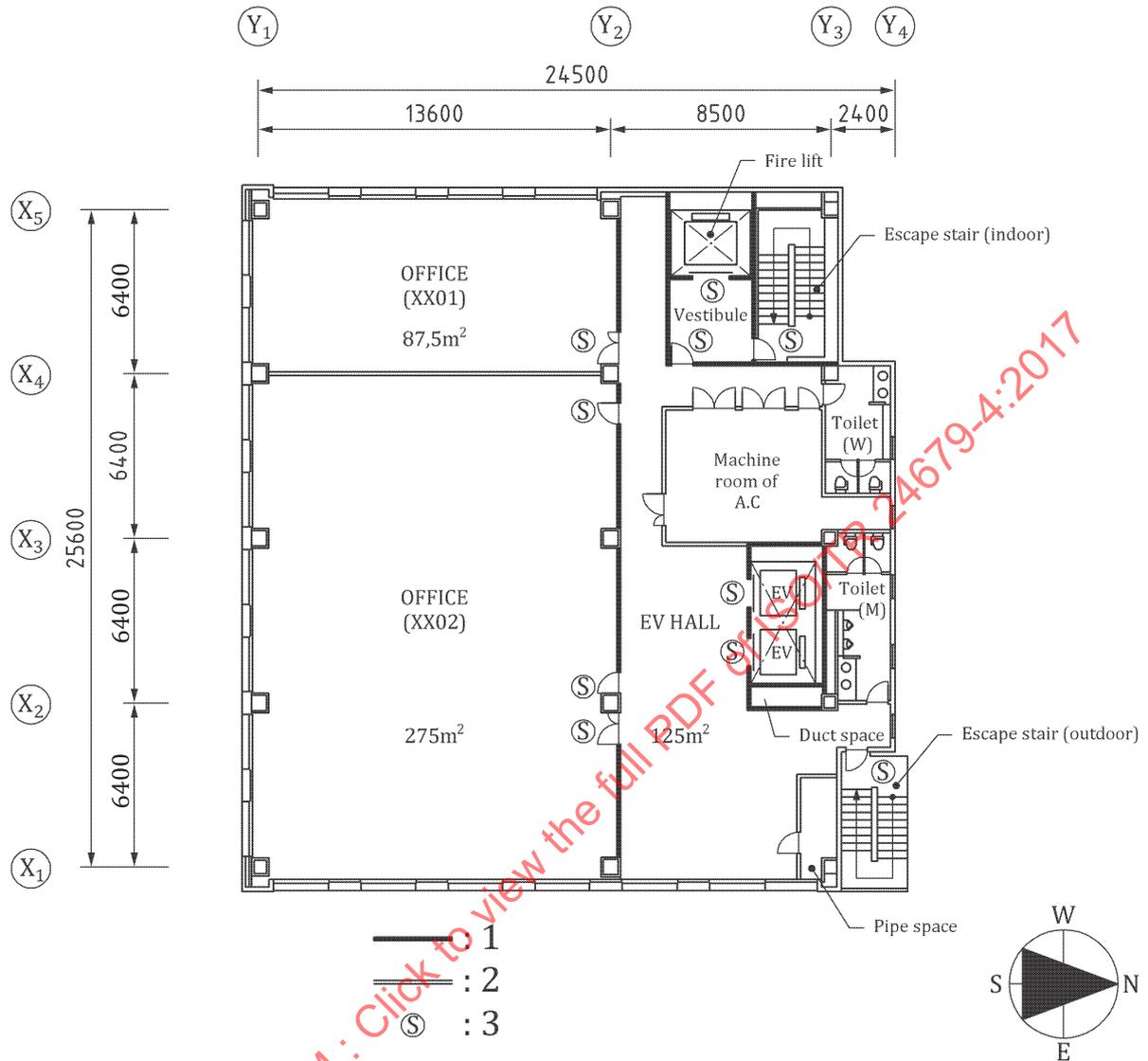
Key

1   fire-rated partition wall (EI60)

2   non-fire-rated partition wall

3   fire door (E60)

NOTE   All the exterior walls are fire-rated (EI60).

Figure 1 — Typical floor plan

6.2.2   Fuel load

As the building is used as office space, a significant amount of combustibles is expected. The design fuel load of a room, Q_r, is calculated as the sum of the following components.

1)   Movable fuel load based on the use of the room, $A_r\, q_l$.

The movable fire load density for an office area is 560 MJ/m² based on the building code.[10] The results are shown in Table 1.

2)   Fixed fuel load based on the type of interior finish materials, $\Sigma A_f\, Q_f$.

The heat of combustion of interior finish materials are accounted as fixed fire loads. The details of calculation are shown in B.5.2. The results are summarized in Table 1.

3) Heat penetrated from adjacent rooms, $\Sigma f_a (A_r q_l + \Sigma A_f Q_f)$.

As the walls between the office areas XX01 and the office areas XX02 are not fire-rated, there is a risk for fire to spread between the rooms. A part of combustion heat in an adjacent room may affect the structural elements in the other room. To account for this "mutual heating" effect, it was assumed that 15 % of heat of combustion (design rule in Japan) may penetrate to adjacent rooms separated by non-fire-rated walls. The calculated results are shown in Table 2.

Table 1 — Fuel load of rooms XX01 and XX02 (XX = 2nd and 15th floors)

Floors	Room No.	Usage	Movable fuel load density q_l (MJ/m²)	Floor area A_r (m²)	Movable fuel load $A_r q_l$ (MJ)	Fixed fuel load $\Sigma A_f Q_f$ (MJ)	Total fuel load of room (MJ)
2 to 15	201, 1501	office	560	87,5	49 000	7 649	56 649
	202, 1502	office	560	275	154 000	22 397	176 397
	corridor	pathway	32	125	4 000	13 722	17 722

Table 2 — Design heat release of a room considering heat penetration from adjacent rooms

Floor	Room	Adjacent rooms	Total fuel load of adjacent rooms (MJ)	Heat penetration coefficient f_a (-)	Penetrated heat (MJ)	Design fuel load (MJ)
2 to 15	201	202,1502	176 397	0,15	26 460	83 108
	1501	Corridor	17 722	0,0	0,0	
	202	201,1501	56 649	0,15	8 497	184 894
	1502	Corridor	17 722	0,0	0,0	

6.2.3 Mechanical actions

The mechanical actions in fire situation are determined in accordance with the building code. Permanent and movable vertical loads are considered, while no horizontal actions are considered such as seismic and wind actions. As a result, the load combination is[10]:

$$1{,}0G + 1{,}0Q \tag{1}$$

where G is sum of all the permanent loads, i.e. self-weight of the building and Q for the variable loads representing the contents of the building. No snow load was considered in this document as the building is located in non-snow region.

As the building is located in seismic region, the following load combination is applied for seismic resistance design:

$$1{,}0G + 1{,}0Q + 1{,}0K \tag{2}$$

where K is the (horizontal) kinetic action. Common for buildings in Japan, the cross-sectional dimensions are governed by seismic design. As a result, the load ratios of structural elements are relatively small during normal use such as in the case of non-seismic and non-windy conditions. Details are described in Step 3.

6.3   Step 2: Identify objectives, functional requirements and performance criteria for fire safety of structures

As the building is used by multiple occupants, the building must not collapse during egress, firefighting and rescue. In addition, as the building is located in an urban area, the building must not collapse during the whole process of fire and subsequent cooling period to prevent fire spread to urban scale. As a result, stability during whole process of fire is necessary.[10] To fulfil this objective, the functional requirement is to have no failure of the building construction elements during the whole process of fire, including the cooling phase. Consequently, the following performance criteria, in terms of stability of the structure, are considered on an element by element basis.

— The temperature of the steel columns does not exceed the minimum of the critical temperatures for overall buckling, local buckling, excessive deformation and joint failures.

— The temperature of the steel beams and girders does not exceed the limit for bending failure and joint failure. Shear failure does not precede the bending failure.

— Floor construction does not exceed the limit for mechanical failures, typically bending failure.

In addition, the following performance criteria are considered in terms of fire containment.

— Fire compartment walls and floor constructions do not transmit excessive heat that may ignite combustibles in opposite side (insulation criterion).

— Fire compartment walls and floor constructions do not penetrate flame and/or hot gases that causes fire spread beyond them (integrity criterion).

6.4   Step 3: Trial design plan for fire safety of structures

Preliminary designs, at room temperature, were carried out to determine the dimensions of the structural members. As the building is located in a seismic region, the members are designed against seismic actions as described by Formula (2).

The floor and beam plan is shown in Figure 2. The frame consists of simple 2 × 4 bays. The trial design of principal construction elements is listed in Table 3. On the second floor, all the elements are made of relatively thick large cross-sectioned steel sections in order to withstand the large seismic actions. For the fire combination, large vertical loads are applied to second floor columns. On the 15th floor, the elements are made of relatively thin and small sections but the applied loads in the fire combination are also small compared with the second floor elements. Further details are shown in Annex A.

Columns and girders are made of SN 490[11] steel with a yield strength of 325 MPa. Secondary beams are made of a SS 400[12] steel with a yield strength of 235 MPa. Columns are made of a box-sectioned tube. Beams and girders are made of H-sectioned elements. To prevent excessive temperature rise, the elements are insulated with a sprayed rock wool cementitious material of a thickness of 25 mm.

The floor slab is made of composite structure of profiled steel plate and concrete. The thickness of concrete varies from 80 mm to 155 mm. The diameter of the reinforcing bars is 13 mm. The concrete cover of reinforcing bars from the bottom side of the slab is 20 mm. Reinforcing wire mesh with 6 mm diameter and spaced 100 mm, is located at 30 mm from the top side of the slab. The compressive strength of concrete is 21 MPa.
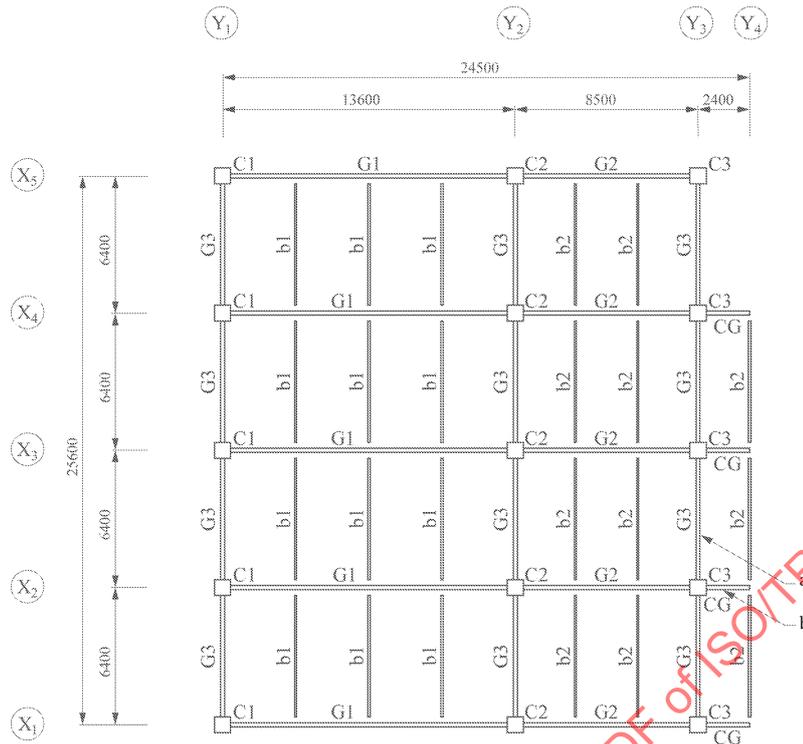
Key

a   Columns, girders and beams are not insulated.

b   All other columns, girders and beams are insulated by 25 mm thick sprayed rock wool.

Figure 2 — Floor and beam plan

Table 3 — Summary of structural members

Floor levels		2nd floor	15th floor
Column (four sides exposed) SN 490 steel, f_y = 325 MPa	C1	box-600 × 40	box-600 × 22
	C2	box-600 × 45	box-600 × 22
	C3	box-500 × 36	box-500 × 19
Primary beam (three sides exposed) SN 490, f_y = 325 MPa	G1	H-900 × 350 × 16 × 25	H-700 × 300 × 14 × 25
	G2	H-900 × 300 × 16 × 25	H-700 × 250 × 14 × 22
	G3	H-900 × 300 × 16 × 25	H-700 × 250 × 14 × 22
Secondary beam (three sides exposed), SS400, f_y = 235 MPa	b1	H-350 × 175 × 7 × 11	
	b2	H-450 × 200 × 9 × 14	
Composite slab, concrete strength: 21 MPa	Steel decking	1,2 mm	
	Concrete thickness	minimum 80 mm, maximum 155 mm	
NOTE See Annex A for details.			

6.5   Step 4: Design fire scenarios and design fires

6.5.1   Design fire scenarios

It is assumed that each room can be an origin of fire. A compartment fire is assumed to grow and decay until the burnout of the combustible materials in the rooms under investigation. No effect of active suppression, such as sprinkler and/or manual intervention, is considered. Only one compartment fire is considered at a time, but the fire may spread to adjacent rooms via non-fire-rated partition walls.

All unprotected openings are assumed to be broken and accounted for the ventilation calculations. Protected openings, such as fire-rated doors, are assumed to be closed and not accounted for in the ventilation calculations.

A nominal localized fire with a constant heat release rate of 3 MW for 20 min, is considered in addition to the fully-developed compartment fire. However, calculations for the localized fire are not included in this document because the heat impact of a fully-developed fire is more severe than that of localized fires in this case.

A nominal exterior fire is assumed to occur in the neighbour of the building. The standard fire temperature as specified in ISO 834-1 for 60 min is assumed as the nominal fire for exterior heating.

6.5.2 Design fires (thermal actions)

A fully-developed compartment fire was considered. It is assumed that all the combustibles burn at a constant rate. The heat release rates of office rooms are shown in Figure 3. The time-temperature curves are calculated using Formula (3), an algebraic equation assuming a uniform temperature in a fire room:

$$T_f = \alpha t^{1/6} + T_0, \ (0 \le t \le t_f) \tag{3}$$

where the fire temperature rise coefficient α (K/min$^{1/6}$) and fire duration t_f (min) are calculated in accordance with the room geometry, window opening size and burning rate of the fuel. Calculation details are provided in Annex C. The results are shown in Figure 4. As the window areas are fairly large and fuel and air ratio is close to stoichiometric, fire burns severely but the duration is short. The fire temperatures are considerably higher than the standard fire temperature as specified in ISO 834-1. The equivalent fire duration time was calculated to be 59,9 min in both fires for rooms XX01 and XX02 as shown in Table 4.
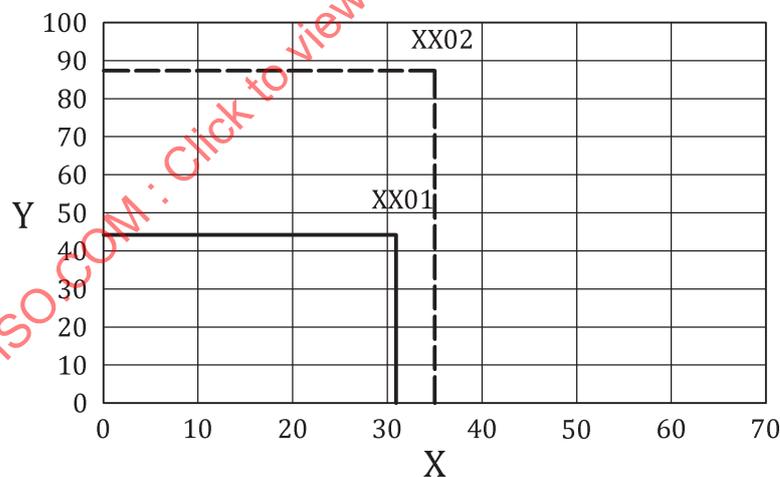
Key

Y   heat release rate (MW)

X   time (min)

Figure 3 — Heat release rates of office rooms, XX01 and XX02
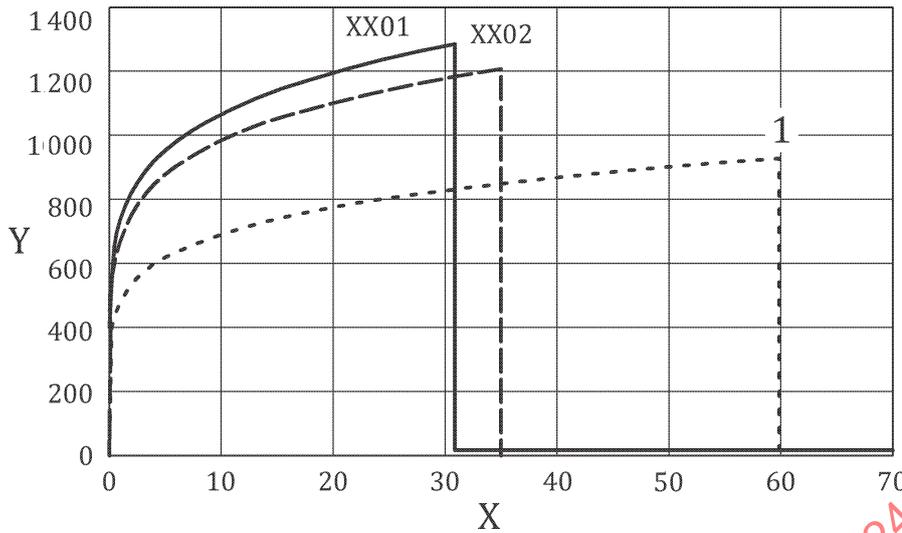
Key

Y   fire room temperature (°C)

X   time (min)

1   equivalent to a fire as specified in ISO 834-1 (59,9 min)

Figure 4 — Fire room temperatures of office rooms, XX01 and XX02

Table 4 — Calculation results of fire room temperatures and equivalent fire duration time

Room	Fire temperature rise coefficient α (K/min$^{1/6}$)	Fire duration time t_f (min)	Equivalent fire duration time t_{eq} (min)
XX01	715	30,9	59,9
XX02	658	35,0	59,9
NOTE The equivalent fire duration of both fires happened to coincide in this specific example. In general, the value is expected to change from room to room.			

6.6   Step 5: Thermal response of the structure

6.6.1   Steel columns and beams

The above thermal actions are applied to the corresponding structural members to calculate their temperatures as functions of time. Heat transfer analyses were carried out by algebraic calculation formulae over time to the calculated temperature rise in the steel beams and columns. The formula takes into account the section factors of the steel members and the applied insulation. The calculation details are described in Annex D. The calculation results of column temperatures are shown in Figure 5 and Table 5. Due to the differences in thickness, the maximum temperature is higher in 15th floor compared with the 2nd floor. The maximum beam temperatures are shown in Figure 6 and Table 6.

Key
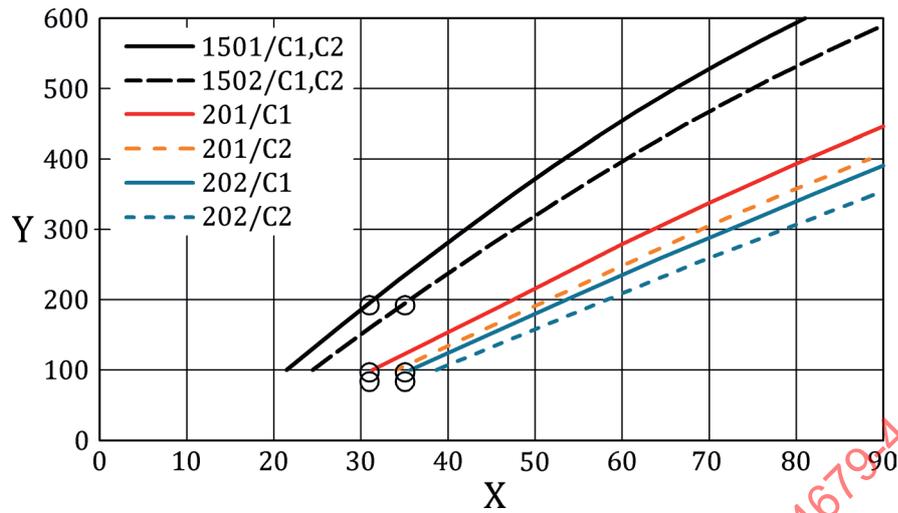
Y   maximum steel temperature (°C)

X   heating duration (min)

Figure 5 — Maximum temperature of steel girders and columns as functions of heating duration

Table 5 — Maximum temperature of steel columns, $T_{s,max}$

Room No.	Column	Maximum temperature (°C)
1501	C1, C2	194
1502	C1, C2	194
201	C1	98
	C2	85
202	C1	98
	C2	85

Key
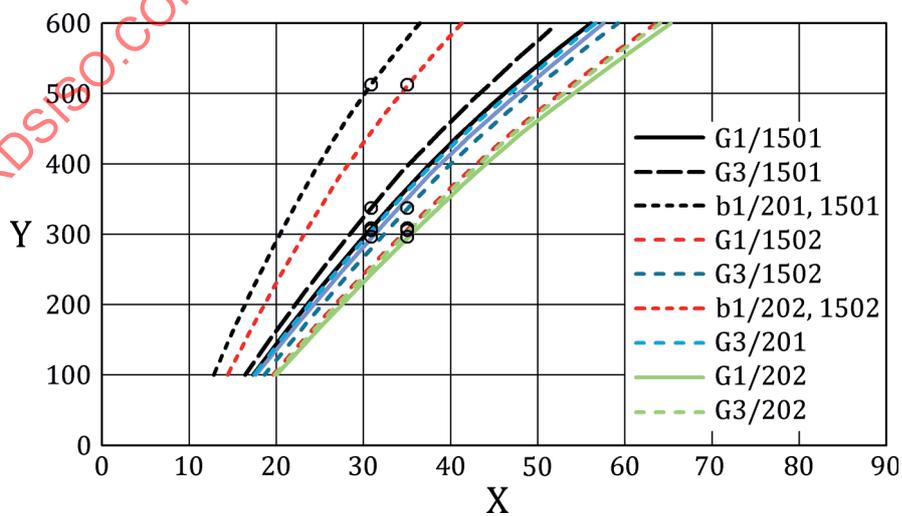
Y   maximum steel temperature (°C)

X   heating duration (min)

Figure 6 — Maximum temperature of steel girders and beams as functions of heating duration

Table 6 — Maximum temperature of steel beams, $T_{s,max}$

Room No.	Beam	Maximum temperature (°C)
1502, 1502	G1	310
	G3	339
	b1	514
201, 202	G1	298
	G3	306
	b1	514

6.6.2 Other construction elements

In cases of floors and walls, no explicit calculations were made, but the equivalent fire duration was compared with the approved fire resistance time of the elements. The results are shown in 6.8.

6.7 Step 6: Mechanical response of the structure

6.7.1 Steel columns

The critical temperature of the steel columns is calculated by considering overall buckling, local buckling, excessive thermal deformation and joint failure.[3] The critical temperature of a steel column is then determined as the minimum of the calculated critical temperatures, as shown in Formula (4):

$$T_{cr} = \min\left\{T_B, T_{LB}, T_{DP}, T_{JT}\right\} \tag{4}$$

Details of calculation are shown in Annex E. Calculated critical temperatures are shown in Table 7. For most cases, critical temperature is determined by limiting temperature for joint failure. In some cases, critical temperature is determined by local buckling. The limiting temperature for excessive deformation was not applied to this study as the building is not large.

Table 7 — Critical temperature of steel columns

Room	Position	Symbol	Limiting temperatures (°C) for Overall buckling, T_B	Local buckling, T_{LB}	Joint failure, T_{JT}	Critical temperature, T_{cr} (°C)
1501	X5-Y1	C1	694	692	550	550
	X4-Y1	C1	687	684		550
	X5-Y2	C2	690	687		550
	X4-Y2	C2	679	673		550
1502	X4-Y1	C1	687	684	550	550
	X3-Y1	C1	687	684		550
	X2-Y1	C1	687	684		550
	X1-Y1	C1	694	692		550
	X4-Y2	C2	679	673		550
	X3-Y2	C2	679	673		550
	X2-Y2	C2	679	673		550
	X1-Y2	C2	690	687		550
201	X5-Y1	C1	656	646	550	550
	X4-Y1	C1	607	592		550
	X5-Y2	C2	634	621		550
	X4-Y2	C2	557	542		542

Table 7 *(continued)*

Room	Position	Symbol	Overall buckling, T_B	Local buckling, T_{LB}	Joint failure, T_{JT}	Critical temperature, T_{cr} (C)
			Limiting temperatures (°C) for			Critical temperature, T_{cr} (C)
202	X4-Y1	C1	607	592	550	550
	X3-Y1	C1	607	592		550
	X2-Y1	C1	607	592		550
	X1-Y1	C1	656	646		550
	X4-Y2	C2	557	542		542
	X3-Y2	C2	557	542		542
	X2-Y2	C2	557	542		542
	X1-Y2	C2	634	621		550

6.7.2 Steel beams

The critical temperature of steel beams is calculated by considering bending, excessive thermal deformation and joint failure.[3] The critical temperature of a steel beam is determined as the minimum of the calculated critical temperatures, as shown in Formula (5):

$$T_{cr} = \min\left\{T_{Bcr}, T_{DP}, T_{JT}\right\} \tag{5}$$

Details of calculation are shown in Annex E. The calculated critical temperatures are shown in Table 8. For most cases, critical temperature is governed by the limiting temperature for joint failure. The critical temperature for excessive deformation was not applied to this study since the structural beams of the building are not extremely long.

Table 8 — Critical temperature of steel beam

Room	Position	Symbol	Bending failure, T_{Bcr} (°C)	Joint failure, T_{JT} (°C)	Critical temperature, T_{cr} (°C)
			Limiting temperatures (°C) for		Critical temperature, T_{cr} (°C)
1501	X4	G1	623	550	550
	X5	G1	633		550
	Y1	G3	690		550
	Y2	G3	693		550
	—	b1	587		550
1502	X1	G1	612	550	550
	X2	G1	623		550
	X3	G1	623		550
	Y1	G3	690		550
	Y2	G3	693		550
	b1	b1	587		550
201	X4	G1	663	550	550
	X5	G1	662		550
	Y1	G3	694		550
	Y2	G3	697		550
	—	b1	616		550

Table 8 *(continued)*

Room	Position	Symbol	Limiting temperatures (°C) for		Critical temperature, T_{cr} (°C)
			Bending failure, T_{Bcr} (°C)	Joint failure, T_{JT} (°C)	
202	X1	G1	654		550
	X2	G1	663		550
	X3	G1	663	550	550
	Y1	G3	694		550
	Y2	G3	697		550
	b1	b1	616		550

6.8   Step 7: Assessment against the fire safety objectives

For the steel elements, the maximum temperatures in Tables 5 and 6 are checked if they are lower than the critical temperatures in Tables 7 and 8. In this document, all the elements meet the criteria. See Formula (6):

$$T_{s,max} \leq T_{cr} \tag{6}$$

In case of floors and walls, approved fire resistance time, t_A, is compared with equivalent fire duration, t_{eq}, as shown in Formula (7):

$$t_{eq} \leq t_A \tag{7}$$

In this document, the equivalent fire duration is 60 min both in XX01 and XX02 rooms. Thus, the wall and floors are one-hour fire-rated as per ISO 834, or longer.

6.9   Step 8: Documentation of the design for fire safety of structures

This document is prepared for the implementation of ISO 24679-1. Therefore, the procedure of the document has been followed.

a)   Interested and affected parties include the owner of the building, tenants of office area and neighbouring bodies.

b)   Scope of the project: The built environment is a 15-storey office building made of steel frame.

c)   Objectives, functional requirements and performance criteria for fire safety of structures were defined according to the occupancy of the building, the properties of the structure, as well as the existing requirements of national codes and standards. The following are the main objectives.

   — The building does not collapse during egress, firefighting and rescue. In addition, as the building is located in urban area, the building does not collapse during the whole process of fire and the subsequent cooling period to prevent fire spread to urban scale.

   — The functional requirement is to have no failure of the building construction elements during the whole process of fire, including their cooling phases.

d)   Trial design plan for fire safety of structures: The building frame is made of steel elements insulated by sprayed rock wool cementitious material.

e)   Design fire scenarios and design fires: In this document, fully-developed fire in each compartment was considered. The thermal impact of other fires such as localized fires are covered by fully-developed fires.

f)   Assessment methods: Algebraic formulae were used for fire behaviour, thermal response of insulated steel elements and critical temperatures of structural elements. The formulae were developed for general design of non-industrial buildings, thus applicable to this building.

g) Data sources: The sources for the data that were used in the assessment of this building were taken from ISO and/or corresponding national standards, fire tests, or widely recognized literature resources.

h) Evaluation of the results of the assessment: The calculation results satisfied the limitation of maximum temperatures and/or fire resistance time as discussed in 6.8.

i) Summary and conclusions: According to the performance verification method for fire resistance, this document building satisfies the objective of fire resistance and functional requirements.

6.10 Factors and influences to be considered in the quantification process

6.10.1 Thermal properties

The effective values of the thermal properties of the insulation material were set to the mean value of existing fire test data on the thermal response of steel members. The thermal resistance factor, R, was determined by fitting the formula to the fire test data. The details of the calculation formula are shown in Annex D.

6.10.2 Mechanical strength of steel material

The effective yield strength of the steel material was set by a collection of data of tensile tests at high temperatures[10].

6.10.3 Uncertainty of material properties

The scatter of thermal property is fairly small in case of this material. See Reference.[6] The effective yield strength of the steel material is set at the lower bound of the existing data by subtracting three times of standard deviation from mean values at each temperature[10].

7 Guidance on use of engineering methods

This clause is not relevant in this example.

Annex A
(informative)

Building and framing design

A.1 Terms and definitions used in this annex

For the purposes of this annex, the terms and definitions given in the main text apply.

A.2 Normative references

The normative references in the main text apply.

A.3 Building façade

Building façades are shown in Figures A.1 and A.2. Exterior walls are made of lightweight concrete panel. Windows are made of ordinary float glass. Details on vertical section around window and spandrel are shown in Figure A.3.
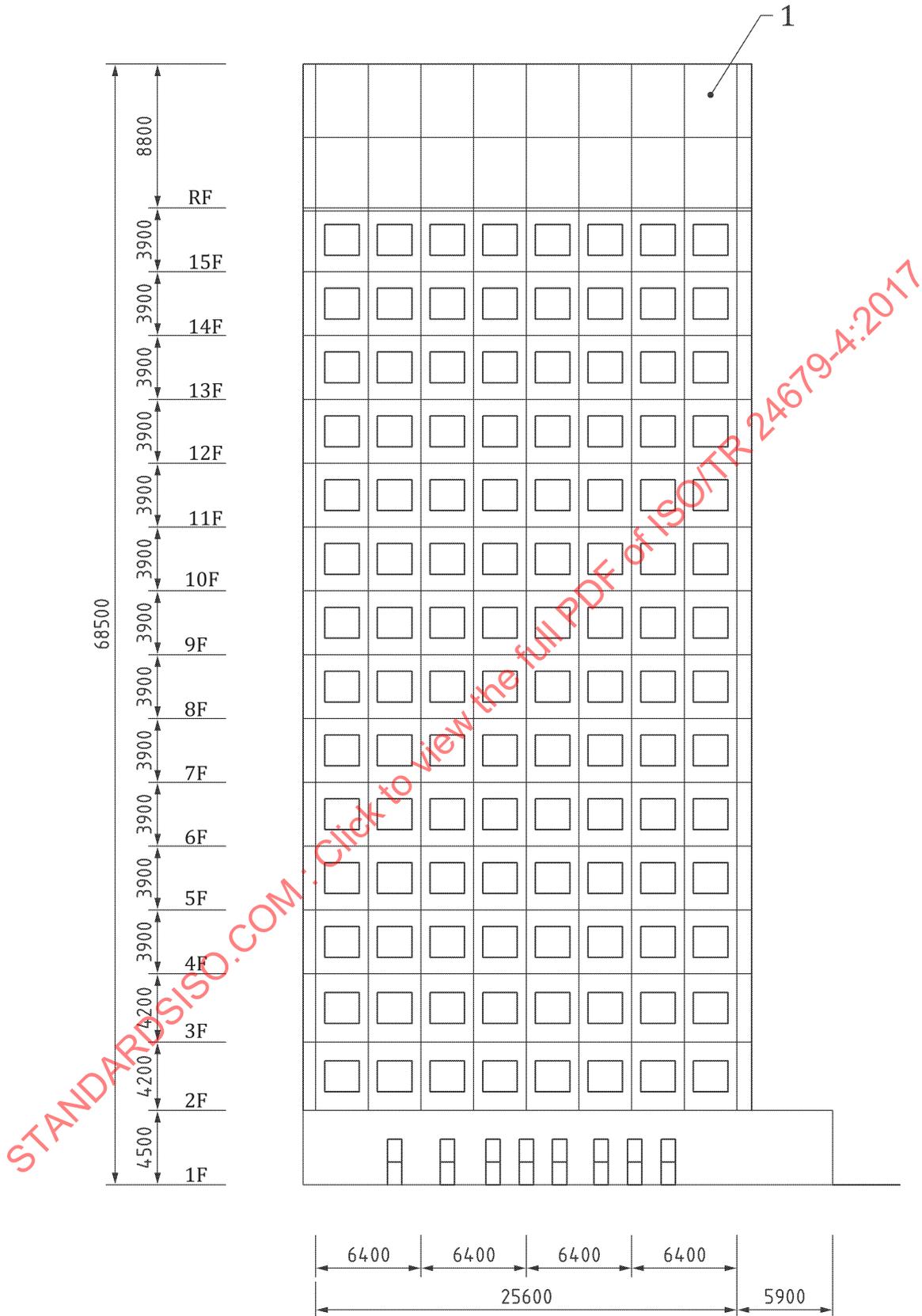
Key
1   PC panel

Figure A.1 — South facade
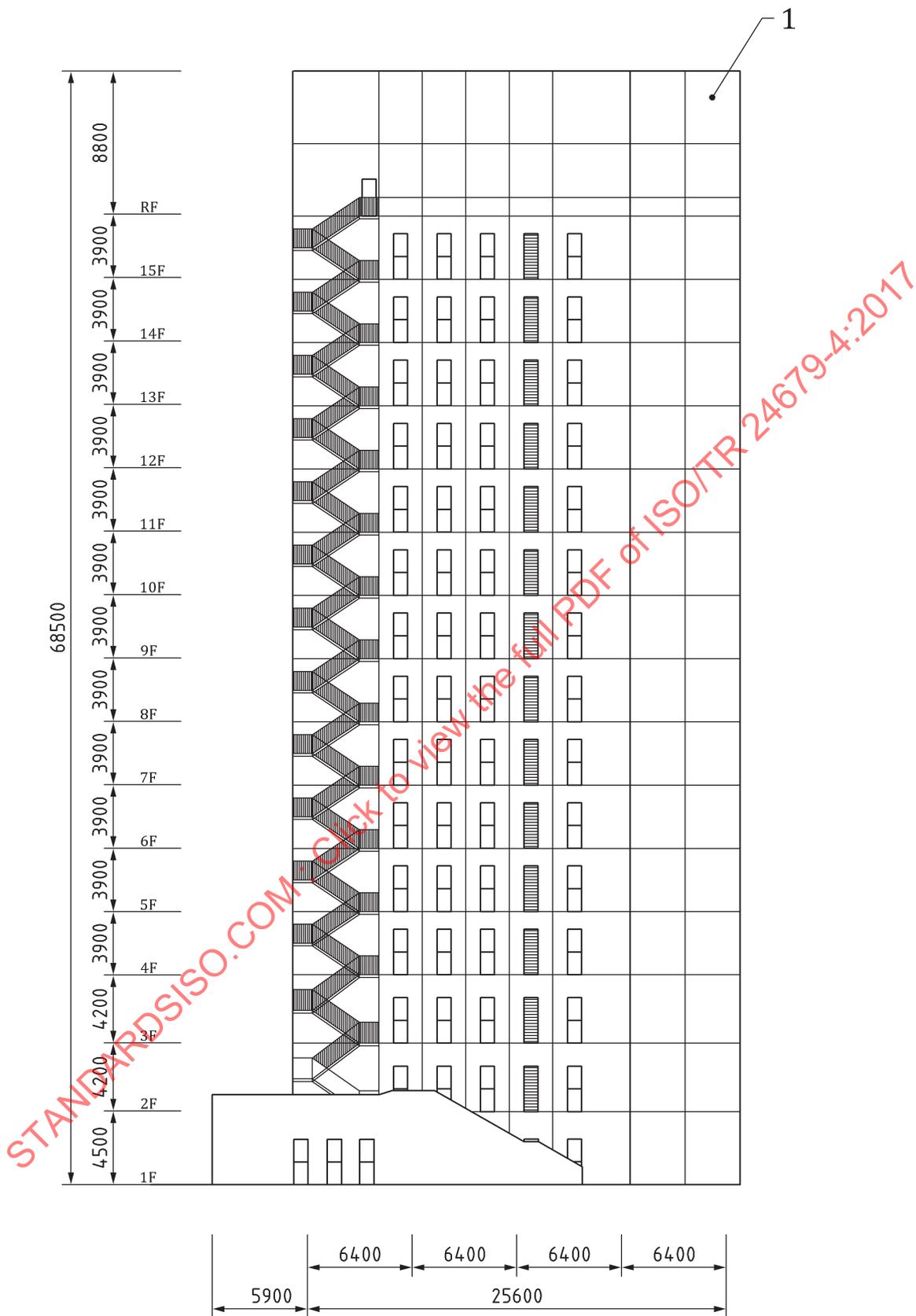
Key
1   PC panel

Figure A.2 — North facade
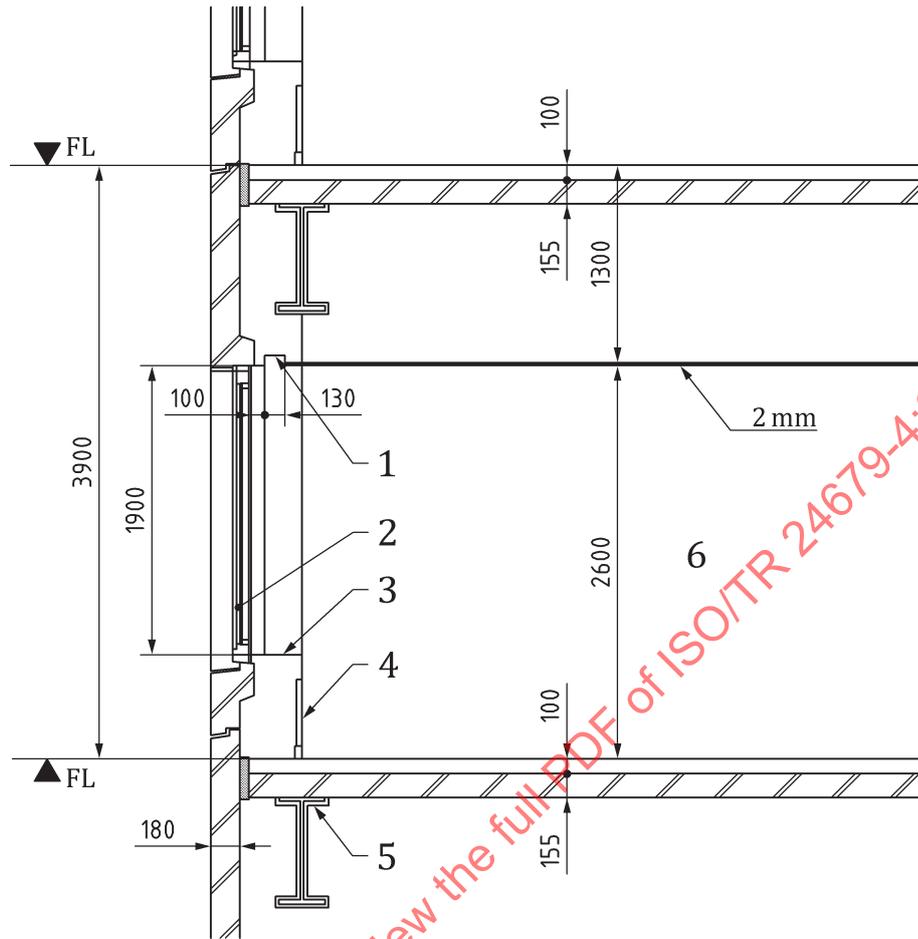
Key

1   blind box steel plate, $t = 1,6$
2   aluminium sash
3   steel plate, $t = 1,6$
4   plaster board
5   sprayed rock wool cementitious insulation, 25 mm
6   office

Figure A.3 — Details of vertical section around window

A.4   Construction of wall and floor assemblies

A.4.1   Partition wall between office area and corridor

The construction of the wall assembly is shown in Figure A.4. Double layers of fire resistant gypsum wall boards are equipped to both sides of studs. The construction is rated to 60 min of integrity and insulation as determined by ISO 834-8.
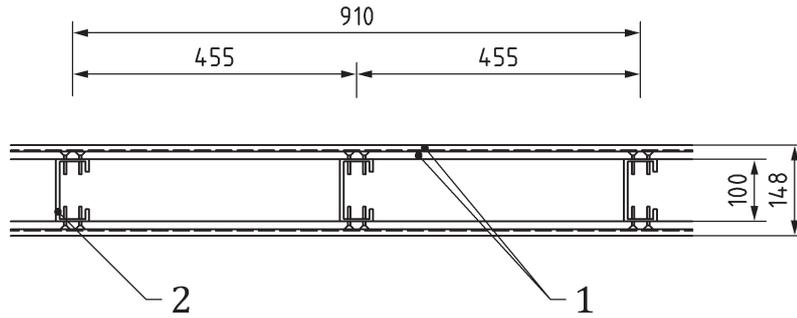
Key

1 type X gypsum board: 12 mm × 2
2 stud: C-3.2 × 100 × 50 × 20

Figure A.4 — Construction of partition wall (60 min of integrity and insulation)

A.4.2 Partition wall between two office rooms

The construction of the wall assembly is shown in Figure A.5. A single layer of regular gypsum wall board is equipped to both sides of studs. The construction may have an inherent level of fire resistance but it is not fire-rated.
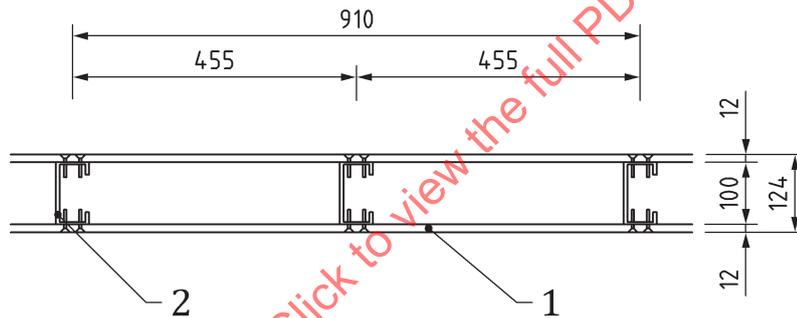
Key

1 regular gypsum board: 12 mm
2 stud: C-3.2 × 100 × 50 × 20

Figure A.5 — Construction of non-fire-rated partition wall

A.4.3 Exterior wall

The construction of the exterior wall assembly is shown in Figure A.6. A precast lightweight concrete panel is used. The thickness is 180 mm. As the thickness is more than 100 mm, the wall is deemed to be fire resistant for more than two hours of integrity and insulation.
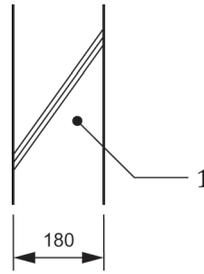
Key

1   precast lightweight concrete panel

Figure A.6 — Construction of exterior wall (with more than 120 min of integrity and insulation)

A.4.4   Floor slab

The construction of the floor slab assembly is shown in Figure A.7. The slab is made of composite construction of normal weight concrete and profiled steel plate. To assure bending capacity during a fire, reinforcing bars of 13 mm diameter are located at 20 mm distance from the bottom of the slab. The thickness of the concrete slab is 80 mm to 155 mm. The slab is a 60-min fire-rated construction.
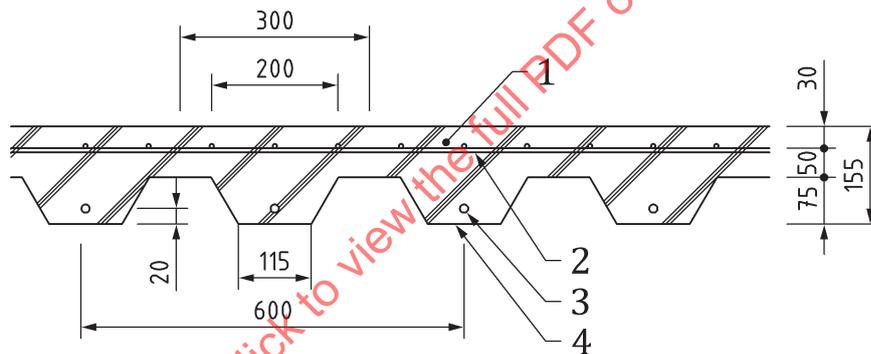
Key

1   concrete, F_c = 21 MPa
2   wire mesh, ϕ 6, @100
3   reinforcing bar, ϕ 13
4   steel plate, 1,2 mm

Figure A.7 — Construction of floor (60 min of load bearing, integrity and insulation)

A.5   Building Frame

A.5.1   Framing Elevation

The framing elevation is shown in Figures A.8 and A.9.
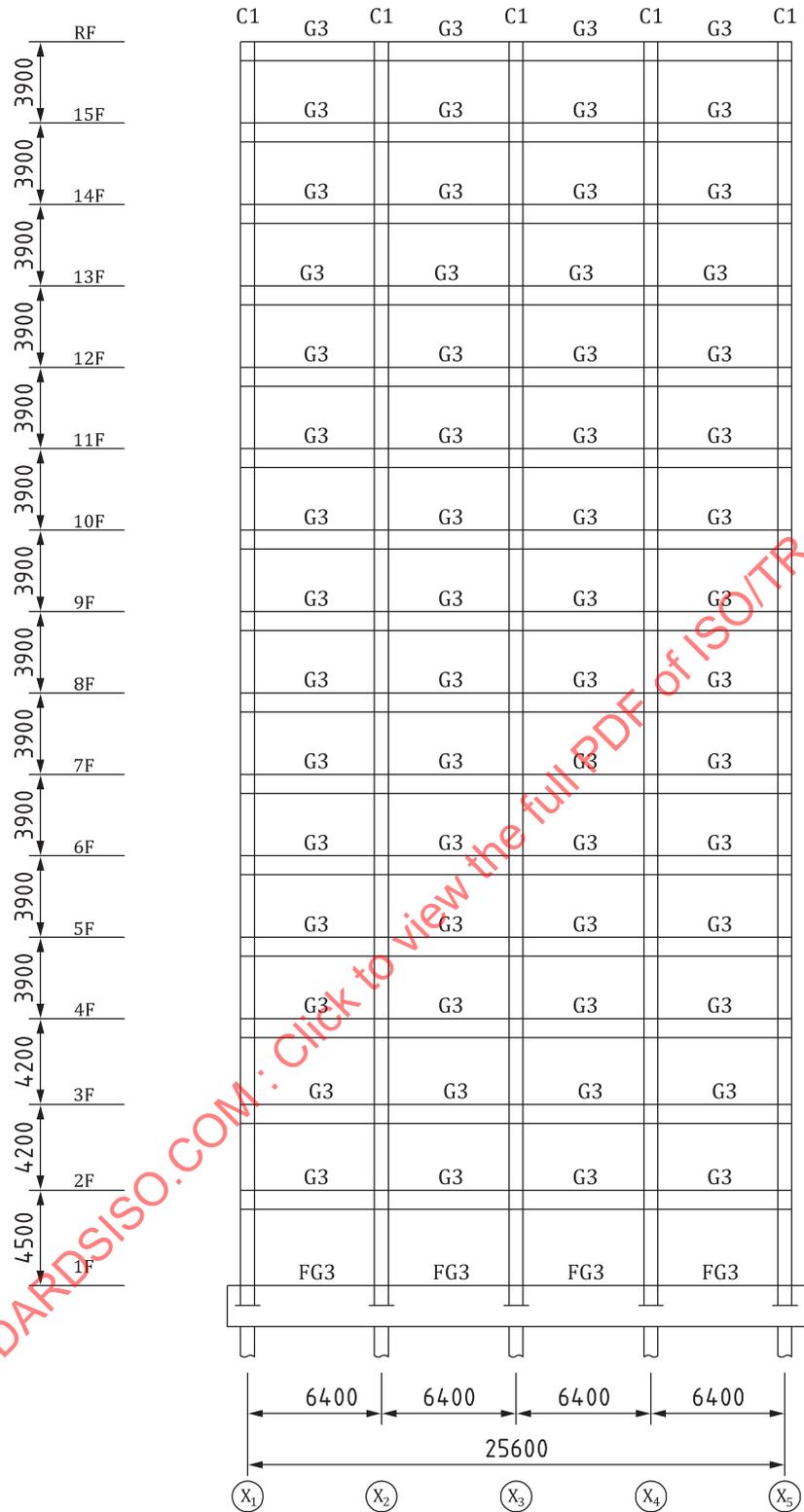
Figure A.8 — Framing elevation at plane Y1
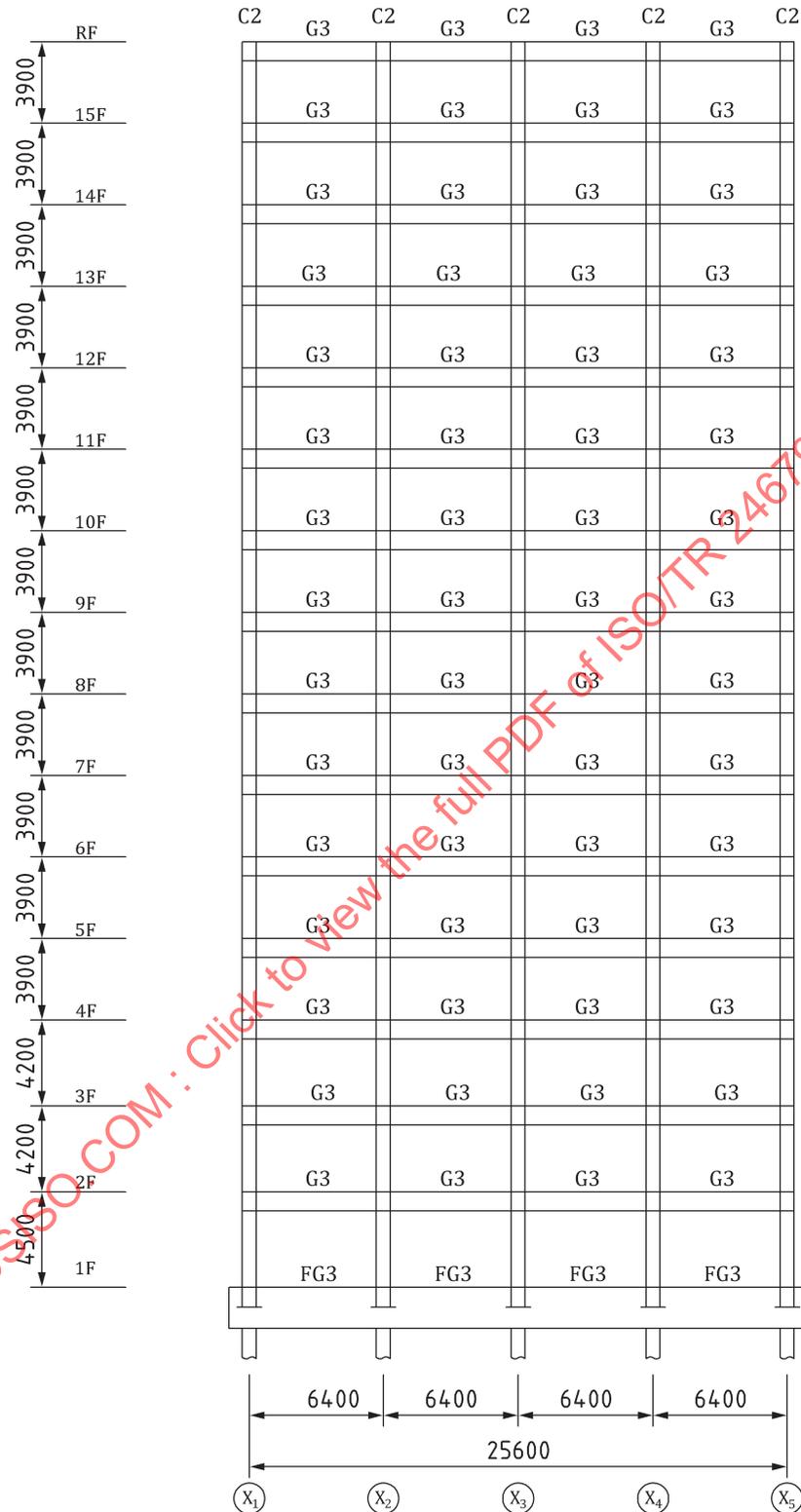
Figure A.9 — Framing elevation at plane Y2

A.5.2   List of sections

The list of columns, girders and beams are shown in Tables A.1, A.2 and A.3. As shown in Table A.1, all the columns are box sectioned. The outer side of column remains the same at all stories but the plate thickness is increased at lower stories in order to support the increased static loads as well as to withstand seismic actions. As shown in Table A.2, all the girders are H-sectioned. The width and height

of the girders are increased at lower floors. For beams, sectional shape remains the same throughout all the floors as shown in Table A.3.

Table A.1 — List of column sections

Floors	C1	C2	C3
R	box-600 × 22	box-600 × 22	box-500 × 19
15			
14			
13			
12	box-600 × 25	box-600 × 28	box-500 × 22
11			
10			
9	box-600 × 32	box-600 × 36	box-500 × 25
8			
7			
6	box-600 × 36	box-600 × 40	box-500 × 32
5			
4			
3	box-600 × 40	box-600 × 45	box-500 × 36
2			
1			
Notation: box-(outer diameter) × (thickness of steel plate).			

Table A.2 — List of girder sections

Floors	G1	G2	G3
R	H-700 × 300 × 14 × 25	H-700 × 250 × 14 × 22	H-700 × 250 × 14 × 22
15			
14			
13	H-700 × 300 × 14 × 25	H-700 × 250 × 14 × 22	H-700 × 250 × 14 × 22
12			
11			
10	H-700 × 300 × 14 × 25	H-700 × 250 × 14 × 25	H-700 × 250 × 14 × 25
9			
8			
7	H-700 × 350 × 14 × 25	H-700 × 300 × 14 × 25	H-700 × 300 × 14 × 25
6			
5			
4	H-900 × 350 × 16 × 25	H-900 × 300 × 16 × 25	H-900 × 300 × 16 × 25
3			
2			
Notation: H-(width) × (height) × (web thickness) × (flange thickness).			

Table A.3 — List of beam sections

Floors	b1	b2
2 to R	H-350 × 175 × 7 × 11	H-450 × 200 × 9 × 14
Notation: H-(width) × (height) × (web thickness) × (flange thickness).		

Annex B
(informative)

Fuel and structural load

B.1 Terms and definitions used in this annex

For the purposes of this annex, the terms and definitions given in the main text apply.

B.2 Normative references

The normative references in the main text apply.

B.3 Symbols used in this annex

A_f surface area of combustible wall lining (m^2)

A_r floor area of a room (m^2)

A_s cross-sectional area of steel (mm^2)

A_t tributary area (m^2)

f_a heat penetration factor

F nominal strength of steel at normal temperature (N/mm^2)

p axial load ratio of column

P axial load on column (N)

q_l movable fuel load density (MJ/m^2)

Q_f heat of combustion of wall lining material per unit area (MJ/m^2)

Q_{rm} heat release from movable room contents (MJ)

Q_{rf} heat release from fixed room contents (MJ)

Q_r design heat release of a room (MJ)

w floor load per unit area (N/m^2)

w_1 load applied directly to a girder from floor (N/m)

w_2 load applied to a girder from floor by way of beams (N/m)

B.4 Fuel load

B.4.1 General

The fuel load of a room is calculated as the sum of the heat to be released from combustible contents (movable fuel load) and from fixed combustible contents (fixed fuel load). In addition to the

aforementioned contents, the heat penetrated from adjacent rooms is considered where there is the possibility of fire spread between the room of fire origin and adjacent rooms[14].

The design heat release of room i is calculated using Formula (B.1):

$$Q_{r,i} = Q_{rm,i} + Q_{rf,i} + \sum_j f_{a,j} \left(Q_{rm,j} + Q_{rf,j} \right)$$ (B.1)

where

$Q_{rm,i}$ is the movable fuel load in room i;

$Q_{rf,i}$ is the fixed fuel load in room i.

The last term represents the heat released at adjacent rooms j, but penetrated into room i.

The movable fuel load is calculated by using characteristic values for movable fuel load density as Formula (B.2):

$$Q_{rm,i} = q_{l,i} A_{r,i}$$ (B.2)

The fixed fire load accounts for combustible wall, ceiling and floor lining materials and so on, as shown in Formula (B.3):

$$Q_{rf,i} = \sum_k A_{f,k} Q_{f,k}$$ (B.3)

where the summation by subscript k corresponds with all the combustibles in room i.

A fire in a room may spread to adjacent rooms due to the presence of non-fire-rated walls. In those cases, construction elements will be exposed to additional heating due to the additional burning taking place in adjacent rooms. The last term of Formula (B.1) is provided to take this effect into account. The heat penetration factor, f_a, is determined in accordance with the fire resistance of walls and door assemblies empirically.

B.4.2 Calculation results

The fixed fuel load is calculated based on specification of surface lining materials. The results are shown in Tables B.1 and B.2. The calculation of total heat release and design heat release are described in 6.2.2.

Table B.1 — Fixed fuel load of rooms 201 and 1501

Position	Material	Area, A_f (m²)	Heat of combustion per unit area, Q_f (MJ/m²)	Heat release, Q_{rf} (MJ)
Wall W	Finish/Paint	8,0	8,0	64
	Base/GB		9,6	76,8
Wall E	Finish/Paint	35,0	8,0	280
	base/GB		9,6	336
Wall S	Finish/Paint	2,5	8,0	20
	Base/GB		9,6	24
Wall N	Finish/Paint	15,0	8,0	120
	Base/GB		19,2	288
Floor	Carpet	87,5	64,0	5 600
Ceiling	RW board		9,6	840
Heat release from fixed combustibles, $\Sigma A_f Q_f =$				7 649

Table B.2 — Fixed fuel load of rooms 202 and 1502

Position	Material	Area, A_f (m^2)	Heat of combustion per unit area, Q_f (MJ/m^2)	Heat release Q_{rf} (MJ)
Wall W	Finish/Paint	35,0	8,0	280
	Base/GB		9,6	336
Wall E	Finish/paint	8,0	8,0	64
	Base/GB		9,6	76,8
Wall S	Finish/Paint	10,0	8,0	80
	Base/GB		9,6	96
Wall N	Finish/Paint	45,0	8,0	360
	Base/GB		19,2	864
Floor	Carpet	275	64	17 600
Ceiling	RW board		9,6	2 640
Heat release from fixed combustibles, $\Sigma A_f Q_f$ =				22 397

B.5 Structural load

B.5.1 General

The structural load was calculated as the sum of movable load on floor and fixed load. The density of the structural load was determined by the building code[13].

B.5.2 Axial loads on columns

The structural design was carried out to determine the cross-sectional shape of the structural members. The final design is summarized in Tables B.3 and B.4. Steel grade is SN 490 as determined by JIS G 3136[11] with nominal design strength 325 N/mm^2. Due to the high seismic load, large cross sections are needed. As a result, the axial load ratio of columns is small, particularly for the columns on 15th floor.

Table B.3 — Axial load ratio of columns at normal temperature, 2nd floor

Position	Symbol	Tributary area, A_t (m^2)	Floor load per unit area, w (N/m^2)	Nominal strength, F (N/mm^2)	Cross-sectional area, A_s (mm^2)	Axial load ratio, $p = P/A_s F$ (-)
X1-Y1	C1	21,9				0,108
X2-Y1	C1	43,8				0,216
X3-Y1	C1	43,8			89 600	0,216
X4-Y1	C1	43,8				0,216
X5-Y1	C1	21,9				0,108
X1-Y2	C2	35,5	143 980	325		0,158
X2-Y2	C2	71,1				0,315
X3-Y2	C2	71,1			99 900	0,315
X4-Y2	C2	71,1				0,315
X5-Y2	C2	35,5				0,158

Table B.4 — Axial load ratio of columns at normal temperature, 15th floor

Position	Symbol	Tributary area, A_t (m²)	Floor load per unit area, w (N/m²)	Nominal strength, F (N/mm²)	Cross sectional area, A_s (mm²)	Axial load ratio, $p = P/A_s F$ (-)
X1-Y1	C1	21,9				0,016 4
X2-Y1	C1	43,8				0,032 8
X3-Y1	C1	43,8				0,032 8
X4-Y1	C1	43,8				0,032 8
X5-Y1	C1	21,9	12 388	325	50 864	0,016 4
X1-Y2	C2	35,5				0,026 6
X2-Y2	C2	71,1				0,053 3
X3-Y2	C2	71,1				0,053 3
X4-Y2	C2	71,1				0,053 3
X5-Y2	C2	35,5				0,026 6

B.5.3 Structural load on girders and beams

The calculation results of structural load on girders and beams are shown in Table B.5 and B.6.

Table B.5 — Structural load on girders and beams on second floor

Position and symbol		Load type	Item	Load per unit floor area (N/m²)	Tributary area (m²)	Load per unit length of girder or beam (N/m)	Load applied directly to a girder from floor, w_1 (N/m)	Load applied to a girder from floor by way of beams, w_2 (N/m)
X1	G1	Fixed load	Girders and beams	—	—	2 832		
			Exterior walls	—	—	12 300	20 909	7 346
			Floor and partition walls	3 897	11,56	3 313		
		Movable load		2 900		2 465		
X4	G1	Fixed load	Girders and beams	—	—	2 832		
			Floor and partition walls	3 897	23,12	6 625	14 387	14 692
		Movable load		2 900		4 930		
X5	G1	Fixed load	Girders and beams	—	—	2 832		
			Exterior walls	—	—	13 816	22 425	7 346
			Floor and partition walls	3 897	11,56	3 313		
		Movable load		2 900		2 465		
Y1	G3	Fixed load	Girders and beams	—	—	2 619		
			Exterior walls	—	—	11 855	18 468	—
			Floor and partition walls	3 897	7,99	2 290		
		Movable load		2 900		1 704		
Y2	G3	Fixed load	Girders and beams	—	—	2 619		
			Floor and partition walls	3 897	15,98	4 579	10 605	—
		Movable load		2 900		3 408		

Table B.5 *(continued)*

Position and symbol		Load type	Item	Load per unit floor area (N/m²)	Tributary area (m²)	Load per unit length of girder or beam (N/m)	Load applied directly to a girder from floor, w_1 (N/m)	Load applied to a girder from floor by way of beams, w_2 (N/m)
—	b1	Fixed load	Girders and beams	—	—	686	8 672	—
			Floor and partition walls	3 897	15,98	4 579		
		Movable load		2 900		3 408		

w_1 floor load directly applied to a girder.

w_2 floor load applied to girder through beams.

Table B.6 — Structural load on girders and beams on 15th floor

Position and symbol		Load type	Item	Load per unit floor area (N/m²)	Tributary area (m²)	Load per unit length of girder or beam (N/m)	Load applied directly to a girder from floor, w_1 (N/m)	Load applied to a girder from floor by way of beams, w_2 (N/m)
X1	G1	Fixed load	Girders and beams	—	—	2 214	21 521	9 815
			Exterior walls	—	—	11 421		
			Floor and partition walls	6 378	11,56	5 421		
		Movable load		2 900		2 465		
X4	G1	Fixed load	Girders and beams	—	—	2 214	17 985	19 629
			Floor and partition walls	6 378	23,12	10 842		
		Movable load		2 900		4 930		
X5	G1	Fixed load	Girders and beams	—	—	2 214	22 928	9 815
			Exterior walls	—	—	12 829		
			Floor and partition walls	6 378	11,56	5 421		
		Movable load		2 900		2 465		
Y1	G3	Fixed load	Girders and beams	—	—	1 894	18 353	—
			Exterior walls	—	—	11 009		
			Floor and partition walls	6 378	7,99	3 747		
		Movable load		2 900		1 704		
Y2	G3	Fixed load	Girders and beams	—	—	1 894	12 795	—
			Floor and partition walls	6 378	15,98	7 494		
		Movable load		2 900		3 408		
—	b1	Fixed load	Girders and beams	—	—	686	11 587	—
			Floor and partition walls	6 378	15,98	7 494		
		Movable load		2 900		3 408		

w_1 floor load directly applied to a girder.

w_2 floor load applied to girder through beams.

Annex C
(informative)

Fire temperatures

C.1 Terms and definitions used in this annex

For the purposes of this annex, the terms and definitions given in the main text apply in addition to the following:

C.1.1

burning type index

fraction of incoming air to compartment over fuel surface area

C.1.2

opening factor

index to mass flow rate of air incoming through an opening

C.2 Normative references

The normative references in the main text apply.

C.3 Symbols used in this annex

A_c	wall area (m^2)
A_f	surface area of interior lining material (m^2)
A_{fuel}	surface area of fuel (m^2)
A_{op}	opening area (m^2)
$A_{op}\sqrt{H_{op}}$	opening factor (m$^{5/2}$)
$\Sigma A_{op}\sqrt{H_{op}}/A_{fuel}$	burning type index (m$^{1/2}$)
A_r	area of floor (m^2)
A_w	wall surface area (m^2)
H_{op}	height of opening (m)
H_r	average ceiling height of room (m)
q_b	heat release rate (MW)
q_l	movable fuel load density (MJ/m^2)
Q_r	design heat release of a room (MJ)

t_f	fire duration time (min)
T_f	fire temperature (K)
T_0	initial temperature (K)
χ	burning type index ($m^{1/2}$)
ϕ	oxygen consumption index
α	fire temperature rise coefficient ($K/min^{1/6}$)
$\sqrt{k\rho c}$	thermal inertia ($kW\ s^{1/2}/m^2\ K$)

C.4 Calculation procedure of room fire temperature

C.4.1 General

The fire temperature is calculated on room by room basis using a closed form formula for compartment fire temperatures[14].

C.4.2 Heat release rate and fire duration time

The heat release rate or the amount of heat released in a room per unit time, q_b (MW), is calculated using Formula (C.1)[15]:

$$q_b = \begin{cases} 1,6\chi A_{fuel} & (\chi \le 0,081) \\ 0,13 A_{fuel} & (0,081 < \chi \le 0,1) \\ \left[2,5\chi \exp(-11\chi) + 0,048\right] & (0,1 < \chi) \end{cases} A_{fuel} \tag{C.1}$$

The parameter $\chi\,(m^{1/2})$ is the burning type index representing oxygen availability per unit surface area of combustible surface, as shown in Formula (C.2):

$$\chi = \max\left(\frac{\sum A_{op}\sqrt{H_{op}}}{A_{fuel}}, \frac{A_r\sqrt{H_r}}{70 A_{fuel}}\right) \tag{C.2}$$

where, A_{op} (m^2) and H_{op} (m) are the area and the height of an opening, respectively, and A_r (m^2) and H_r (m) are the floor area and the average height of fire room, respectively.

The fuel surface area, A_{fuel} (m^2), is calculated using Formula (C.3)[4]:

$$A_{fuel} = 0,26\, q_b^{1/3}\, A_r + \sum \phi A_f \tag{C.3}$$

where the oxygen consumption coefficient, ϕ, represents relative oxygen consumption rate of a finishing material to wood in burning.

The duration of a fire, t_f (min), is determined by Formula (C.4), assuming constant burning rate:

$$t_f = \frac{Q_r}{60 q_b} \tag{C.4}$$

C.4.3 Fire room temperature

The fire room temperature curve is calculated by using Formula (C.5):

$$T_f(t) = \alpha\, t^{1/6} + T_0 \quad \left(0 \le t \le t_f\right) \tag{C.5}$$

where the fire temperature rise coefficient, $\alpha(\text{K/min}^{1/6})$, expresses the severity of the fire and calculated by using Formula (C.6)[5]:

$$\alpha = 1280 \left(\frac{q_b}{\sqrt{\sum A_w \sqrt{k\rho c}}\ \sqrt{\Sigma A_{op} \sqrt{H_{op}}}} \right)^{2/3} \tag{C.6}$$

where A_w (m²) and $\sqrt{k\rho c}$ (kW·s$^{1/2}$/m²·K) are the surface area and the thermal inertia of each part of enclosure walls, floor and ceiling of the room.

C.5 Calculation results room fire temperature

C.5.1 Surface area of fuel

The calculation results of the surface area of fuel are shown in Tables C.1 and C.2.

Table C.1 — Surface area of fuel in room 201 and 1501

Position	Material	Material classification	Oxygen consumption coefficient, ϕ	Surface area of interior lining material, A_f (m²)	Effective surface area, ϕA_f (m²)
Wall W	Paint	Combustible	1	8	8
Wall E	Paint	Combustible	1	35	35
Wall S	Paint	Combustible	1	2,5	2,5
Wall N	Paint	Combustible	1	15	15
Floor	Carpet	Combustible	1	87,5	87,5
Ceiling	Rock wool board	Non-combustible	0,1	87,5	8,75
				$\Sigma(\phi \times A_f) =$	156,75
				$A_{fuel} = 0{,}26 \times q_l^{1/3} \times A_r + \Sigma(\phi \times A_f) =$	344,3

Table C.2 — Surface area of fuel in room 202 and 1502

Position	Material	Material classification	Oxygen consumption coefficient, ϕ	Surface area of interior lining material, A_f (m²)	Effective surface area, ϕA_f (m²)
Wall W	Paint	Combustible	1	35	35
Wall E	Paint	Combustible	1	5	8
Wall S	Paint	Combustible	1	10	10
Wall N	Paint	Combustible	1	45	45
Floor	Carpet	Combustible	1	275	275
Ceiling	Rock wool board	Non-combustible	0,1	275	27,5
				$\Sigma(\phi \times A_f) =$	400,5
				$A_{fuel} = 0{,}26 \times q_l^{1/3} \times A_r + \Sigma(\phi \times A_f) =$	989,8

C.5.2   Opening factor

The calculation results of the opening factor are shown in Tables C.3 and C.4.

Table C.3 — Opening factor of rooms 201 and 1501

Opening posi-tion	Opening area A_{op} (m^2)	Opening height H_{op} (m)	Opening factor $A_{op}\sqrt{H_{op}}$ (m$^{5/2}$)
Opening W	15,96	1,9	22,0
Opening S	7,98	1,9	11,0
Fire door	2,64	2,2	0,0
$\sum A_{op}\sqrt{H_{op}} =$			33,0
$A_r\sqrt{H_r}/70 =$			2,4
$f_{op} = \max\left\{\sum A_{op}\sqrt{H_{op}}, A_r\sqrt{H_r}/70\right\} =$			33,0

Table C.4 — Opening factor of rooms 202 and 1502

Opening posi-tion	Opening area A_{op} (m^2)	Opening height H_{op} (m)	Opening factor $A_{op}\sqrt{H_{op}}$ (m$^{5/2}$)
Opening E	15,96	1,9	22,0
Opening S	23,94	1,9	33,0
Fire door	7,92	2,2	0,0
$\sum A_{op}\sqrt{H_{op}} =$			55,0
$A_r\sqrt{H_r}/70 =$			7,6
$f_{op} = \max\left\{\sum A_{op}\sqrt{H_{op}}, A_r\sqrt{H_r}/70\right\} =$			55,0

C.5.3   Heat release rate and fire duration time

The calculation results of the heat release rate are shown in Table C.5.

Table C.5 — Heat release rate and fire duration time of rooms 201, 1501, 202 and 1502

Room	χ (m$^{1/2}$)	Design heat release of the room, Q_r (MJ)	Heat release rate, q_b (MW)	Fire duration time, t_f (min)
201,1501	0,096	83,108	44,8	30,9
202,1502	0,056	184,894	88,0	35,0

C.5.4   Fire temperature rise coefficient

The calculation results of the fire temperature rise coefficients are shown in Tables C.6 and C.7.

Table C.6 — Fire temperature rise coefficient of rooms 201 and 1501

Part	Material	Wall area A_c (m²)	Thermal inertia $\sqrt{k\rho c}$ (kWs$^{1/2}$/m²K)	Thermal response conductance $A_c\sqrt{k\rho c}$ (kWs$^{1/2}$/K)
Wall W	Concrete	9,3	1,75	16,3
Wall E	Gypsum board	35	0,35	12,4
Wall S	Concrete	2,94	1,75	5,1
Wall N	Gypsum board	15	0,4	6,0
Fire door	Steel	2,64	1,08	2,9
Floor	Concrete	87,5	1,75	153,1
Ceiling	Concrete	87,5	1,75	153,1
			$\sum A_c\sqrt{k\rho c} =$	349
			Fire temperature rise coefficient: $\alpha =$	715

Table C.7 — Fire temperature rise coefficient of rooms 202 and 1502

Part	Material	Wall area A_c (m²)	Thermal inertia $\sqrt{k\rho c}$ (kWs$^{1/2}$/m²K)	Thermal response conductance $A_c\sqrt{k\rho c}$ (kWs$^{1/2}$/K)
Wall W	Gypsum board	35	0,35	12,4
Wall E	Concrete	9,3	1,75	16,3
Wall S	Concrete	11,7	1,75	20,5
Wall N	Gypsum board	45	0,4	18,0
Fire door	Steel	7,92	1,08	8,6
Floor	Concrete	275	1,75	481,3
Ceiling	Concrete	275	1,75	481,3
			$\sum A_c\sqrt{k\rho c} =$	1 038
			Fire temperature rise coefficient: $\alpha =$	658

Annex D
(informative)

Maximum temperature of insulated steel elements

D.1 Terms and definitions used in this annex

For the purposes of this annex, the terms and definitions given in the main text apply in addition to the following.

D.1.1
section factor

heated perimeter of element divided by cross-sectional area

D.2 Normative references

The normative references in the main text apply.

D.3 Symbols used in this annex

A_i cross sectional area of insulation material (m²)

A_s cross sectional area of steel element (m²)

a_w temperature rise delay time coefficient (min/m²)

C heat capacity ratio, $\rho_i c_i / \rho_s c_s$

c_i specific heat of insulation material (J/kg·K)

c_s specific heat of steel (J/kg·K)

h steel element temperature rise coefficient (min⁻¹)

H_s heated perimeter of steel element (m)

H_i heated perimeter of insulation material (m)

K_0 basic temperature rise rate (m/min)

R thermal resistance coefficient (m⁻¹)

t_{eq} equivalent fire duration as replaced with a fire as specified in ISO 834-1 (min)

t_{post} time to maximum steel temperature since the stop of heating

t_p thickness of insulation

t_w time delayed by evaporation of water in the insulating material (min)

t_0 time to start temperature rise (min)

T_f fire temperature (K)

T_s temperature of steel elements

$T_{s,max}$ maximum temperature of steel

T_0 initial temperature (K)

ϕ perimeter ratio, H_i/H_s

α fire temperature rise coefficient (K/min$^{1/6}$)

ρ_s density of steel (kg/m^3)

ρ_i density of insulation material (kg/m^3)

D.4 Calculation procedure of maximum steel temperature

D.4.1 General

The steel temperature rise was calculated by an experimental correlation derived from standard fire resistance tests conducted in accordance with ISO 834-1. The correlation was extended by using the concept of equivalent fire exposure.

D.4.2 Temperature rise of steel element under a standard heating curve as specified in ISO 834-1

The temperature rise of a steel element over time insulated by sprayed rock wool can be calculated using Formula (D.1) and Formula (D.2)[3]:

$$T_s = \left(T_f - T_0\right)\left\{1 - \exp\left[-h\left(t - t_w - t_0\right)\right]\right\} + T_0 \tag{D.1}$$

$$h = \frac{(H_i / H_s) K_0 (H_s / A_s)}{\left(1 + \dfrac{H_i / H_s}{H_i / A_i} R\right)\left(1 + \dfrac{\phi}{2} \dfrac{H_s / A_s}{H_i / A_i} C\right)} \tag{D.2}$$

where

t_0 is the time to start temperature rise (min);

t_w is the time delayed by evaporation of water in the insulating material (min).

The maximum temperature will be archived shortly after (equivalent) heating duration, t_{eq} in Formula (D.3):

$$T_{s,max} = (T_f - T_0)\left\{1 - \exp\left[-h\left(t_{eq} + t_{post} - t_w - t_0\right)\right]\right\} + T_0 \tag{D.3}$$

where t_{post} is the time to maximum steel temperature since the stop of heating. Assuming that t_{post} is fairly close to t_0, the maximum steel temperature is approximated by using Formula (D.4):

$$T_{s,max} = (T_f - T_0)\left\{1 - \exp\left[-h\left(t_{eq} - t_w\right)\right]\right\} + T_0 \tag{D.4}$$

In case of a fire as specified in ISO 834-1, the temperature can be approximated by using Formula (D.5):

$$T_f = 345\log(8t + 1) + T_0 \approx 460t^{1/6} + T_0 \tag{D.5}$$

By combining Formulae (D.4) and (D.5), the final form would be Formula (D.6):

$$T_{s,max} = 460t_{eq}^{1/6}\left\{1 - \exp\left[-h\left(t_{eq} - t_w\right)\right]\right\} + T_0 \tag{D.6}$$

The parameters for steel elements insulated by sprayed rock wool are shown in Table D.1.

Table D.1 — Parameters for temperature calculations of steel elements insulated by sprayed rock wool

Insulation type	Delay time coefficient, a_w (min/m²)	Basic temperature rise coefficient, K_0 (m/min.)	Thermal resistance coefficient, R (m⁻¹)	Heat capacity ratio, C (-)
Box-sectioned column heated from all sides	19 600	0,001 16	390	0,081
H-sectioned beam heated from three sides	26 000	0,000 67	235	0,081

D.4.3 Equivalent fire duration and maximum steel temperature

For fires described by $T_f = \alpha t^{1/6} + T_0$, the equivalent fire duration can be approximated by using Formula (D.7)[3]:

$$t_{eq} = \left(\frac{\alpha}{460}\right)^{3/2} t_f \tag{D.7}$$

Putting Formula (D.7) into Formula (D.6), the maximum steel temperature under thermal action can be calculated using Formula (D.8):

$$T_{s,max} = 460\left[\left(\frac{\alpha}{460}\right)^{3/2} t_f\right]^{1/6}\left\{1 - \exp\left[-h\left(\frac{\alpha}{460}\right)^{3/2}\left(t_f - t_w\right)\right]\right\} + T_0; \tag{D.8}$$

D.5 Calculation results of maximum steel temperature

D.5.1 Columns

The calculated parameters for maximum steel temperatures of columns are shown in Tables D.2 and D.3.