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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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Contents

Page

Foreword

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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*

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 m^2 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.

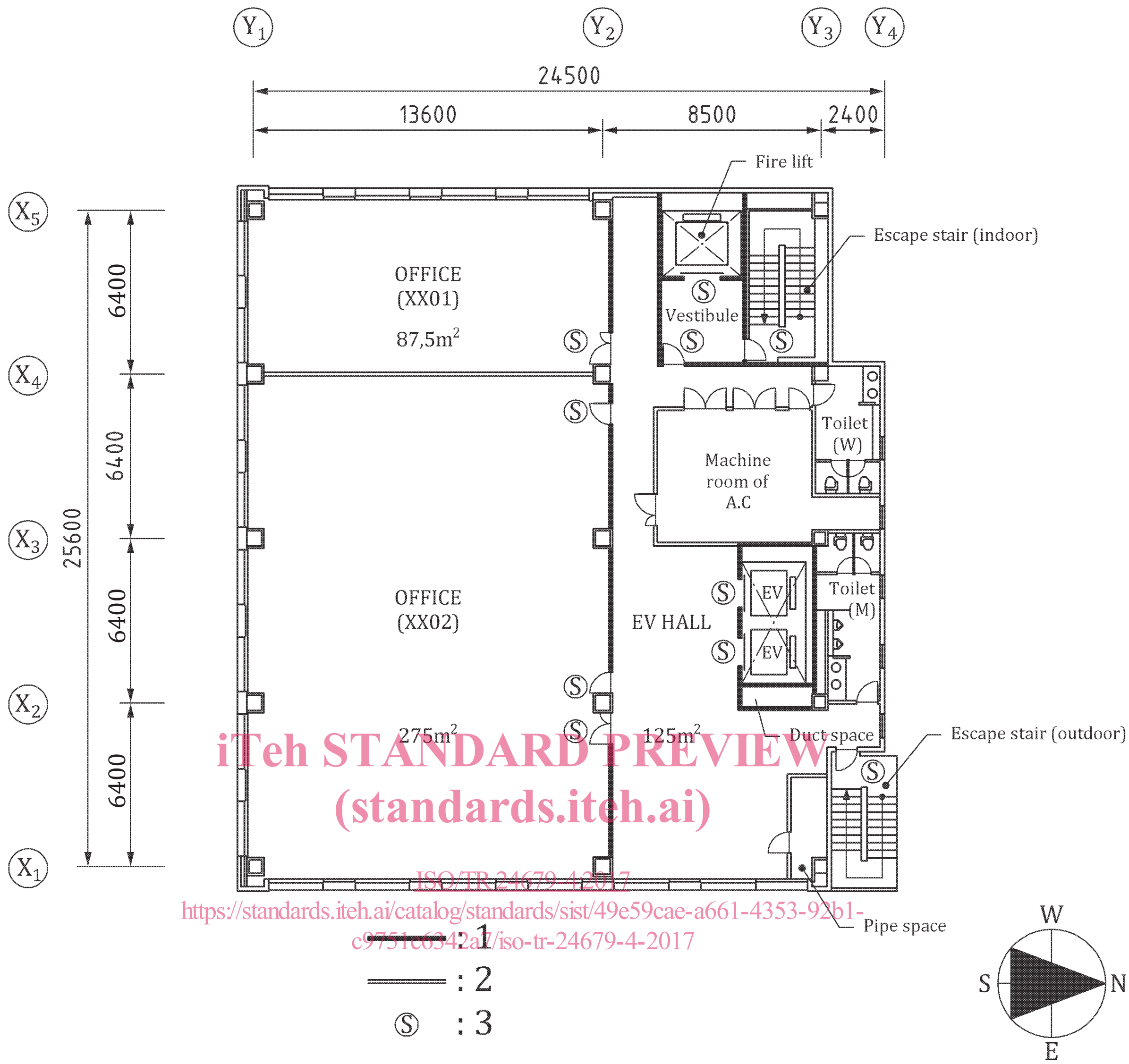
The applied load of design on the floors is taken as follows:

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

— self-weight of floor: 3,65 kN/m^2.

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/m^2 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/m^2)	Floor area A_r (m^2)	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]:

$$1{,}0G + 1{,}0Q \quad (1)$$

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:

$$1{,}0G + 1{,}0Q + 1{,}0K \quad (2)$$

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).

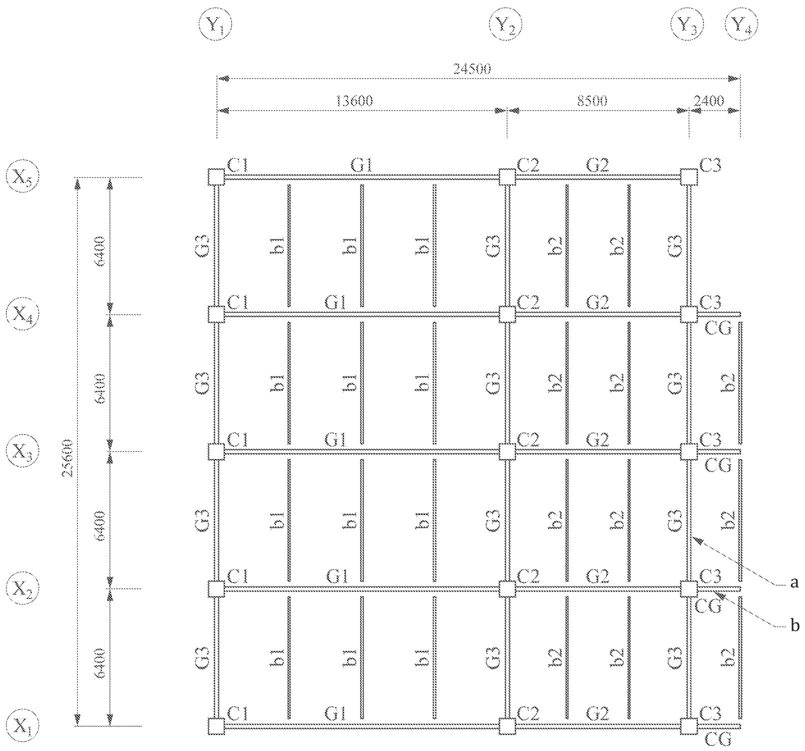
6.4 Step 3: Trial design plan for fire safety of structures

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.

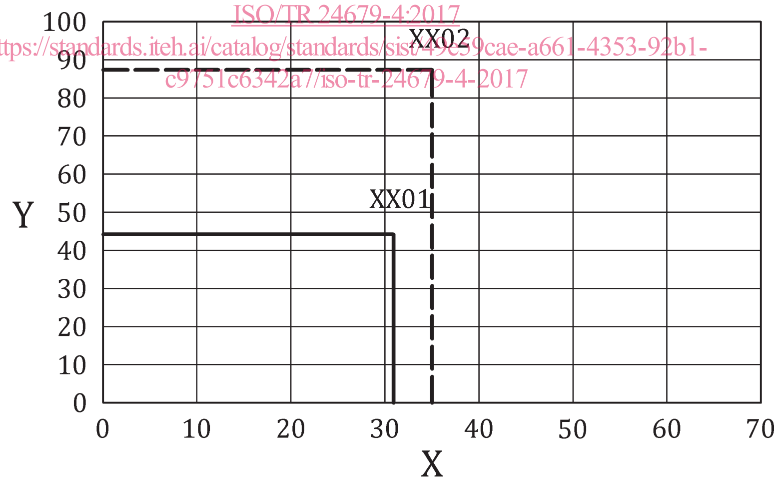
A nominal exterior fire is assumed to occur in the neighbour of the building. The standard fire temperature as specified in ISO 834-1 for 60 min is assumed as the nominal fire for exterior heating.

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:

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

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

