Development of Fire-safety wooden multi-story building

A Master Thesis submitted for the degree of
"Master of Science"

Supervised by
Univ. Prof. DDI. Wolfgang Winter
Univ. Ass. Dr. Yoshiaki Amino

Institute of Architectural Sciences
Structural Design and Timber Engineering

Vienna University of Technology

0628068
Masahide Nakane

16/09/2008, Vienna, Austria

Contents

Abstract

With increasing awareness of environmental conservation in recent years, building with wood has been gaining popularity worldwide. Technological improvements concerning wood industry and building construction in the 20th century have been making it possible to realize large dimensional building with wood. However, middle-to-high rise building with wood in urban area has not gained popularity enough. The major reason comes from problems of fire protection, due to the material characteristics and regulations.

Proper design concepts from aspects considering fire protection are indispensable. In other words, developments of fire-safety measure expand possibilities for use of wood as a building material. This thesis is intended to study the feasibility of wooden multi-story building in urban area by means of considering the issue of fire safety. Concepts of fire safety design are studied from the three viewpoints: fire-resistive structure, smoke control and evacuation. The study of fire-resistive structure includes study of fire protection measures and a conceptual proposal. The study of smoke control and evacuation also includes a conceptual proposal.

Applying the concepts described above, an example of building is designed as a prototype building. The project includes proposals of fire-resistive structure, smoke control and safe evacuation. And finally, structural calculation is carried out in order to prove briefly that the proposal of the structure is realizable.

Chapter 1. Introduction

1. 1. Background

1. 1. 1. Building with wood

Wood has been used as a major building material by tradition in many countries due to available resources and handiness character. In recent years, with increasing awareness of environmental conservation, building with wood has been gaining popularity worldwide due to environmental friendliness and sustainability, as well as health and comfort indoor environment. Following reasons are generally mentioned as advantages of building with wood.

– Wood stores carbon even after it is used as timber building materials, and reduces carbon dioxide in the atmosphere, which is cause of global warming as a green house gas.
– Fossil energy consumptions of timber building materials during production and wooden building during construction are much lower than other building materials, e.g. steel and concrete.
– Timber can be reused or recycled for some manufactured wood products e.g. chip board, fiber board and strand board. And finally can be used as biomass energy by incineration.
– By using wood from local forests, it is possible to revitalize the forest industry, and appropriate control of forests contributes to prevent natural disasters, e.g. flood and landslide.
– Wooden-surfaced room contributes to high comfort of indoor environment due to humidity control property and optical and psychological effects.

1. 1. 2. Multi-story wooden building in urban area

Technological improvements concerning wood industry and building construction in the 20th century have expanded possibilities for use of wood as a building material. Especially in large dimensional wooden buildings, the improvements of technologies, e.g. engineered wood, CNC cutting, construction machines and computing on design, have played a significant role. Many examples of large dimensional wooden buildings have been realized, especially in large span buildings (e.g. sports halls, **Figure 1.1.**), and low-to-middle rise buildings (e.g. apartment in suburban area, **Figure 1.2.**).

Compared to the above examples, middle-to-high rise building in urban area has not gained popularity enough. Though it is clear that it is effective for increasing opportunities of building with wood, middle-to-high rise buildings in urban area have been hardly realized. In structural aspect, the technological improvements and studies have been making it possible to design large dimensional structure which is able to be applied to middle-to-high rise building. The major reason why middle-to-high rise wooden buildings are not realized enough, comes from problems of fire protection

1. 1. 3. Fire protection

Fire protection is crucial problem on wooden building, due to the material characteristics and regulations. Timber ignites lower temperature than concrete and steel and continues combusting by itself. Therefore, wooden construction is sorted in the weakest structural type against fire, and building codes in many countries contain high and detailed fire protection requirements. Especially in urban area, regulations are tighter than rural area, because distances between buildings are usually narrow. And on middle-to-high-rise building there are more things to consider than low-rise building regardless of regulations.

For the reasons, proper design concepts from aspects considering fire protection are indispensable in order to realize multi-story wooden buildings in urban area. In other words, developments of fire-safety measure expand possibilities for use of wood as a building material.

Figure1.1. An example of a large span wooden building
Multi-purpose Arena, Joensuu, Finland, 2006

Figure1.2. An example of a middle-rise wooden building
Mühlweg apartment, Vienna, Austria, 2006

1.2. Purpose of the thesis

This thesis is intended to study the feasibility of wooden multi-story building in urban area by means of considering the issue of fire safety.

The topic of fire safety on wooden building is crucial problem. Therefore, many studies and researches have been carried out especially in the field of building physics and engineering. However, in the field of architecture design and structural design, the topic is hardly mentioned, though it affects building design and planning considerably, because it is usually thought a barrier of design. In this thesis, the topic of fire safety is studied from aspects of architecture design and structural design. By this measure, a new design concept of fire safety is achieved, and it expands possibilities for use of wood as a building material.

1.3. Method of the thesis

In the chapter 2, basic concepts of fire safety is studied. And in the same chapter conceptual proposal of fire safety design is presented. In the chapter 3, a building example is proposed as a prototype building of the proposed concepts of fire safety design. In the chapter 4, structure calculation is carried out, in order to prove that the concepts and the prototype building are realizable in a practical level.

Chapter 2. Fire-resistive structure

2.1. Introduction

In this chapter and the next chapter, concepts of fire safety design are studied from the three viewpoints: Chapter2. fire-resistive structure, Chapter3. smoke control and evacuation. Each chapter includes study of basic idea and conceptual proposal which is applied for the building example in the chapter 4.

The three topics on the table of fire phase are presented in **Figure 2.1**. On the table, progress and general prevention measure are shown on each phase. The five progresses are concerning building design and planning: Start of evacuation (Phase1), Evacuation from fire room (Phase3), Generation of poisonous gas (phase4), Declination of load-bearing capacity (Phase5) and Smoke diffusing toward neighboring space (Phase5). The table shows that the three topics widely cover the fire phase.

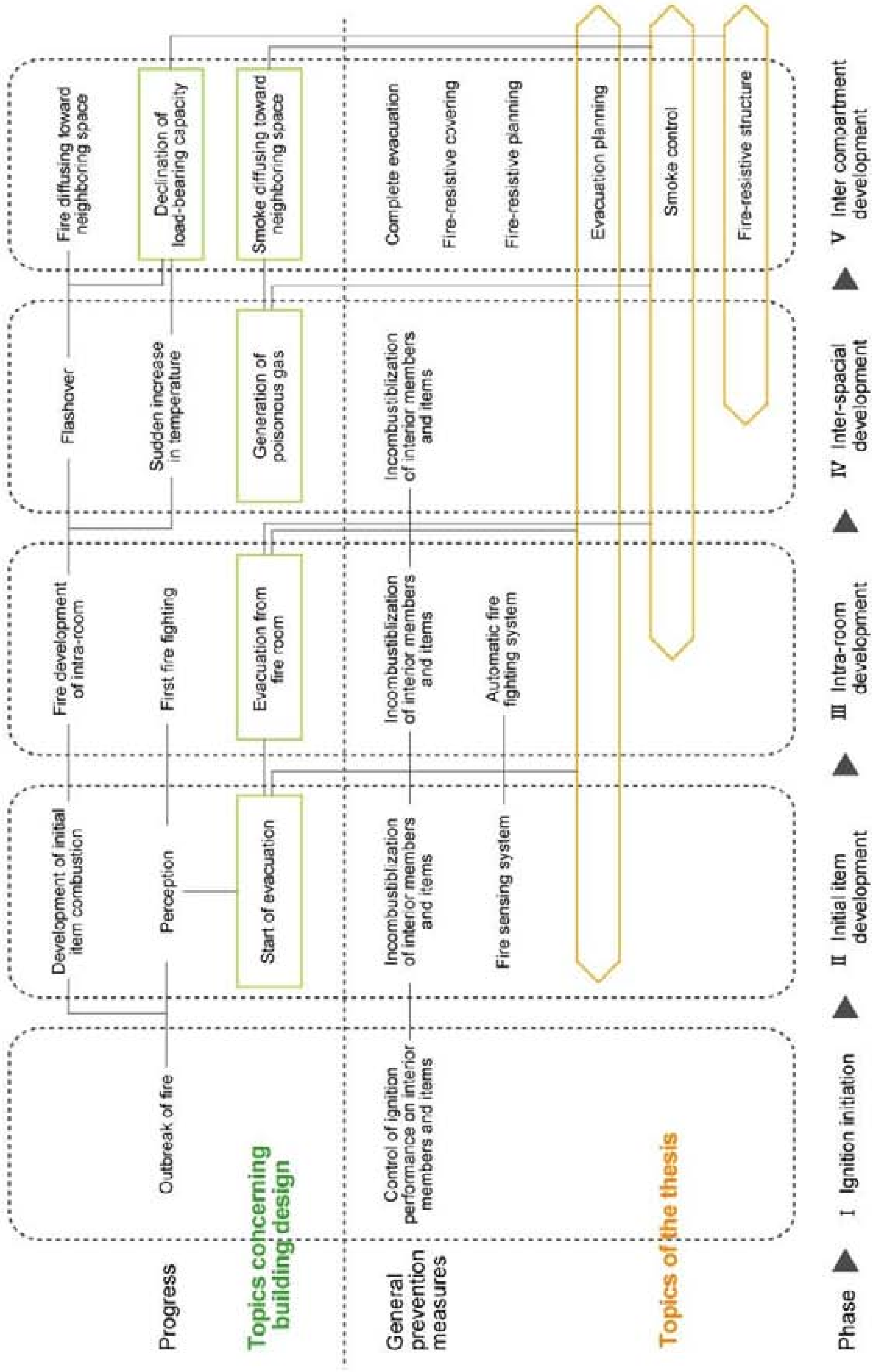


Figure2.1. Fire phase – progress and general prevention measure

2.2. Fire-resistive performance

Requirements for fire-resistance concerning building structure, on building codes in several countries are basically as follow. Load-bearing capacity of construction can be assumed for a specific period of time. On high-rise building up to 5 stories, 90-180 minutes fire rating is often required. **Figure 2.2.** In addition, on the building standard law of Japan, it is required that the building withstands until the end of fire.

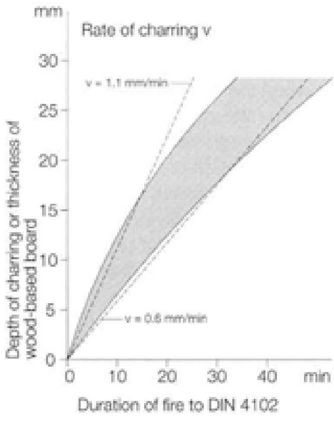
"Fire-resistive buildings: Buildings that conform to the following criteria:
Those which can withstand the heat of a fire predicted to occur inside the building according to the construction, building equipment, and use of the said building until the end of the said fire." (The building standard law of Japan, Article2,9-2,(a),(2),(i)). [1]

That is to say, wood can not be used as a load-bearing member without fire-protecting treatment such as incombustible covering. Because wooden members combust and do not stop charring by themselves, and in the end the members lose the load-bearing capacity. Therefore, it is not sufficient to attach just burning marginal thickness on structural members according to the rate of charring.

Rate of charring v in mm/min [$v_{DIN\ 4102\ pt\ 4\ (Mar\ 94)} = v_{ENV\ 1995\text{-}1\text{-}2}$]

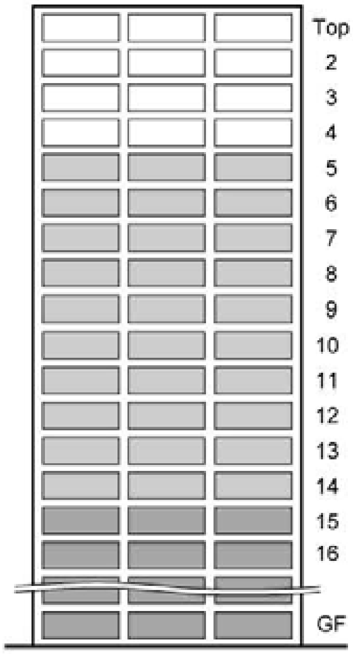
Type of timber 1)		Rate of charring 1) v in mm/min
Generally	Boundary conditions	$v_{top} = v_{side} = v_{btm}$ $v_{beam} = v_{col} = v_{ten\ mem}$
Glued laminated timber	Softwood, including beech	0.7
Solid timber		0.8
Solid timber	Hardwood with $\rho > 600$ kg/m^3 except beech	$0.56 = 0.7 \times 0.8$ 1)

1) There are the following differences between the DIN standard and ENV 1995-1-2:
a) Softwood according to the ENV has a density $\rho \geq 290$ kg/m^3 and a min. dimension of 35 mm (not specified in the DIN standard) *
b) The limit for hardwood in the ENV is $\rho > 450$ kg/m^3 ($\rho > 600$ kg/m^3 in the DIN standard).
c) v-hardwood $_{(solid\ timber\ or\ glulam\ ENV)}$ = 0.5 mm/min instead of 0.56 mm/min in the DIN standard
* ρ means the characteristic value for the species of wood (5% fractile, oven-dry density)



Depth of charring or thickness of wood-based board product with $\rho > 600$ kg/m^3 (chipboard, wood fibreboard, plywood)

Figure 2.2. Rate of charring [2]



story	wall	column	floor	beam
1-4	1	1	1	1
5-14	2	2	2	2
15-	2	3	2	3

hour

Figure 2.3. An example for requirements of fire-resistive time (The building standard law of Japan) [1]

2.3. Fire-resistive structure

Since it is not sufficient to attach just burning marginal thickness on structural members according to the rate of charring as described above, load-bearing wooden members needs a fire-protecting treatment, in order to achieve the fire-resistive structure. The performance can be evaluated by three types of design concepts. That is to evaluate the fire-resistance of (1) member materials, (2) building members, and (3) building frames.[3] The three concepts are explained as follows:

(1) Member materials

To achieve the fire-resistive structure by evaluating the fire-resistance of building materials of members is to prevent wooden members from igniting. Wood ignites generally around 240-270 degree and combustion starts. When the combustion of members continues, loss of the cross-section increase and the members are destroyed. Therefore, when the wooden members are prevented from igniting by fire exposure, the members do not lose their cross-section and are able to keep the necessary load-bearing capacity. As a result, the building does not collapse.

Two measures of preventing wooden members from igniting are described. One is to control heat approaching members. An example of this measure is to cover the members with incombustible fire-protection member, e.g. gypsum board. **Figure 2.4.** Advantages of this measure is that it is already in practical use and easy to realize. And also there is no limit of species of wood, as long as the covering material is designed properly. However, in this measure wooden surfaces are not visible. Therefore, some of advantages of building with wood are not available. Another measure is to improve fire-resistive performance of the member itself, e.g. treatment with fire-resistive chemicals and painting. In this measure, wooden surface can be visible. However, since the treatment take much work, members become expensive.

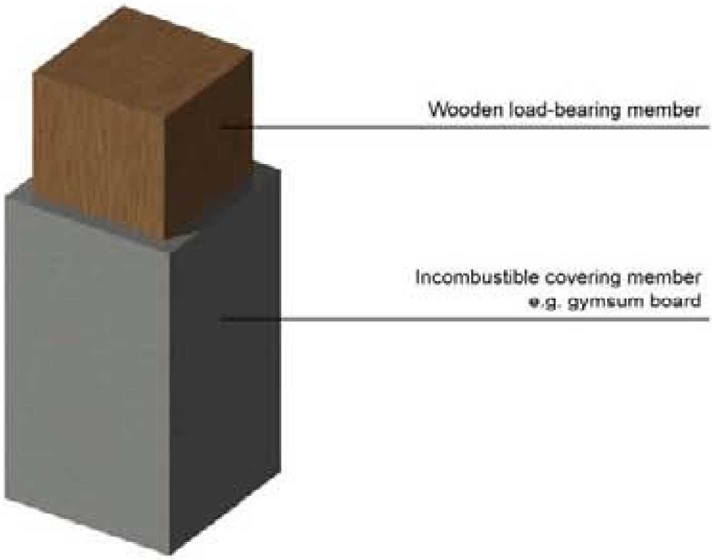


Figure 2.4. (1) Member materials: Wooden member covered by incombustible member

(2) Building members

To achieve the fire-resistive building by evaluating the fire resistance of building members is to prevent members from destruction. In this concept, ignition of wooden members is admitted. However, when the combustion of the members stops after losing a certain amount of the cross-section, they are able to keep the load-bearing capacity with the rest of the combusted members. Consequently, the building does not collapse.

The combustion of the wooden members is admitted during a certain period of time. But if the members continue to combust after the fire finishing, the members lose the cross-section and the load-bearing capacity. Therefore, self-charring-stop performance of members is required.

An example of the measure to achieve the self-charring-stop performance is to insert a high-density wooden member, steel member or incombustible member as a self-charring-stop layer at an assumed position in the wooden members. **Figure 2.5. 2.6. 2.7**

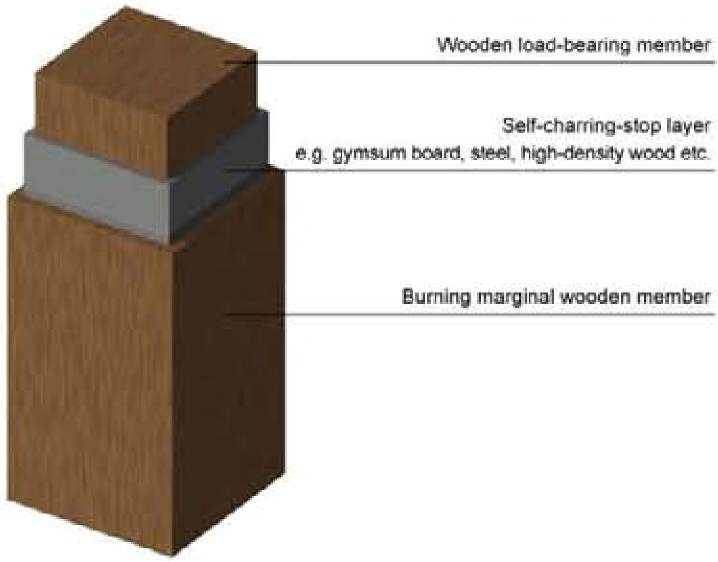


Figure 2.5. (2) Building members: Self-charring-stop layer installed in wooden member

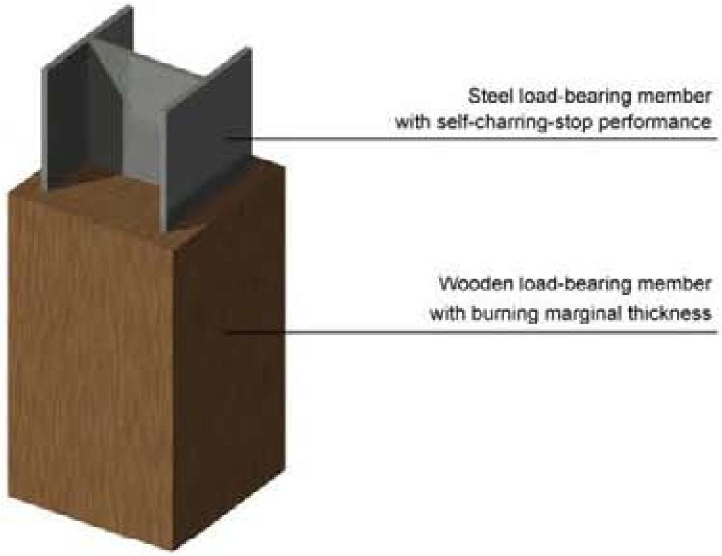


Figure 2.6. (2) Building members: Steel member covered by wooden member

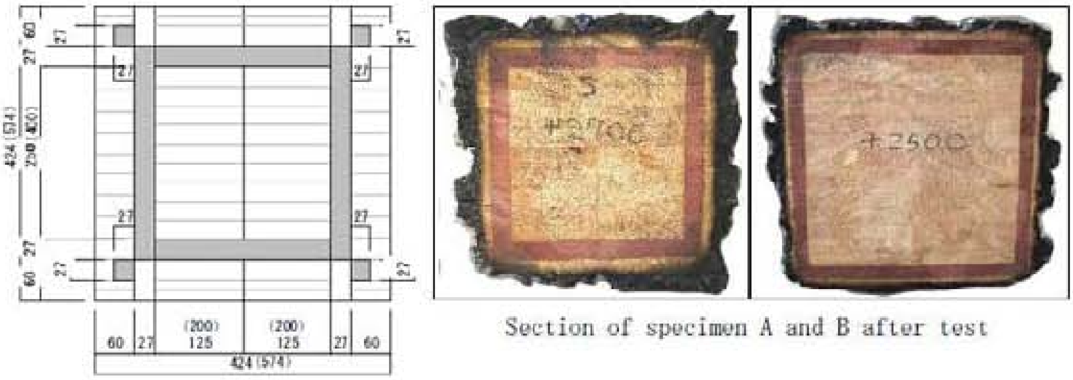


Figure 2.7. An example of fire-resistive member with self-charring-stop layer of high-density wood (Jarrah). [4]

(3) Building frames

To achieve the fire-resistive building by evaluating the fire-resistance of building frame is to prevent the building frame from destruction. In this measure, incombustibleness of wooden member is not indispensable. The primary target, to prevent the building from destruction is achieved by utilizing the peculiarities of fire as an external force in fire-resistance design. That is to say, the locality of fire in the whole construction, and it is not necessary to take into account combination of fire and seismic force or wind load.

An example of the measure is to use combustible wooden member as short-term load resistance member, such as seismic-resistant and wind-resistant members. Since combination of fire, seismic force and wind load is not taken into account, if long-term resistance members have fire-resistant performance, collapse of the building can be prevented, even after short-term load resistance members are lost by combustion.

In addition, fire-resistive building can be achieved by considering the locality of fire, together with reserve capacity of members for short-term load. In other words, even if some of members lose their load-bearing capacity by combustion, the load can be reallocated to circumjacent members which hold reserve capacity, and collapse of the building is prevented.

In the three design concepts described above, researches and tests of the concept (1) and (2) have carried out in many research institute. And some examples of application of the concept (1) and (2) can be seen in some realized buildings. The concept (3) requires more exact analysis on design. On the other hand, more rational fire-resistive building can be planed, since peculiarities of fire are taken into account. And on the concept (3), compared to the other 2 concepts, solutions can be considered on architectural design and structural design. A conceptual proposal of fire-resistive structure proceeded in next section is based on the concept (3).

2.4. Conceptual proposal of fire-resistive structure

A conceptual proposal of fire-resistive structure based on the study in the previous section is presented as follow. The conceptual proposal is proceeded with the concept (3) Building frames. The example building project proceeded in the chapter 4 is based on the conceptual proposal.

In the proposed structure, a hut truss structure is installed on the top floor of a multi-story building of post and beam structure. The columns of the structure are composite column which is composed of wooden column as a compression member and steel rod as a tensile member installed inside of the column. And core walls are installed each floor through the whole structure from the ground to the hut truss on the both side of the structure. **Figure 2.7. 2.8.**

In normal times, the hut truss assumes a role of deformation control member against horizontal load, seismic force and wind load. In case of fire, the hut truss is converted into a wide span beam which suspends floors above the fire floor by the steel rods installed in columns. Since it is not necessary to take into account combination of fire and seismic force or wind load as described above, in case of fire, the hut truss does not need to work as deformation control member. **Figure 2.9. 2.10.**

In case that all load-bearing wooden columns on the fire floor are lost by combustion, the structure system below the fire floor does not become different from normal times. On the other hand, the structure system above the fire floor is changed into a tensile structure, in which the loads of the floors are transferred to the core walls on both side, through the hut truss suspending the floors above the fire floor by the steel rods in columns. As a result, collapse of the building is prevented. In addition, since the whole building withstands until the end of fire, and column can be reinstalled, it is possible to recover the structure after fire. In order to achieve this structure, it is also important that the core walls, floors and ceilings are protected against fire by incombustible covering. In the proposal is considered based on the peculiarities of fire, the peculiarities of fire, the locality of fire and needlessness of considering combination of fire and seismic force or wind load.

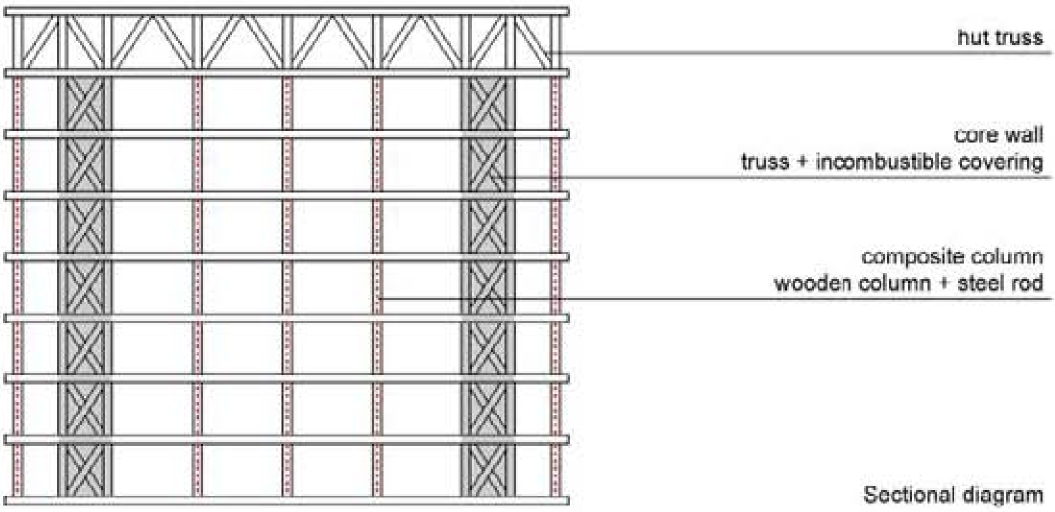


Figure 2.8. Diagram of structure: hut truss + core wall + composite column

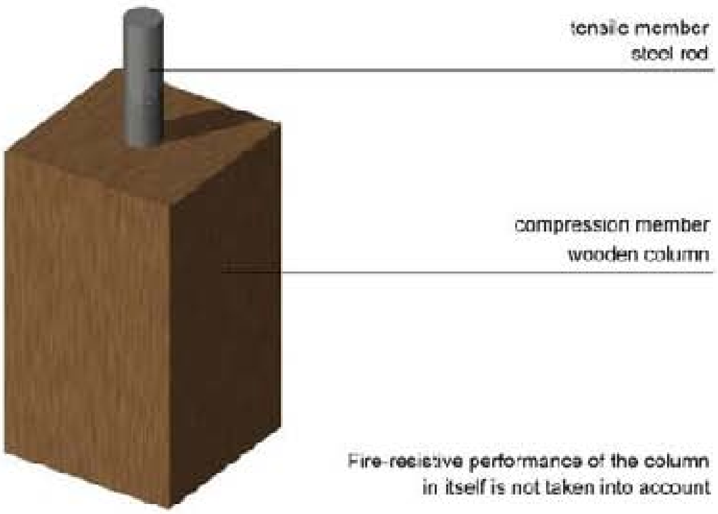


Figure 2.9. Diagram image of composite column: wooden column + steel rod

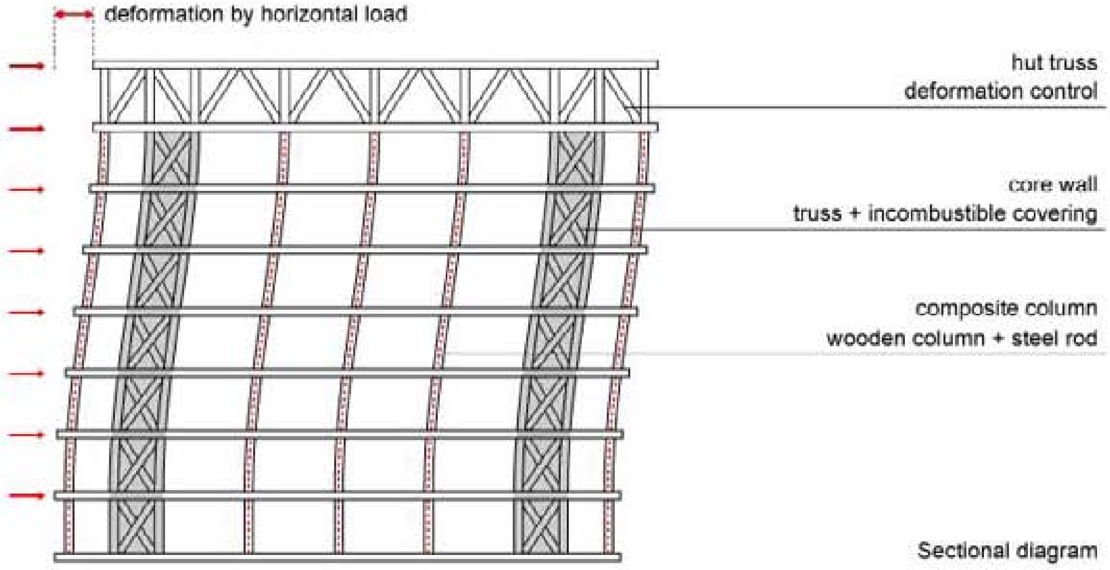


Figure 2.10. Diagram of structure: horizontal load

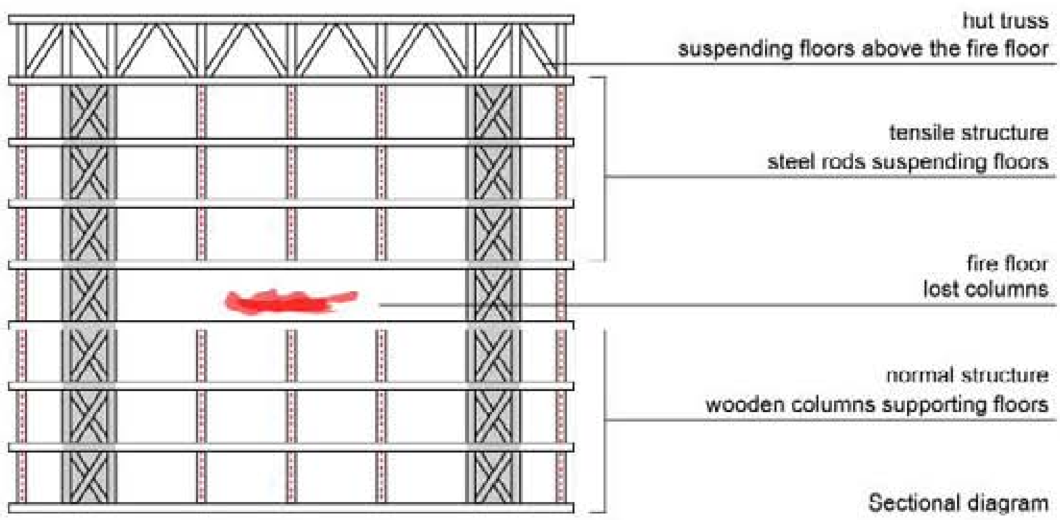


Figure 2.11. Diagram of structure: in case of fire

Chapter 3. Smoke control

3.1. Introduction

In the previous section, fire-resistance is studied and a conceptual proposal is presented from the aspect of structure. However, it is not necessarily the case that fire-resistive structure always guarantees safe of people. It must be considered at the same time that how human safety is achieved.

3.2. Risk of smoke

Case examples indicate some characteristics of danger from fire in middle-to-high rise buildings, especially in mixed use buildings. First one is danger of poisoning death by smoke. The most of victims die from inhaling carbon monoxide gas. Secondly, on fire in middle-to-high rise buildings, it is not necessarily the case that space around the start of fire is always the most dangerous. In many cases, people died on upper floors above the fire floor. The reason comes from the buoyancy of smoke. The fact that it is hazardous even on spaces distant from the start of fire indicates that smoke is risk to life, even after diluted. Thirdly, some people died in a group in places where do not appear to be safe, e.g. a bathroom, a kitchen and a small room. The fact indicates that people are under psychological stress and lose their judgment, because if they act calmly, it seems unlikely to go to such places. At the same time, it appears that they lose their visibility.

The characteristics show the topics, harmful effect of smoke, diffusion phenomenon of smoke, and people's psychological actions. The topics must be considered in more detail in order to solve the problems. [5]

3.3. Stream of smoke

Since there is a limit to reduce combustible items from commodities, it is not easy to decrease harmful effects from smoke in case of fire. In other words, in order to ensure occupants' safety, it is important how to deal with smoke in buildings, e.g. devices of spatial composition, ways of evacuation and building equipment for smoke control.

Many cases show that smoke is diffused through vertical shafts, e.g. elevator shafts and stair cases. In order to avoid the effect, air tightness of connecting doors between floors and vertical shafts are important. However, in case that the doors are opened by occupants for some reason, it causes a serious accident.

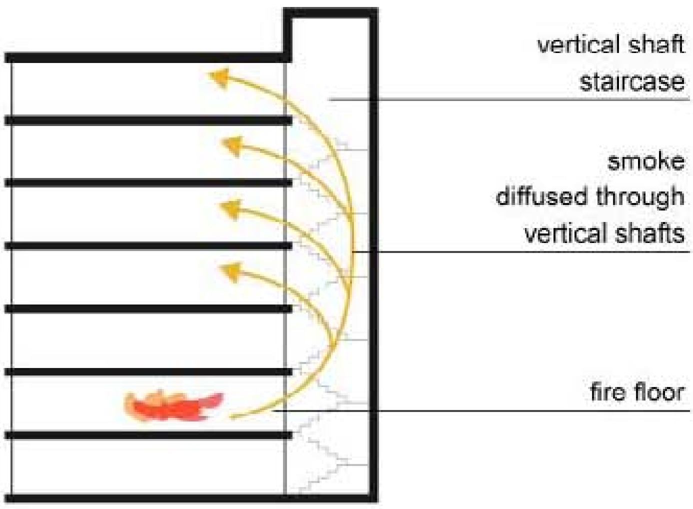


Figure 3.1. Smoke diffused through vertical shafts

Since, depending on scale of a building, it is difficult to ensure occupants' safety from smoke by spatial composition, smoke control by mechanical equipments is required. The basic idea of smoke proof and evacuation measure is to let the air pressure of evacuation routes, (e.g. stair case), higher than fire floor in order to protect the routes from smoke. The major methods are to open smoke vent in case of fire automatically, to exhaust smoke by fan and to pressurize evacuation routes by fan. However, it also must be considered that in case of fire caused by earthquake, trouble of machine or electric power failure invalidating the system.

3.4. Evacuation

In order that occupants may evacuate in safety, it is important to comprehend characteristics of human behavior in fire. Following tendencies must be taken into account. Firstly, people try to take a route where is used mundanely. Secondly, people try to head for open and light direction. Thirdly, people get scared when they lose their position in the building.

Floor planning must be carefully done with considering the said characteristics. Since start of fire have possibility to be at any place, it is important to have redundancy for evacuation in floor planning. In other words, more than two evacuation routes must be guaranteed at any place in the building. To install balconies on every floor around the building is effective to achieve easy and clear evacuation. In addition, it prevents fire from diffusing to upper floors through windows.

3.5. Atrium chimney

In recent years, chimney effect in an atrium is often utilized in order to generate natural ventilation for reducing energy consumption and good indoor environment. However, from the aspect of fire safety, chimney effect makes easily smoke diffuse to upper floors of the building.

A research to solve this problem has been carried out by Hasemi et al [6] [7]. In the research, by focusing attention on the similarity between natural ventilation and smoke exhaust, smoke control measure by means of an atrium solar chimney has been studied.

The basic idea of chimney effect and pressure distribution is shown in **Figure 3.2.** In inlet of the chimneys on the bottom, air pressure of inside is lower than outside and in outlet of the chimneys on the top, air pressure of inside is higher than outside. However, in the narrow top chimney, difference of pressure in inlet is narrower than outlet. On the other hand, in the narrow bottom chimney, difference of pressure in inlet is wider than outlet. Neutral plane, where the difference of pressure between inside and outside of chimney is zero, is higher in the narrow bottom chimney, and lower in the narrow top chimney. If a horizontal hole on a chimney is made above neutral plane, smoke flows out from the chimney, and if below neutral plane, smoke flows in.

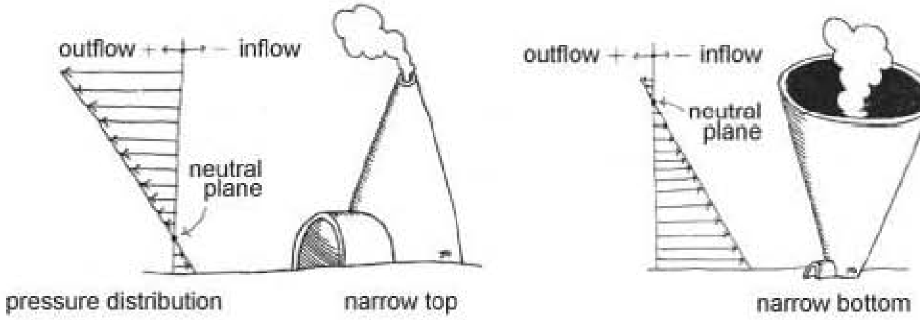


Figure 3.2. Chimney effect and pressure distribution [5]

The same principle can be applied in an atrium of a building. An atrium with a chimney can control smoke diffusing to upper floors and by keeping the neutral pressure plane in the chimney part and the pressure of the atrium lower than outside, the rooms can be secured from smoke **Figure 3.3.**

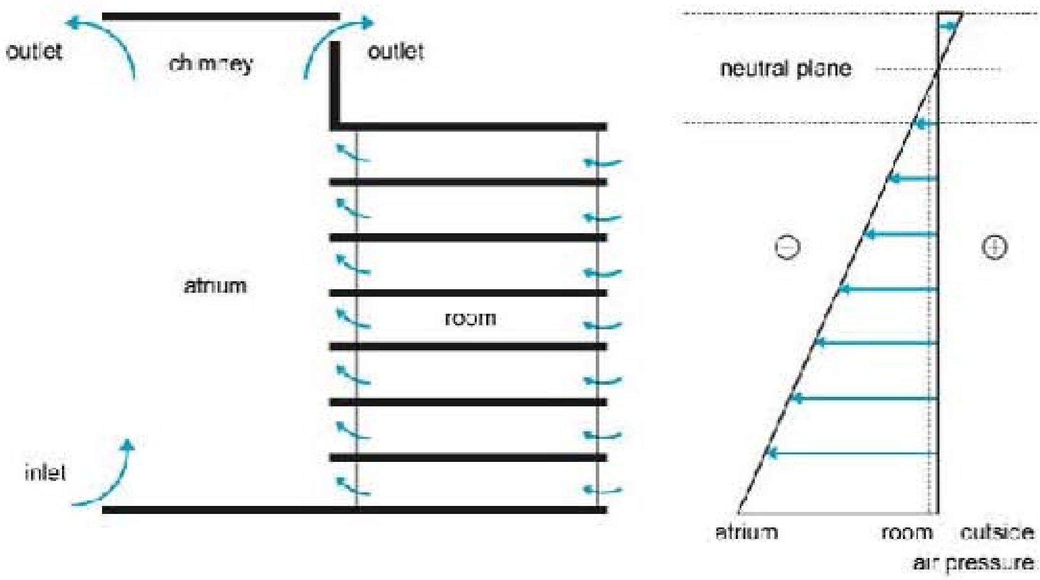


Figure 3.3. Atrium chimney and pressure distribution

Prerequisites for the neutral pressure staying in the chimney, are considered as follow. In the study model, it is assumed that inlet opening is installed only on the bottom of the atrium. The height of neutral plane is derived as follows.

$$H_n = \frac{1}{(1/k)^2 + 1} H \qquad (1)$$

$$k = \frac{A_{top}}{A_o} \sqrt{\frac{\rho_s}{\rho_{out}}} \qquad (2)$$

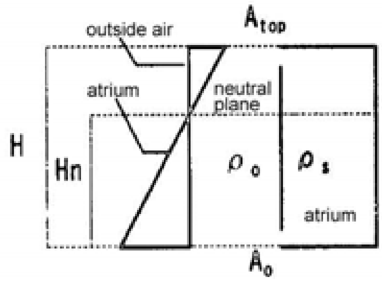


Figure 3.4. Model and equation of pressure distribution [7]

When *k* increases, the height of the neutral plane rises up as well. When *k* exceeds 2, the increasing rate significantly becomes smaller. And when outlet area/inlet area is 2, the height of neutral plane stays 80% of the whole space (atrium + chimney). The height of the neutral plane stays in the chimney, namely when the height of the chimney is more than 20% of the whole space.

That is to say, the prerequisites for the neutral pressure staying in the chimney can be described as follows:

- The outlet area is more than 2 times larger than the inlet area.
- The height of the chimney part is more than 20% of the height of the ceiling.

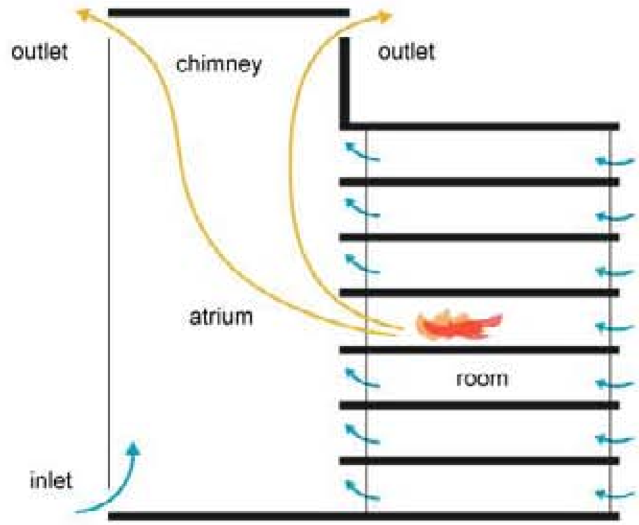


Figure 3.5. In case of fire in a room

In case that fire happens in a room, smoke is not diffused to upper floor, when the neutral plane stays in the chimney part.

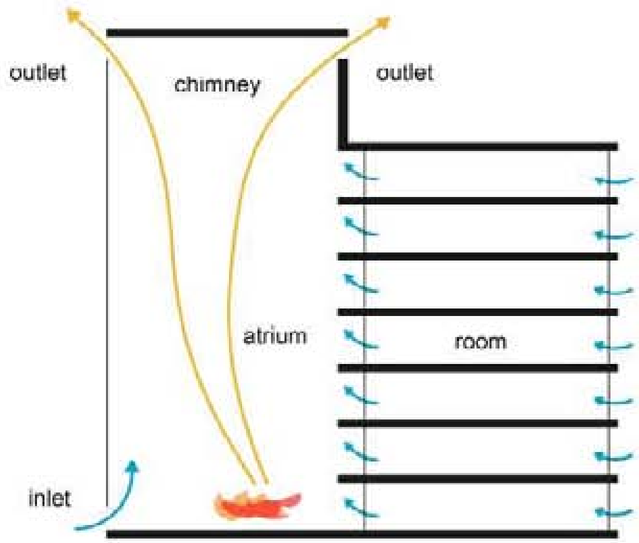


Figure 3.6. In case of fire in the atrium

In case that fire happens in the atrium, smoke is not diffused to rooms, when the neutral plane stays in the chimney part.

3.6. Conceptual proposal of smoke safety planning

A conceptual proposal of smoke safety planning based on the study in the previous sections is presented as follows. The building project proceeded in the next chapter is based on the conceptual proposal.

The idea is that to utilize the atrium chimney as a smoke control as well as natural ventilation. In the proposed planning, there is no vertical shaft of stair case installed, which diffuses smoke to upper floor. Instead of it an atrium is installed which has three functions, i.e. stair case, amenity space and atrium chimney. In normal times, occupants use the atrium as a main route to access rooms, and the atrium supplies natural ventilation at the same time. In case of fire, smoke is controlled by the atrium and occupants evacuate through outside stair cases. Considering the characteristics of human behavior, balconies are installed on every floor around the building. In normal times, occupants use them as an amenity space, and in case of fire the outside stair cases can be reached through the balconies.

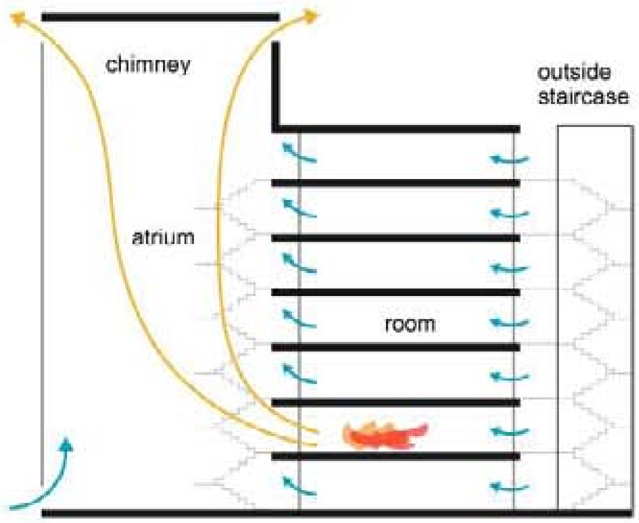


Figure 3.7. The proposal of atrium chimney as a smoke control considering evacuation

Chapter 4. Building example

4. 1. Overview

In this chapter, a building example is presented as a prototype building. The main concept is based on the conceptual proposals which are presented in the chapter2 and 3.

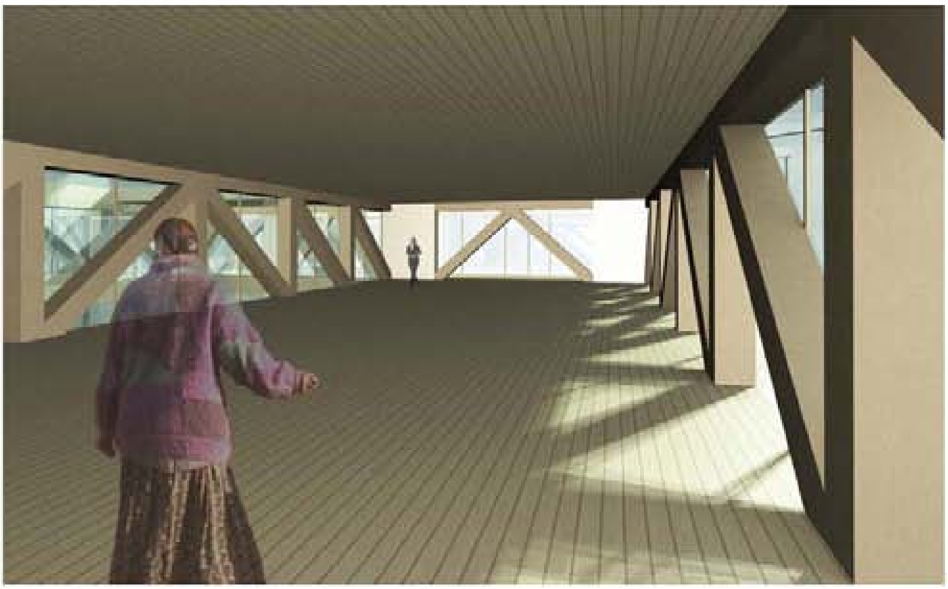
The location of the building is on a typical business district in the city center of a middle-to-large city in Japan. In such an area replacements of buildings are relatively frequent. Therefore, building with wood in the area is effective for environmental conservation. And by utilizing proper prefabrication during construction, economical loss by obstruction can be reduced. The building is an office building and partly mixed use, which is a typical building type in the area. The scale of the building is 8-story. By realizing the flexible floor plan, no column and no wall large space, it is also possible to convert into other programs, e.g. housing, which contributes to prevent frequent replacement of the building.

Due to the scale and the location of the building, the regulation concerning fire protection requires a fire-resistive structure and two hours fire-resistive time. Since the building must withstand until the end of fire, self-charring-stop performance on structural members are also required(Chapter2).

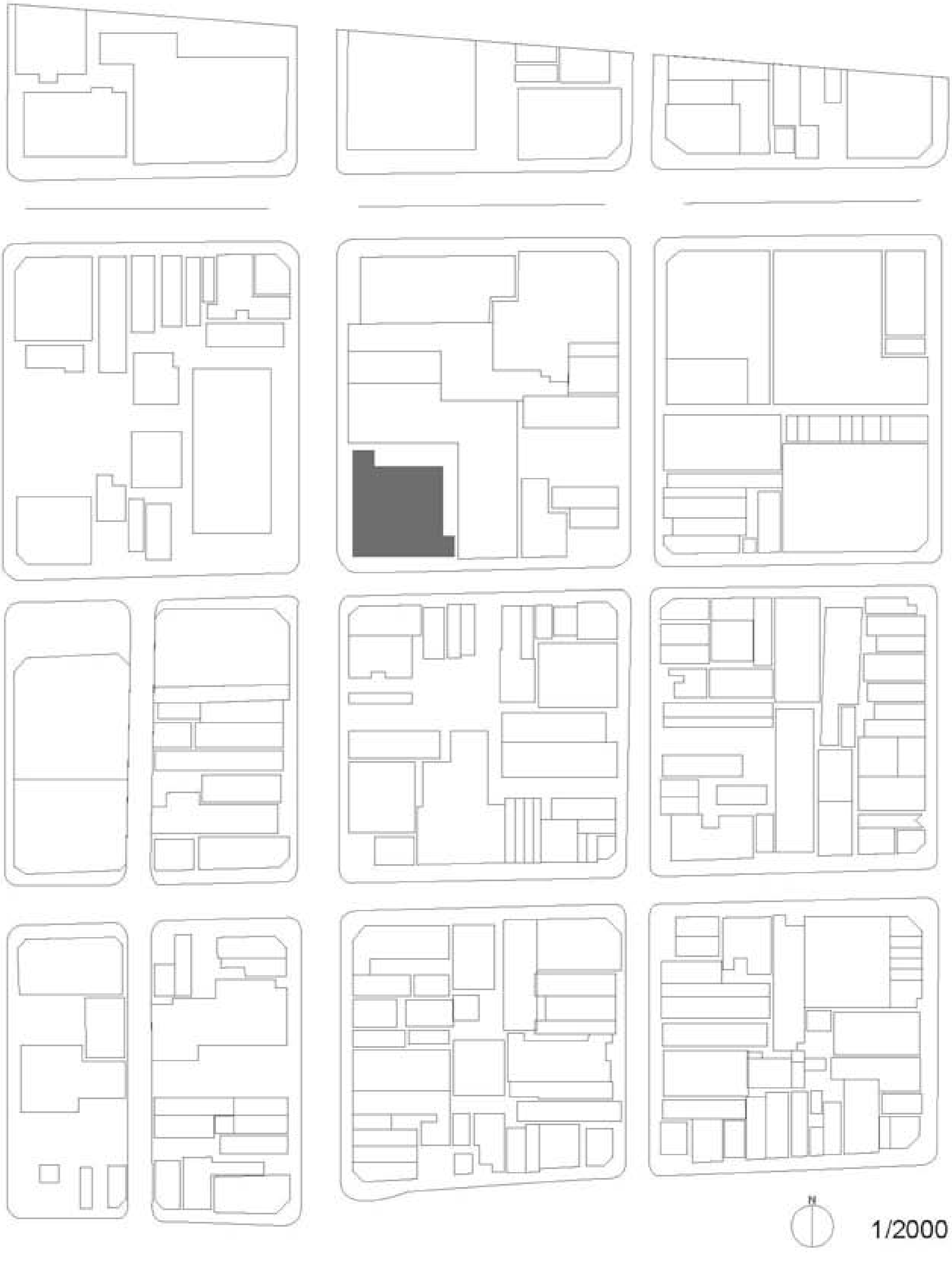
The floor planning on typical floor consists of two office space, common spaces and an atrium in between. The office spaces are 10m x 24m, no column spaces which are flexible use. The common spaces are used as amenity space and access route. The atrium has a chimney part on it. The natural ventilation and smoke control function, described in the chapter3. In addition, evacuation is considered on floor planning. The building has balconies faced on the office spaces. In order not that smoke may diffuse through vertical shafts, evacuation stairs are installed out of the building, and which is accessed through the balconies. The balconies are also effective for preventing fire from spreading on upper floors.

The structural concept of the building is based on the conceptual proposal presented in the chapter2. The structure of the building consists of four parallel truss frames, and connected similar truss frames on the other direction. In the truss frames columns and beams are installed. The columns are composite, steel rods are installed inside of the wooden columns. The trusses, columns and beams are made by spruce glued laminated timber, except for the steel rods and joint parts. Floor panels made by cross-laminated timber panel, are installed on the beams.

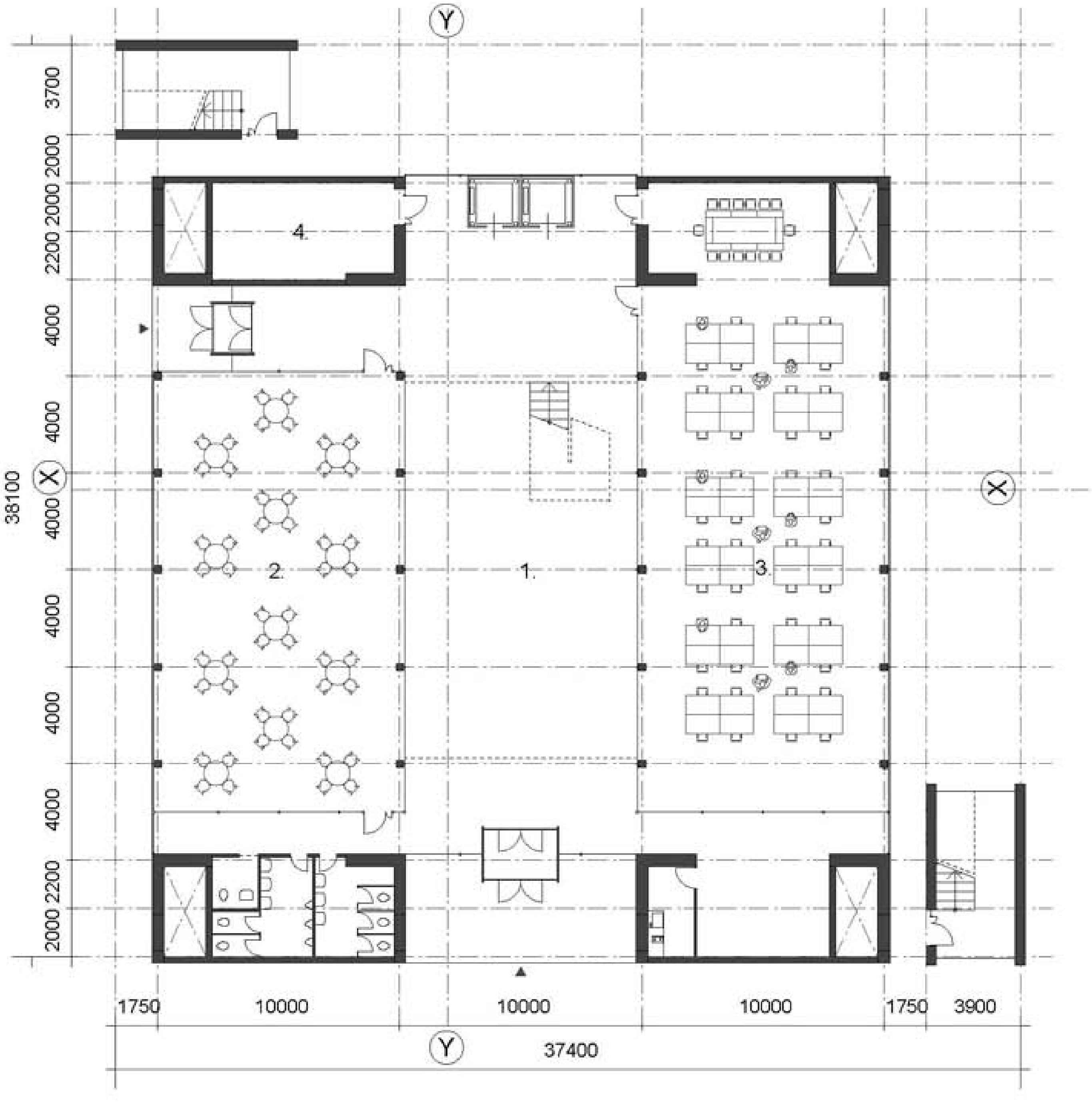
4.2. Architectural drawing



Site plan



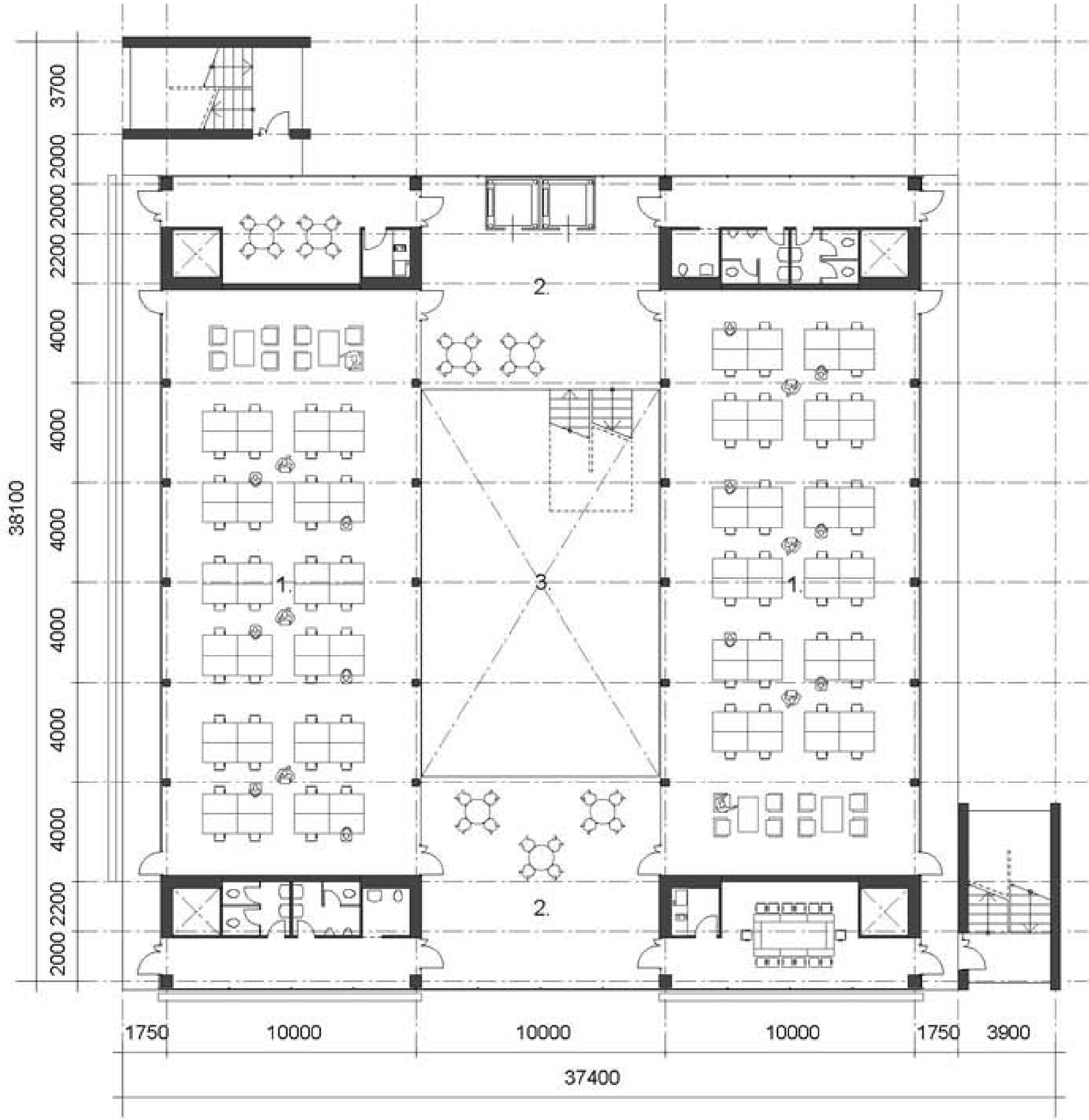
Ground floor plan



1. Entrance hall
2. Multi-purpose rental space (180m²)
3. Room (240m²)
4. Storage

1/250

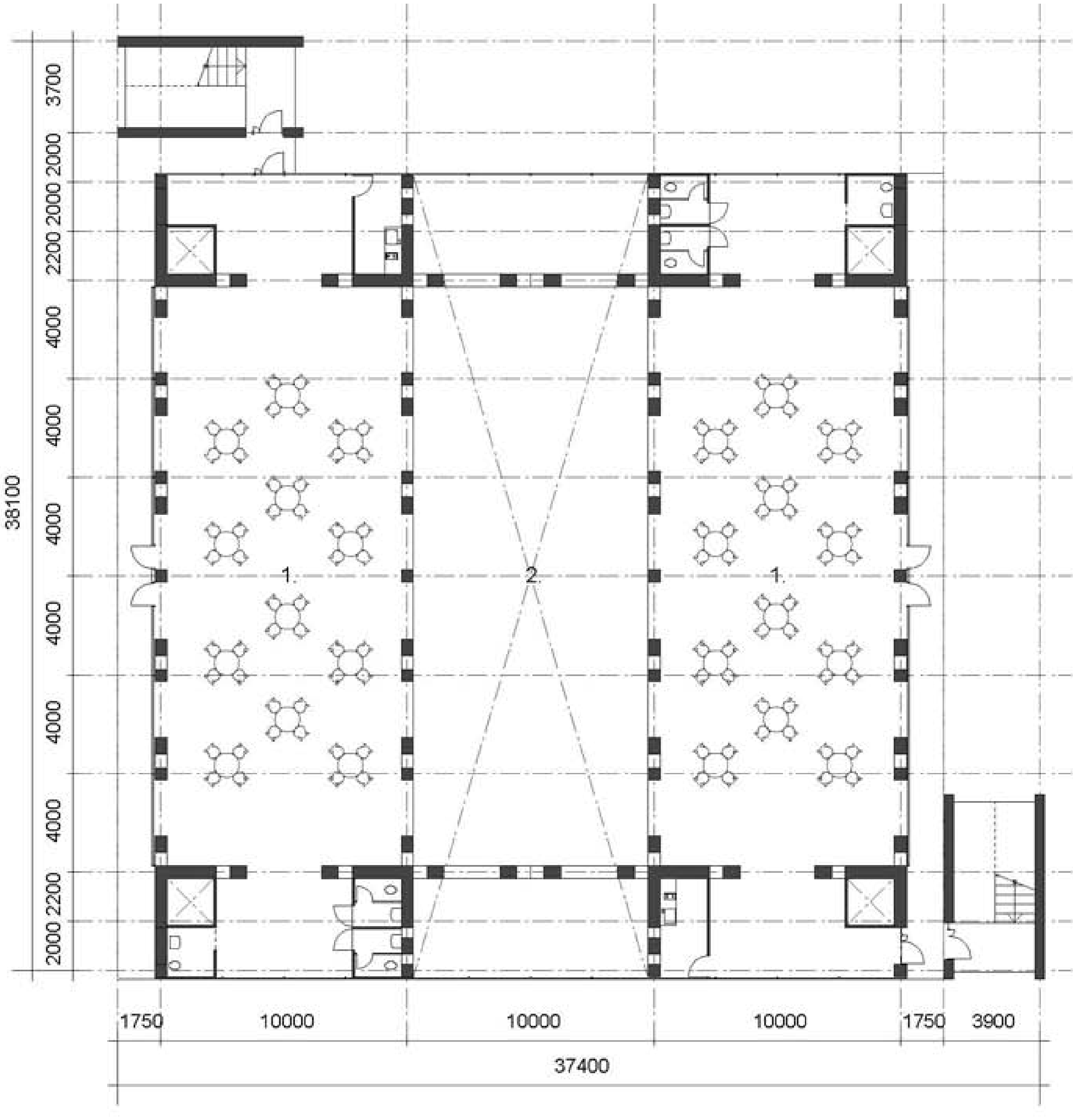
Typical floor plan



1. Room (240m²)
2. Common space (82m²)
3. Atrium chimney (Void)

1/250

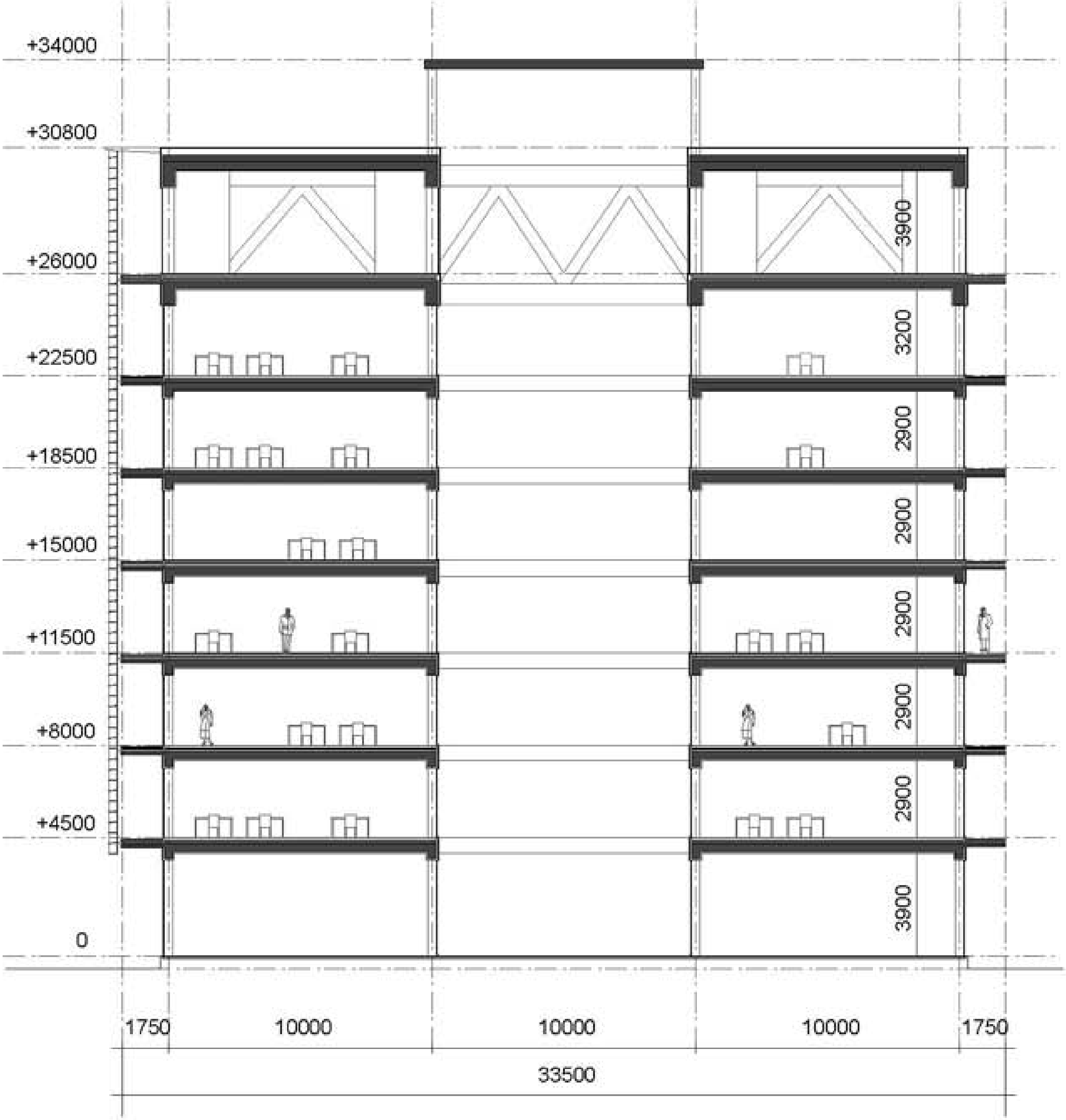
Top (8th) floor plan



1. Multi-purpose space (240m²)
2. Atrium chimney (Void)

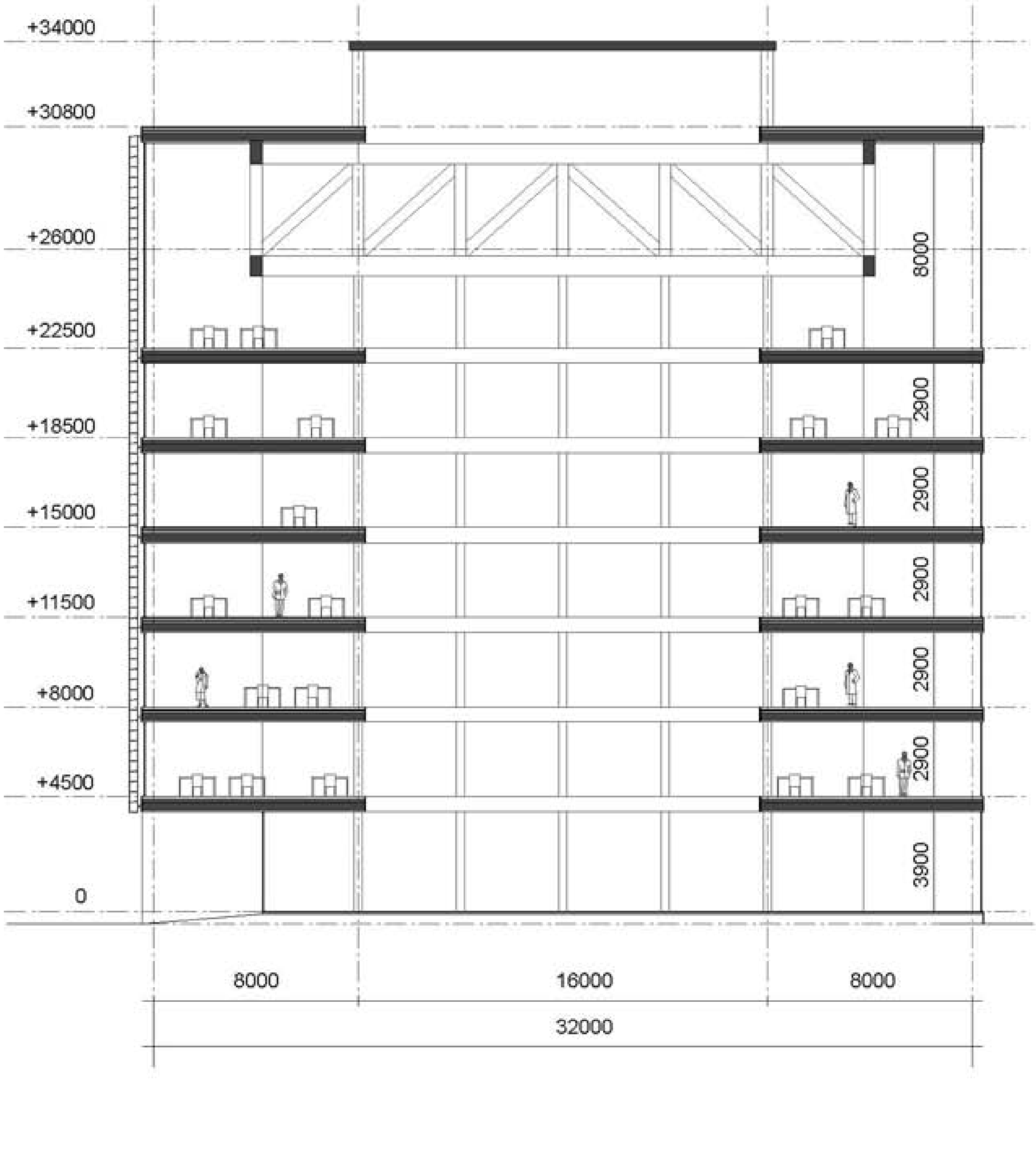
1/250

X Section



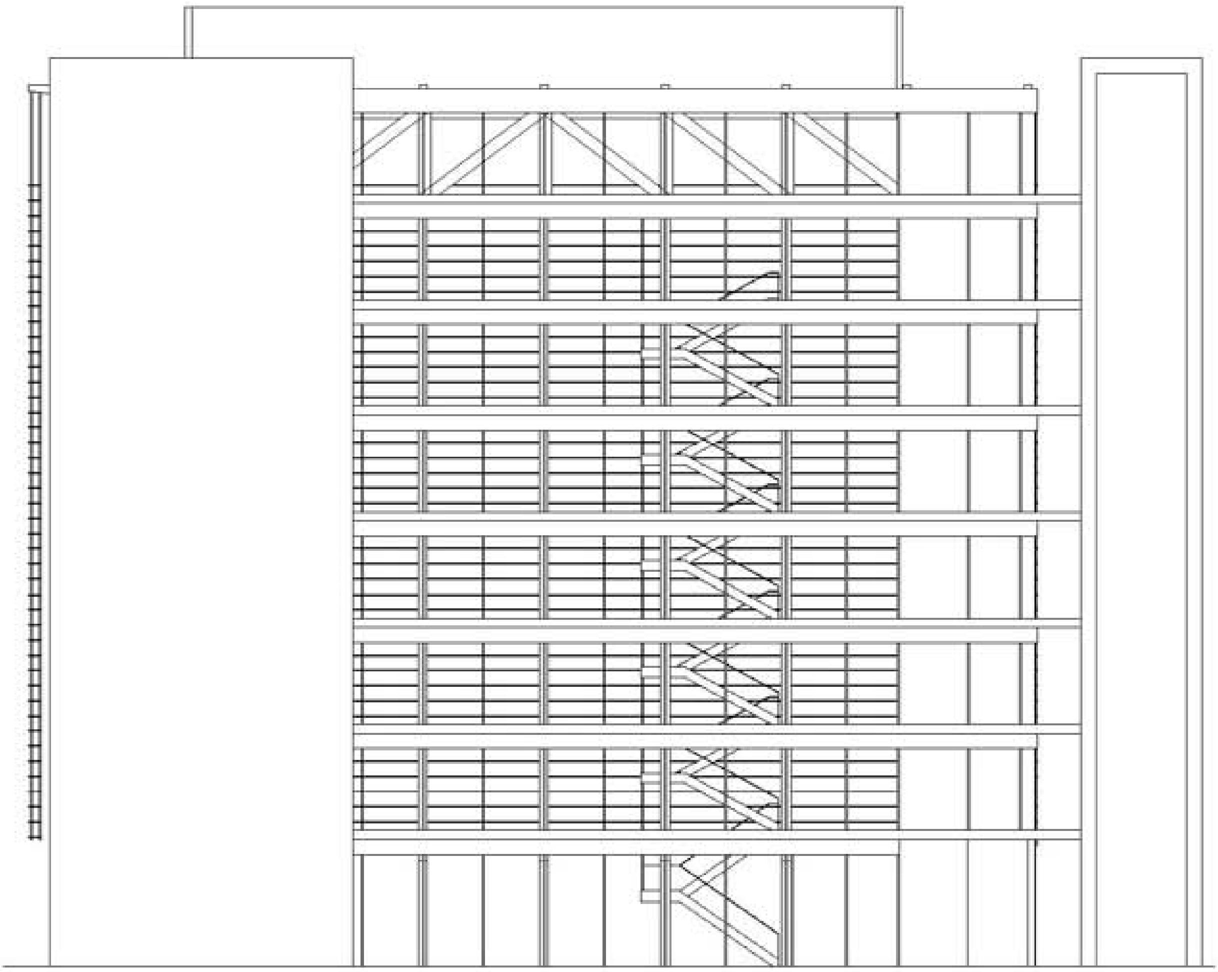
1/250

Y Section



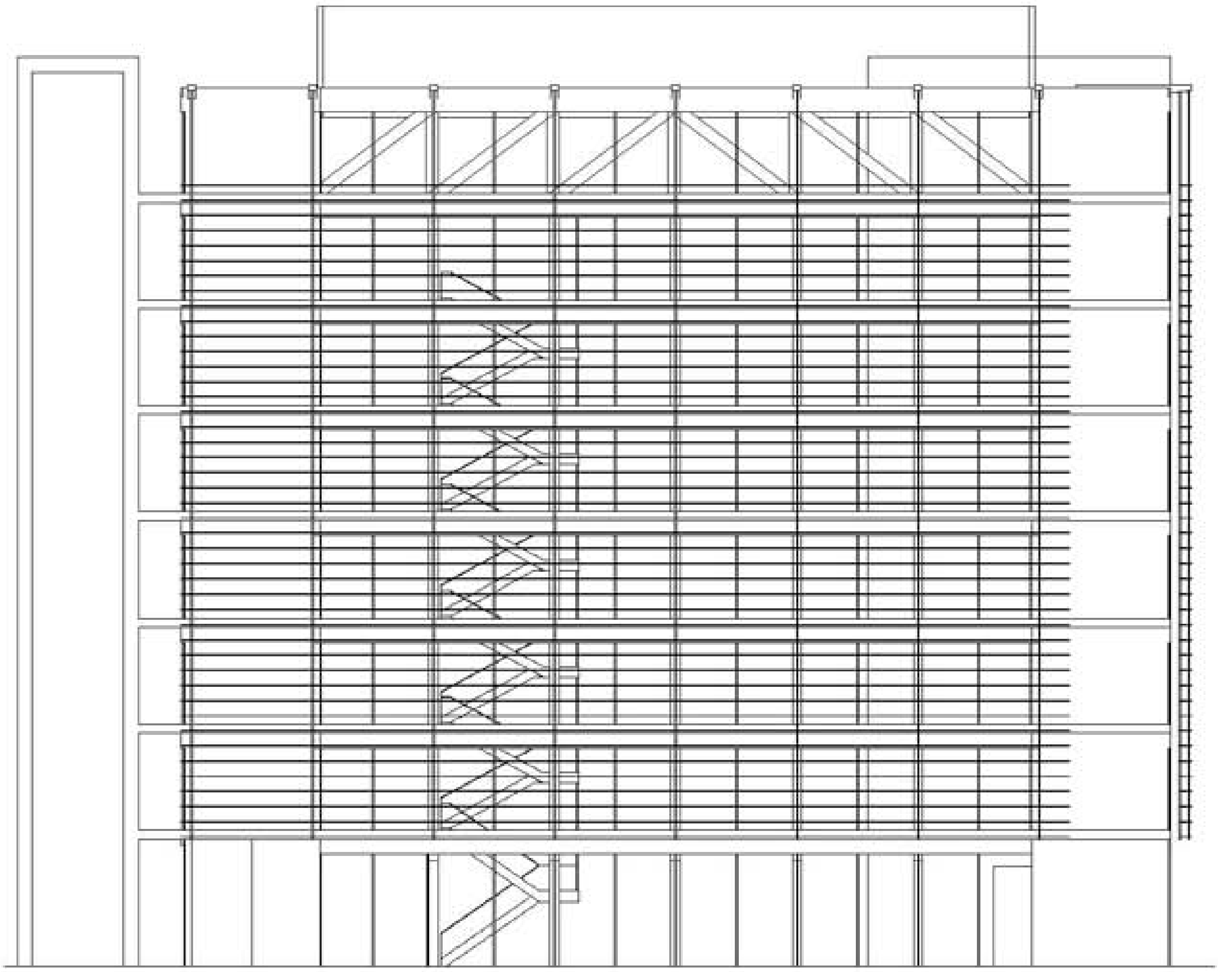
1/250

East elevation



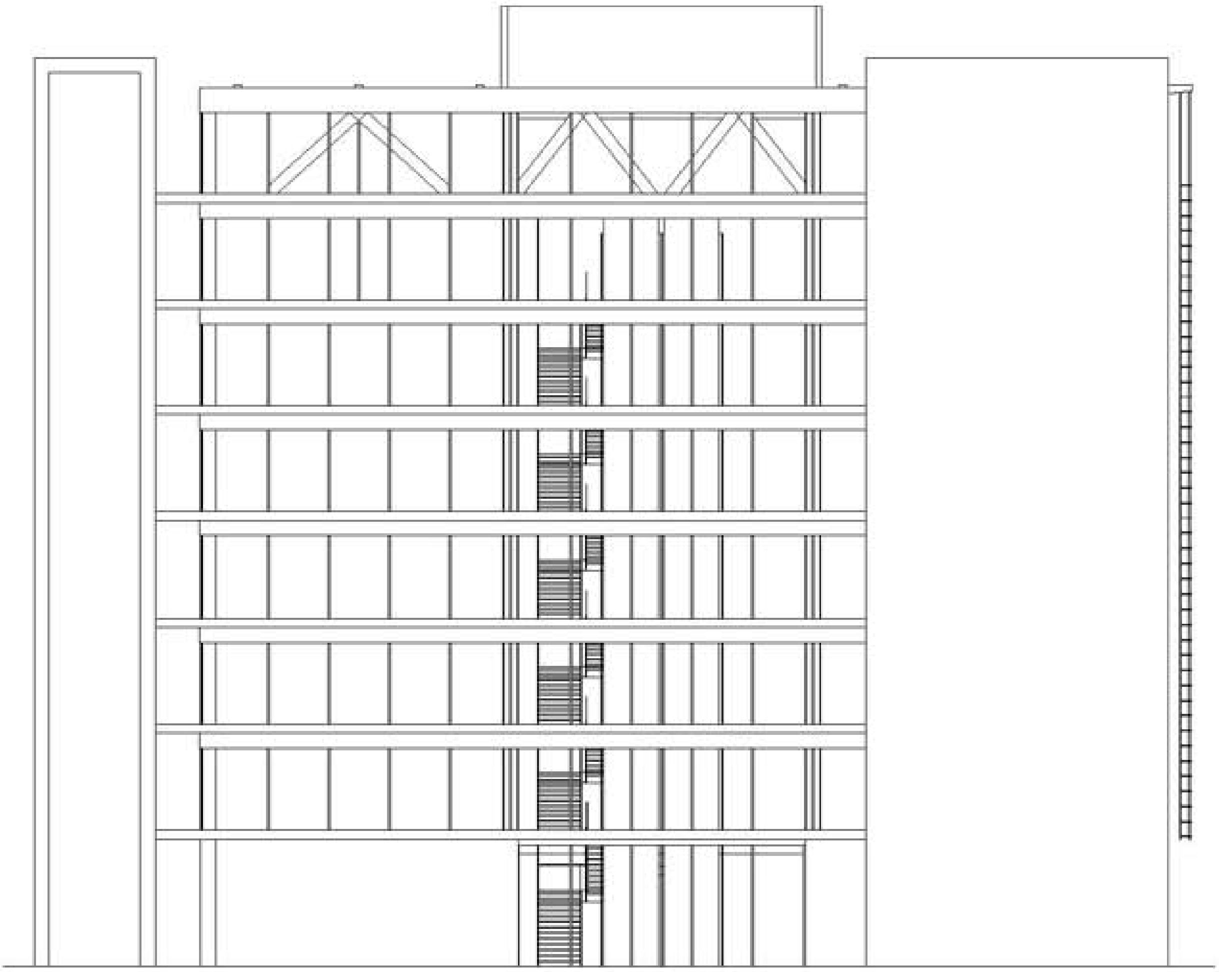
1/250

West elevation



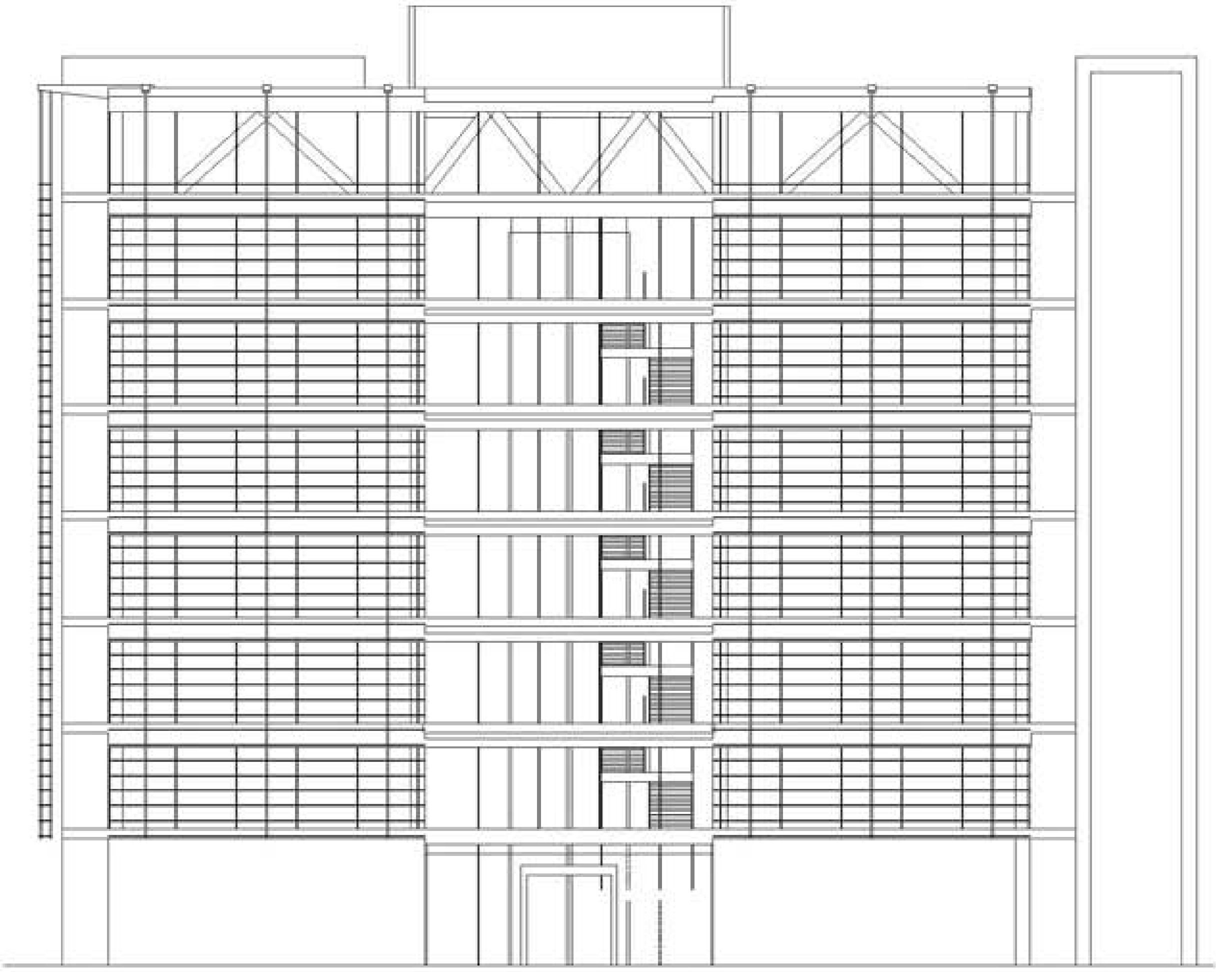
1/250

North elevation



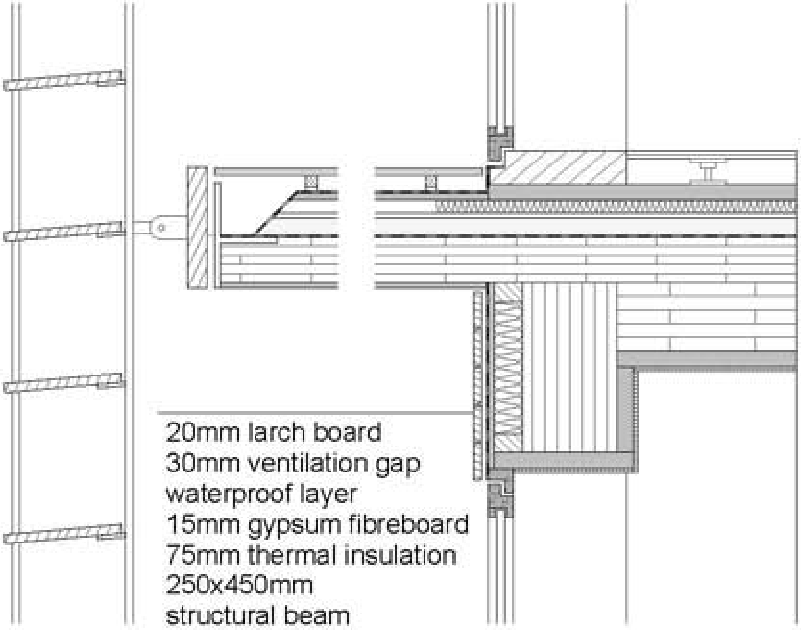
1/250

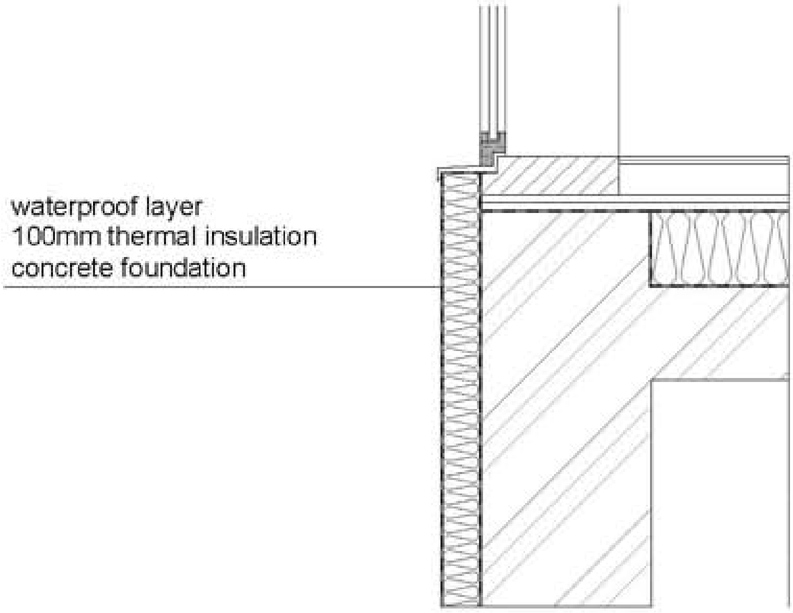
South elevation



1/250

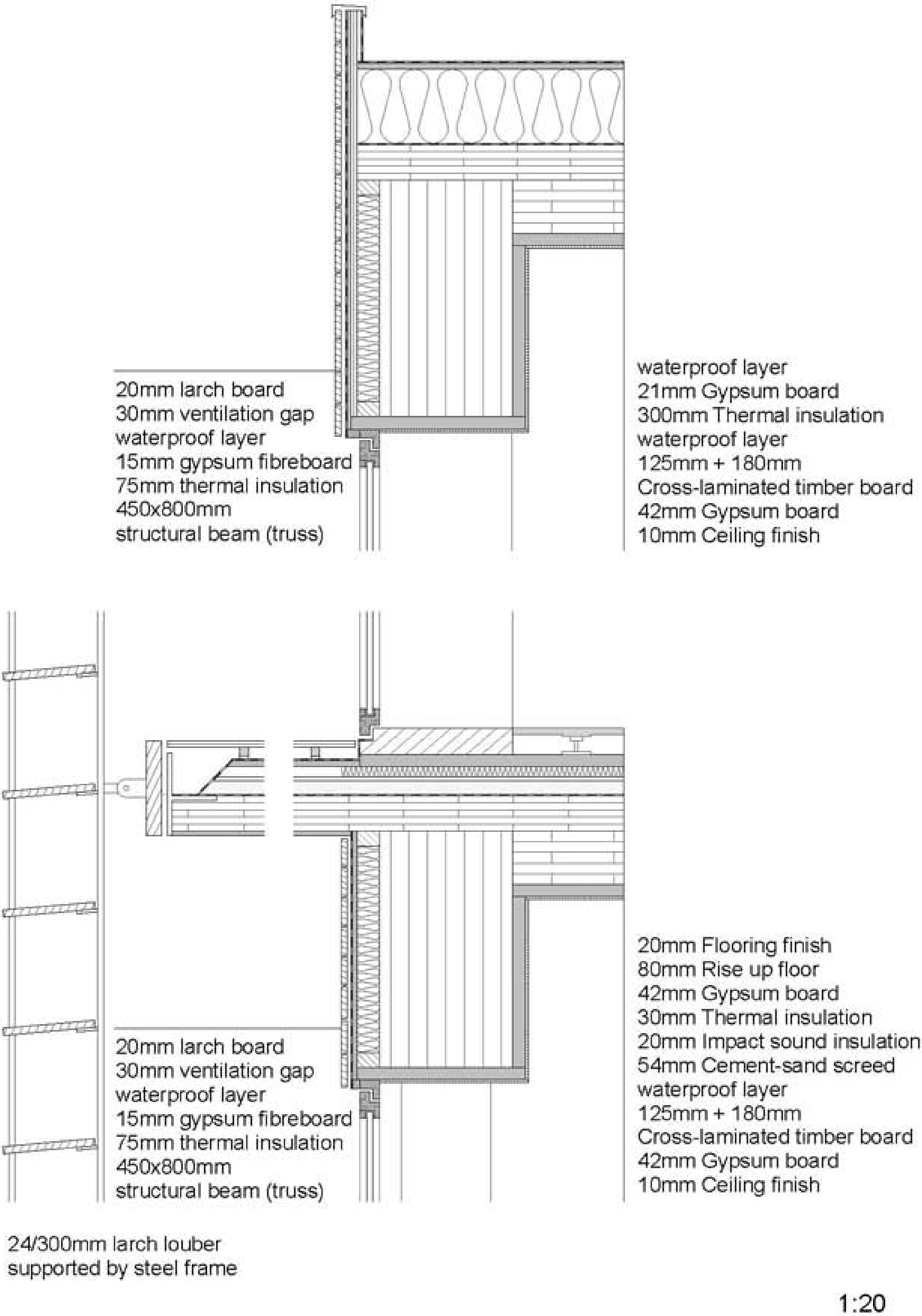
Detail section



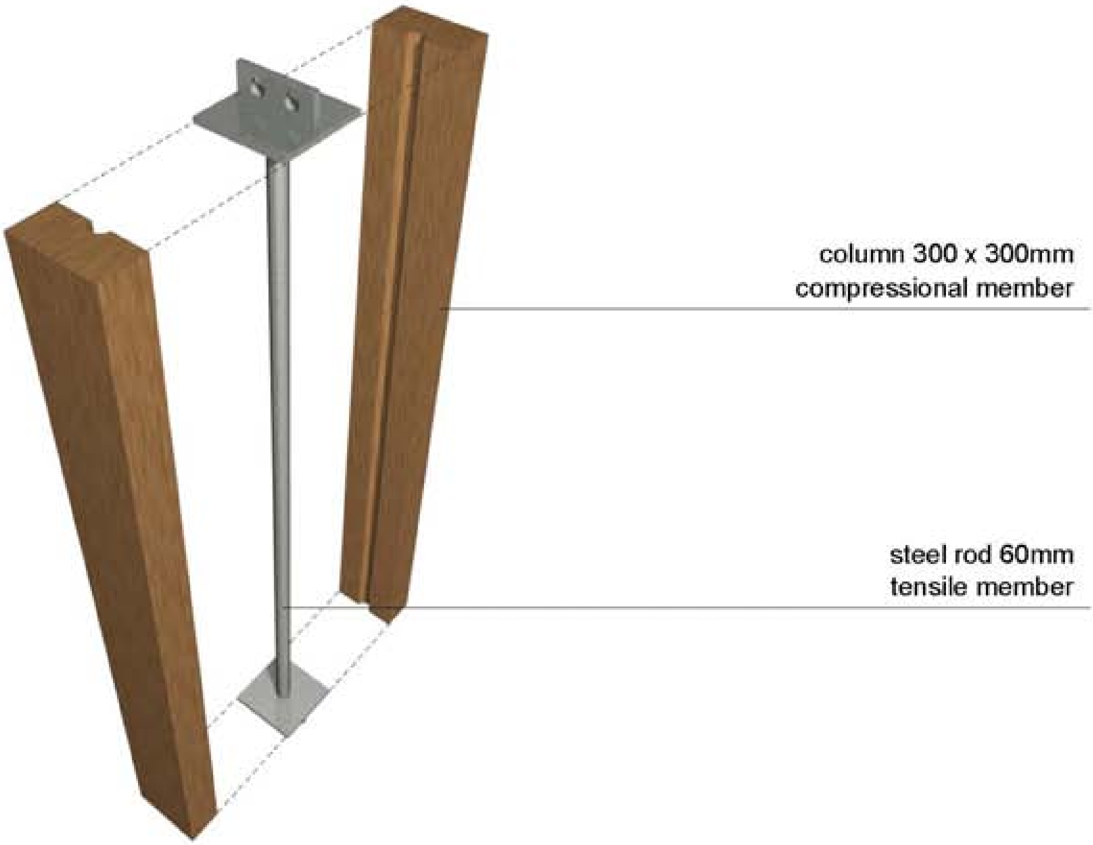


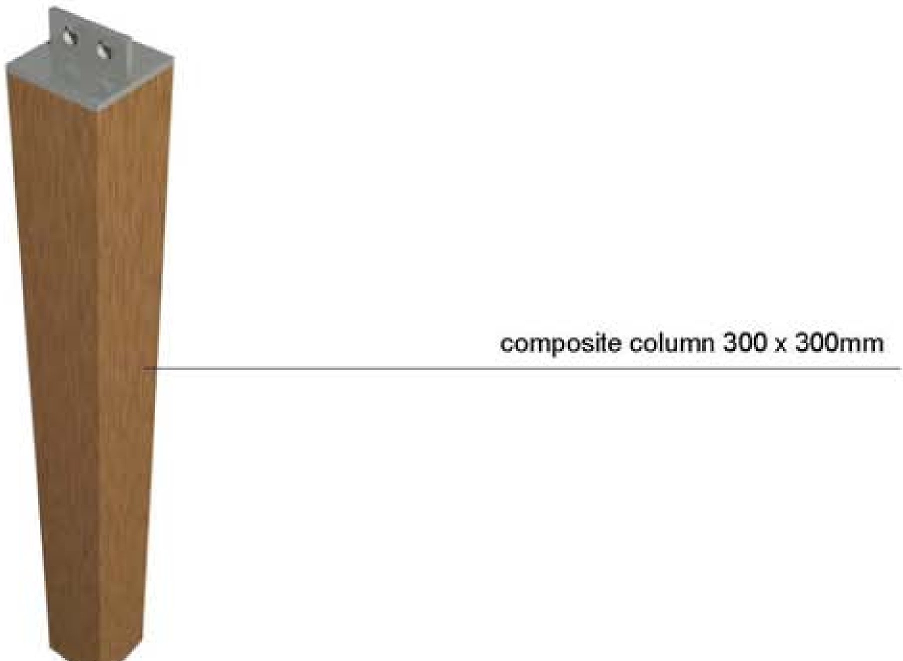
1:20

Detail section

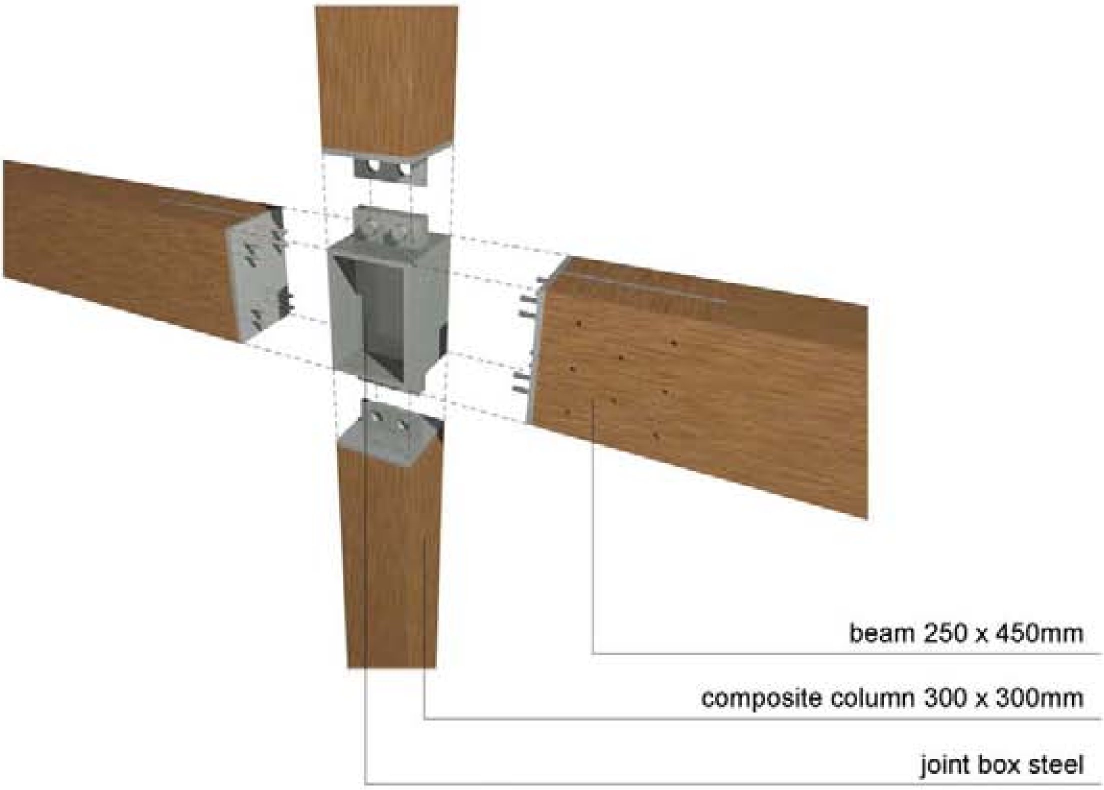


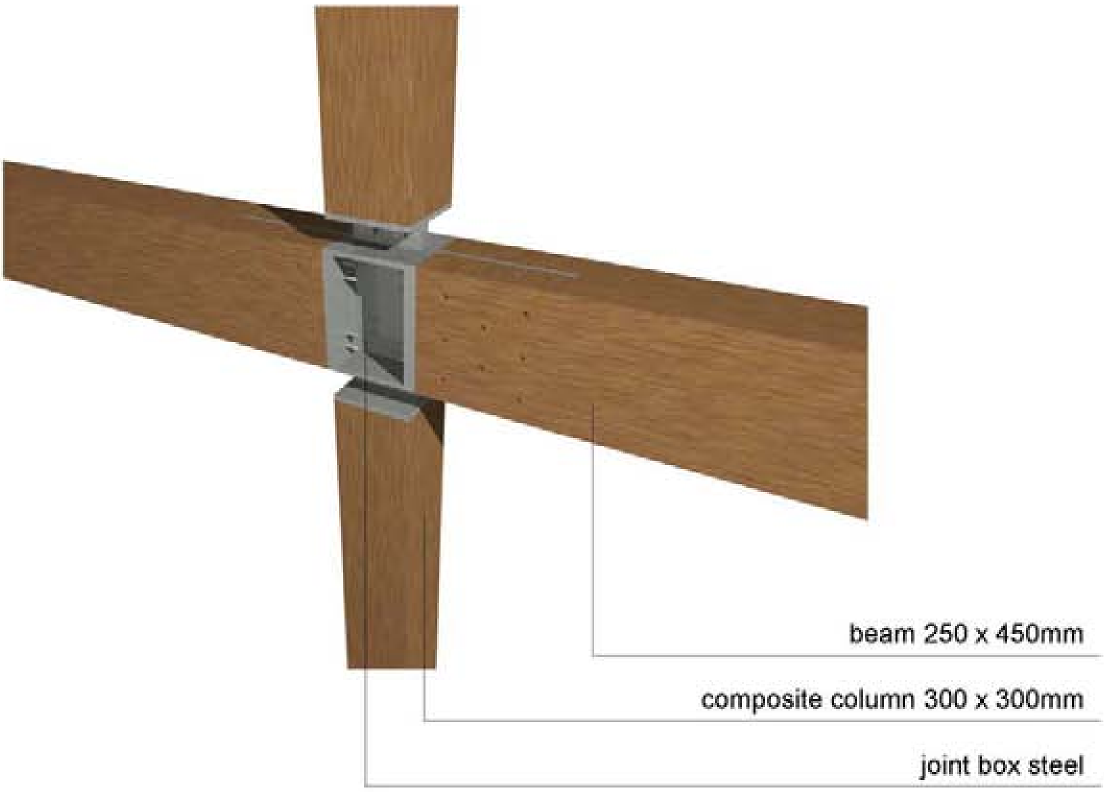
Composite column





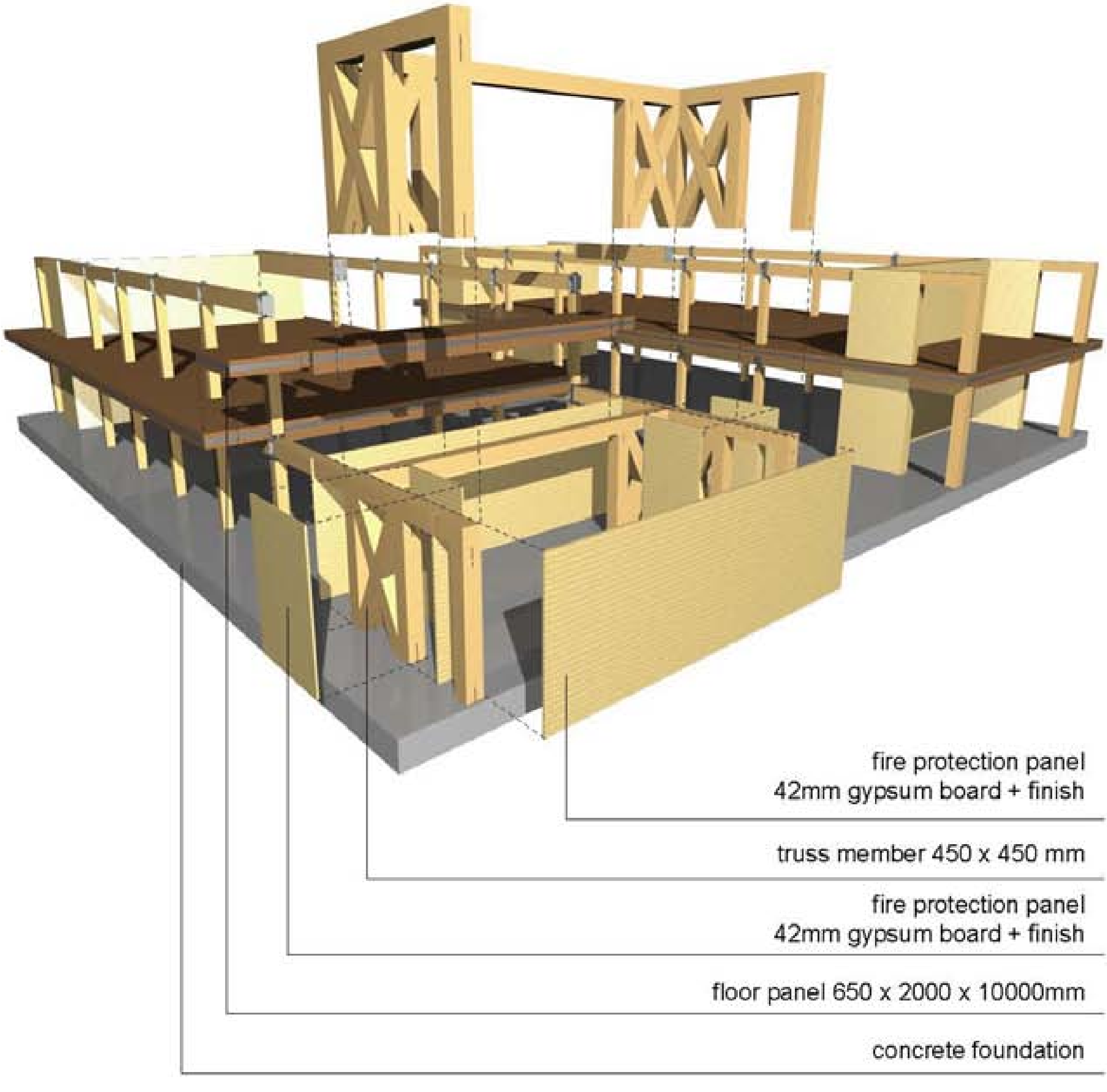
Joint detail



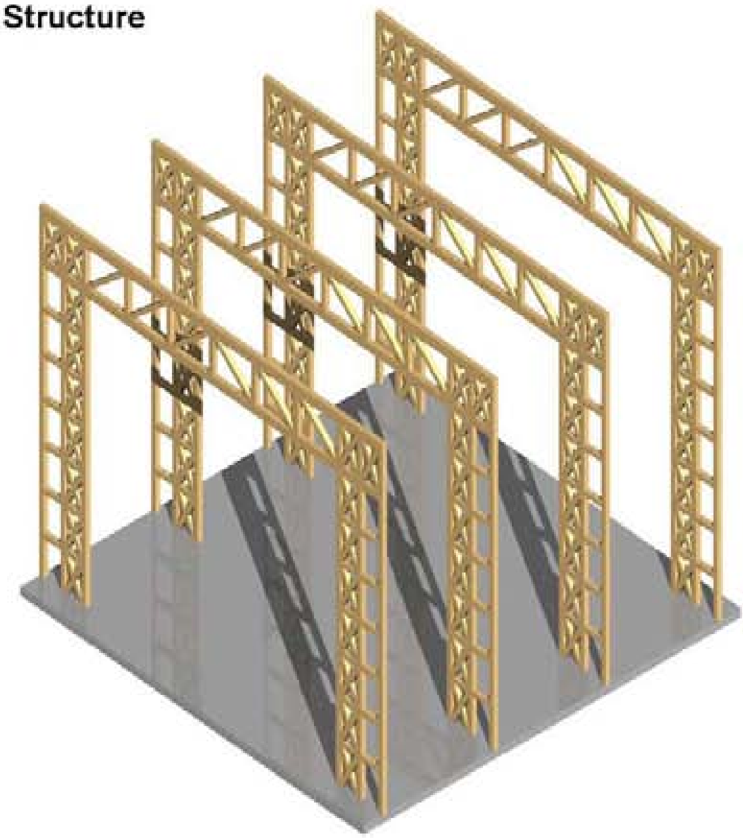


Floor detail

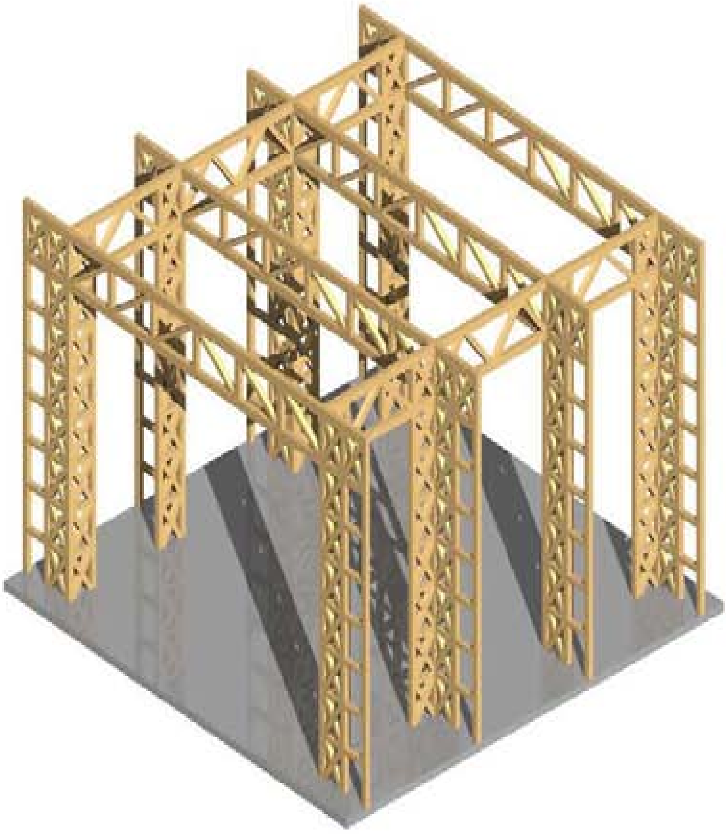
Floor detail



Structure

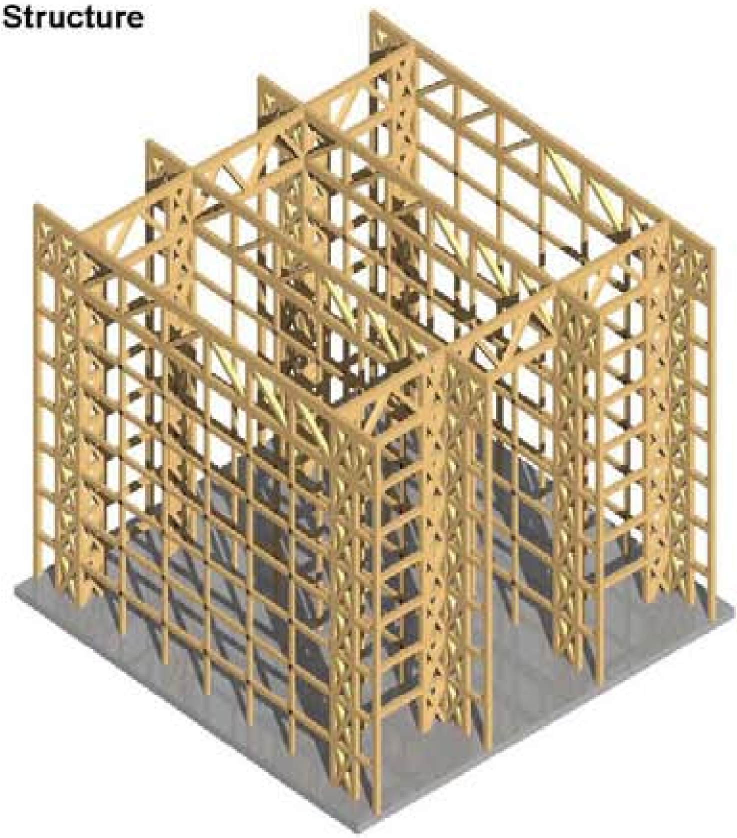


Truss in Y-direction

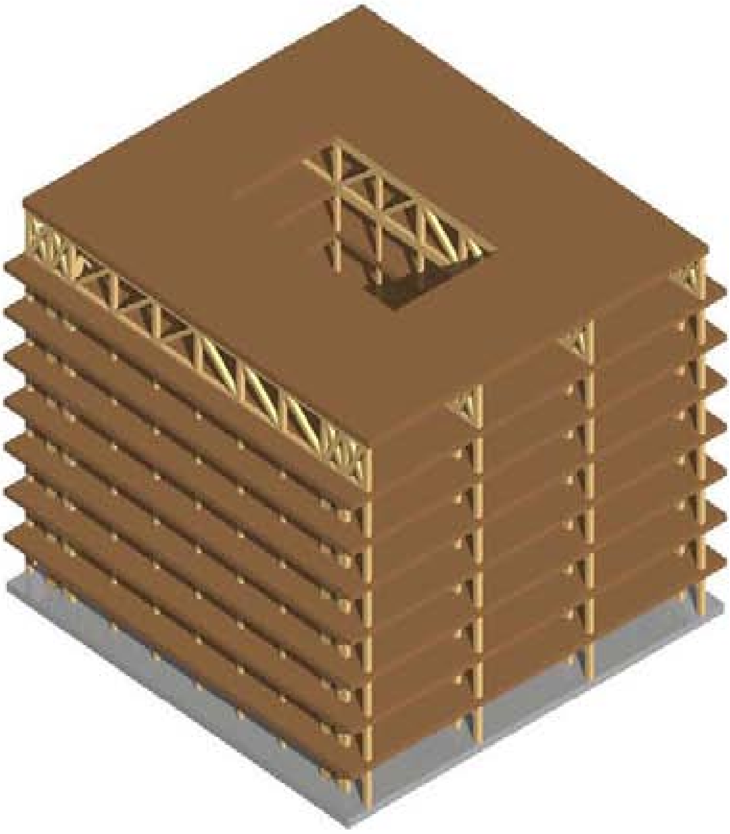


Truss in X-direction
+
Truss in Y-direction

Structure

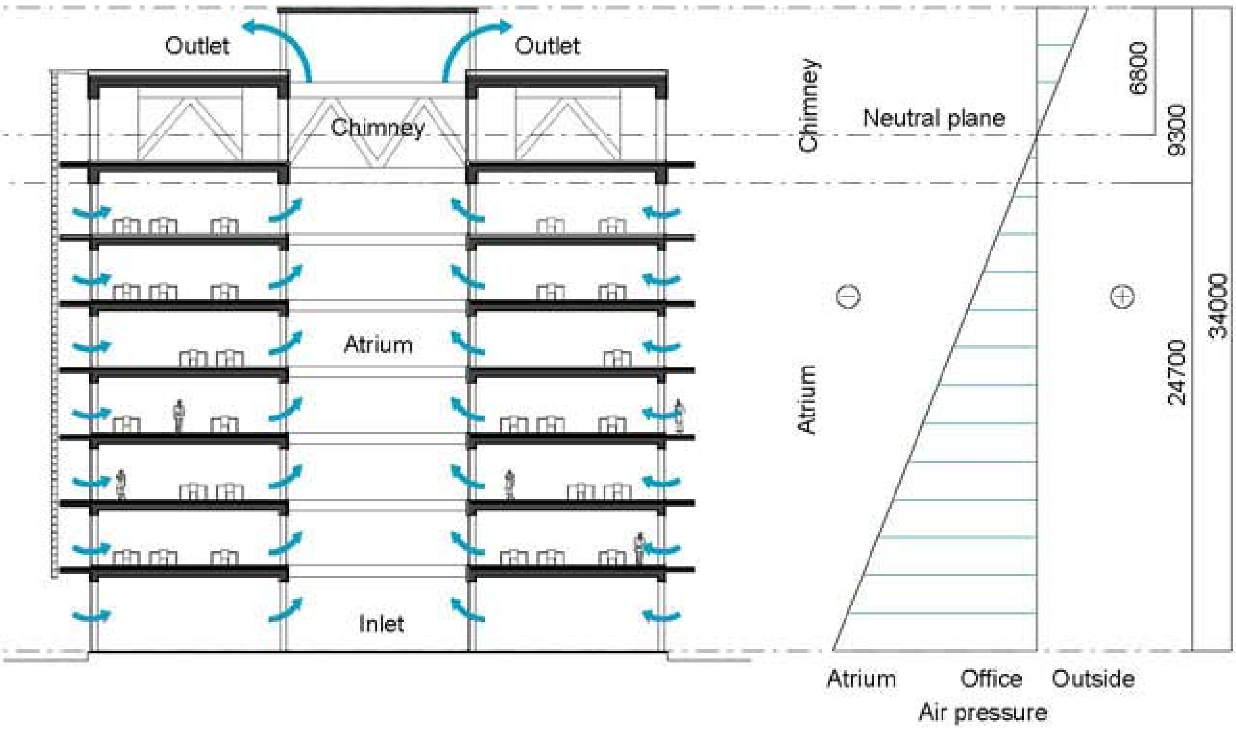


Beams and columns
+
Truss in X-direction
+
Truss in Y-direction



Floor planels
+
Beams and columns
+
Truss in X-direction
+
Truss in Y-direction

Atrium chimney



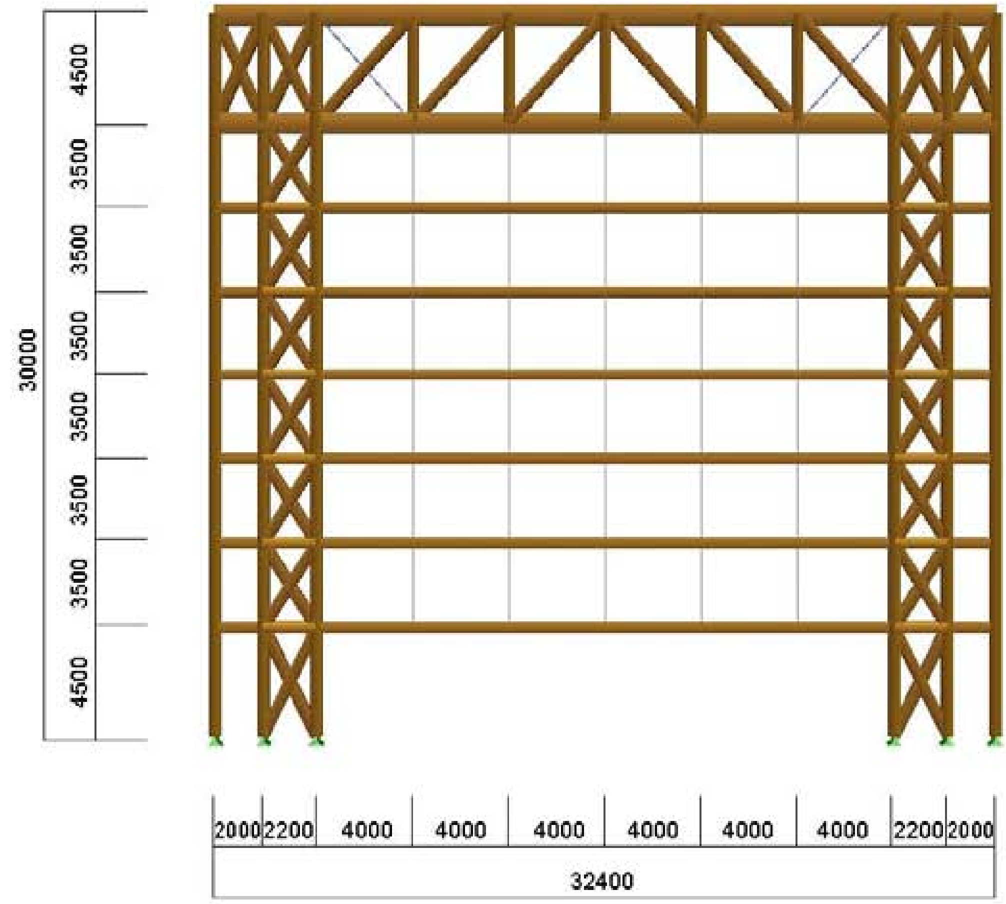
Chapter 5. Structural calculation

5. 1. Introduction

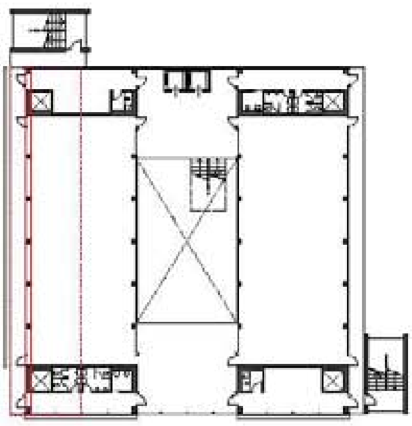
In this chapter, structural calculation of the presented building example is carried out. Results of frame analysis are shown in three cases. In case of fire, all columns on a floor are lost, the hut truss suspends the floors above fire floor. In this analysis, the worst case, all columns on ground floor are lost, is assumed. In this case, combination with horizontal load is not taken into account. In normal times, not fire case, horizontal load is considered in X and Y direction. The hut truss, in this case, functions as a deformation control against horizontal load.

5.2. Frame analysis 1

Case of fire, all columns on the ground floor are lost



Calculation model



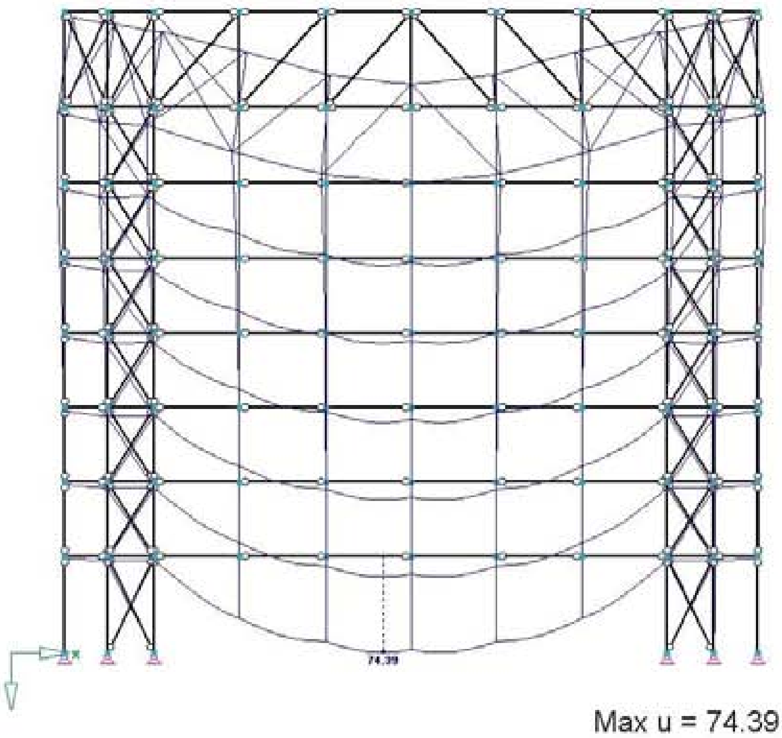
Load

Dead load: $g = 1.5\ kN/m^2$

Live load: $p = 3.5\ kN/m^2$

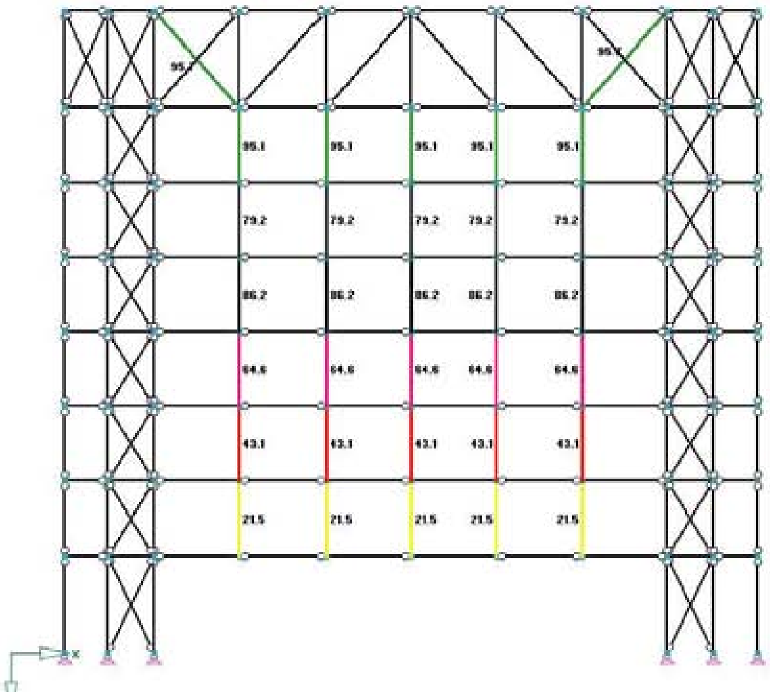
Profile	**Material**
Truss member 450 x 450mm	BS14, S13
Hut truss 450 x 450mm	BS14, S13
Hut truss beam 450 x 800mm	BS14, S13
Steel rod 60mm	

Deformation



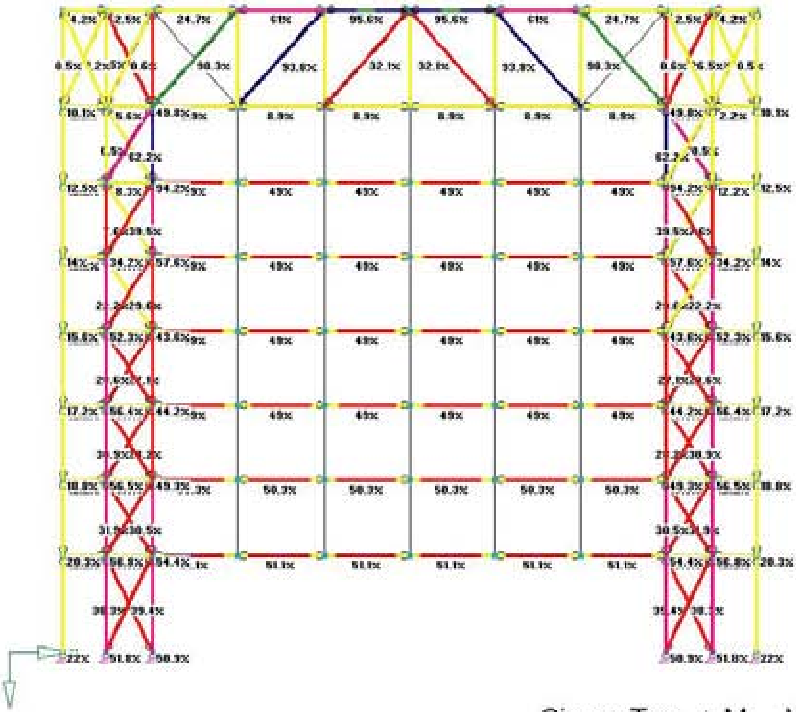
Max u = 74.39 mm < H/300

Steel stress analysis



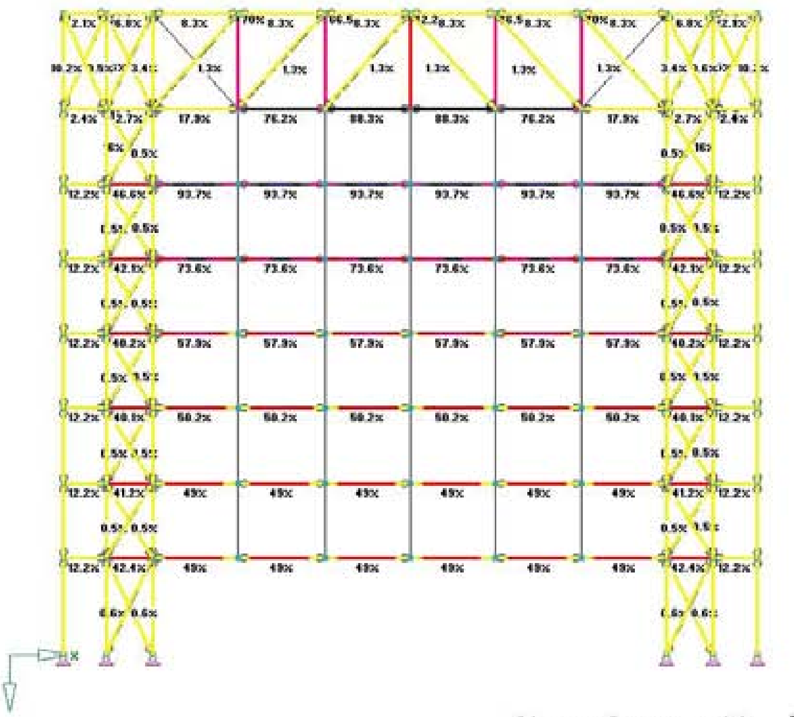
Sigma Total Max = 95.7%

Timber stress analysis



Sigma Ten. + M Max = 93.7%

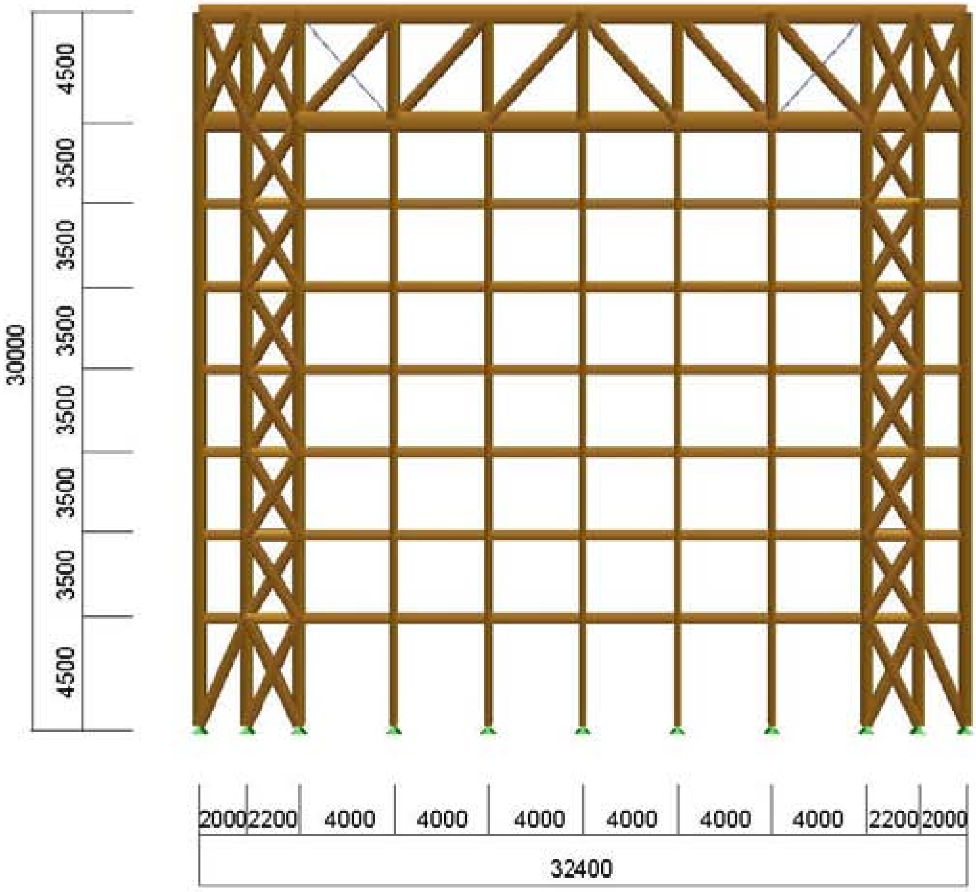
Timber stress analysis



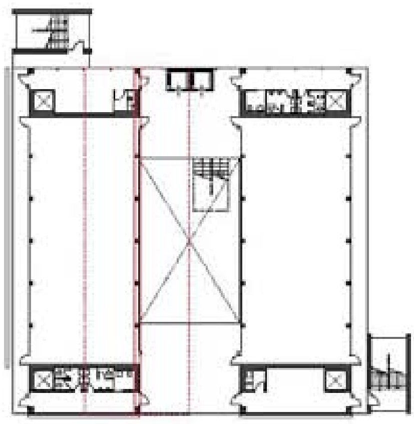
Sigma Comp. + M Max = 98.3%

5.3. Frame analysis 2

Truss frame Y direction, wind load



Calculation model



Load

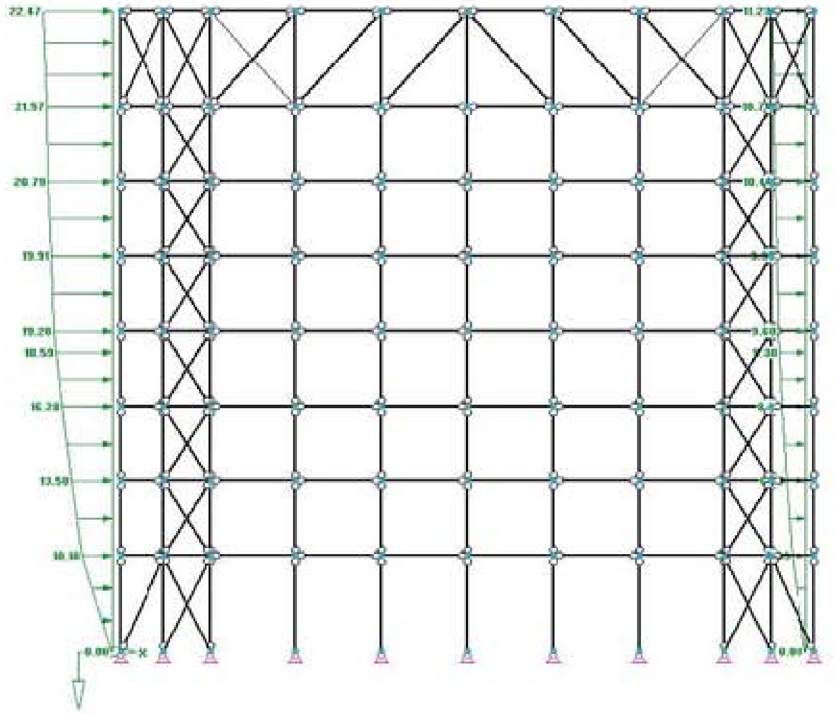
Dead load: g = 1.5 kN/m²

Live load: p = 3.5 kN/m²

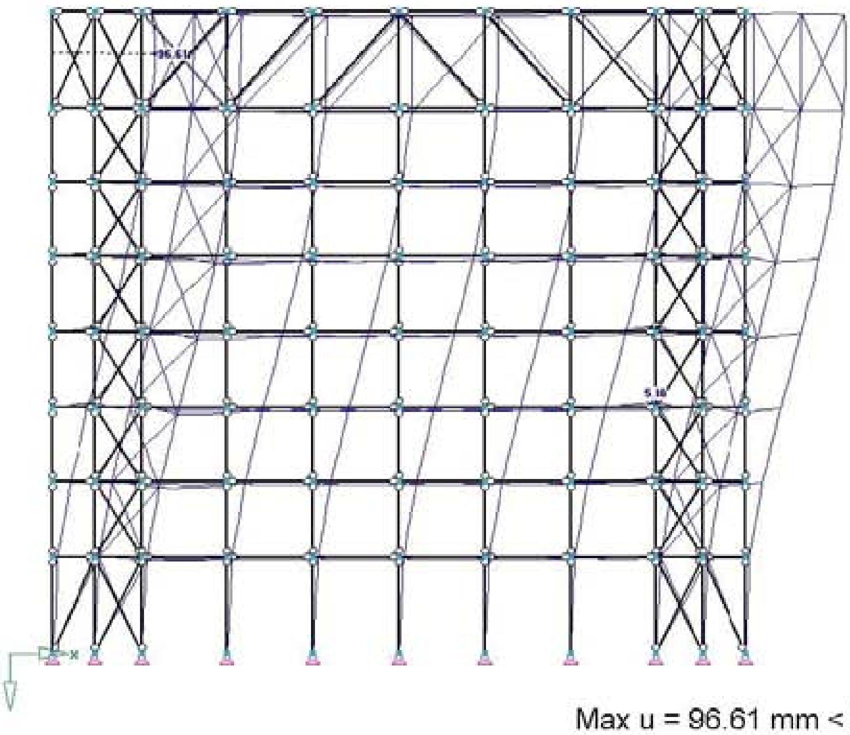
Wind load LK3: 1g + 1.5w

Profile	Material
Truss member 450 x 450mm	BS14, S13
Hut truss 450 x 450mm	BS14, S13
Hut truss beam 450 x 800mm	BS14, S13

Wind load

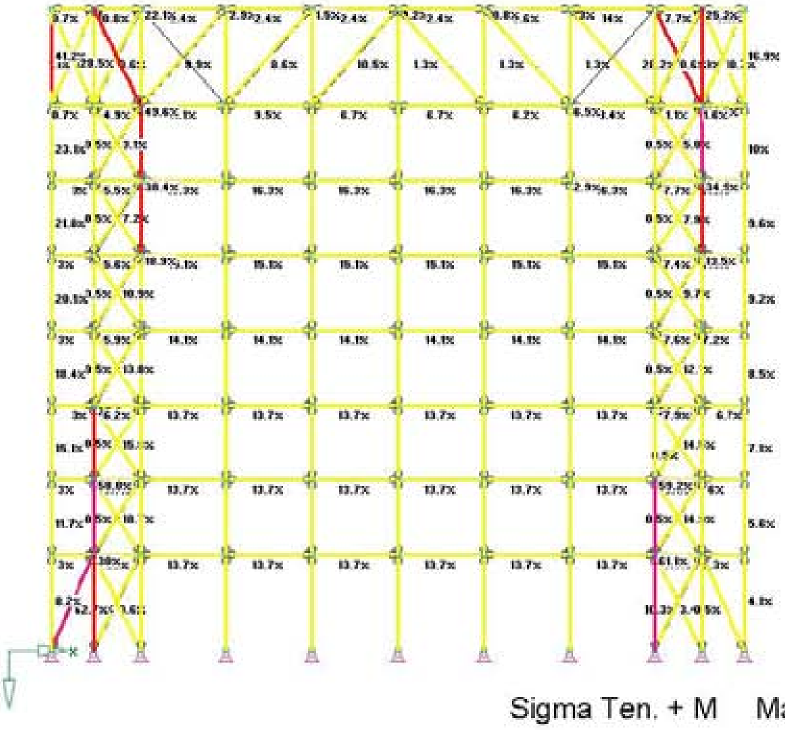


Deformation



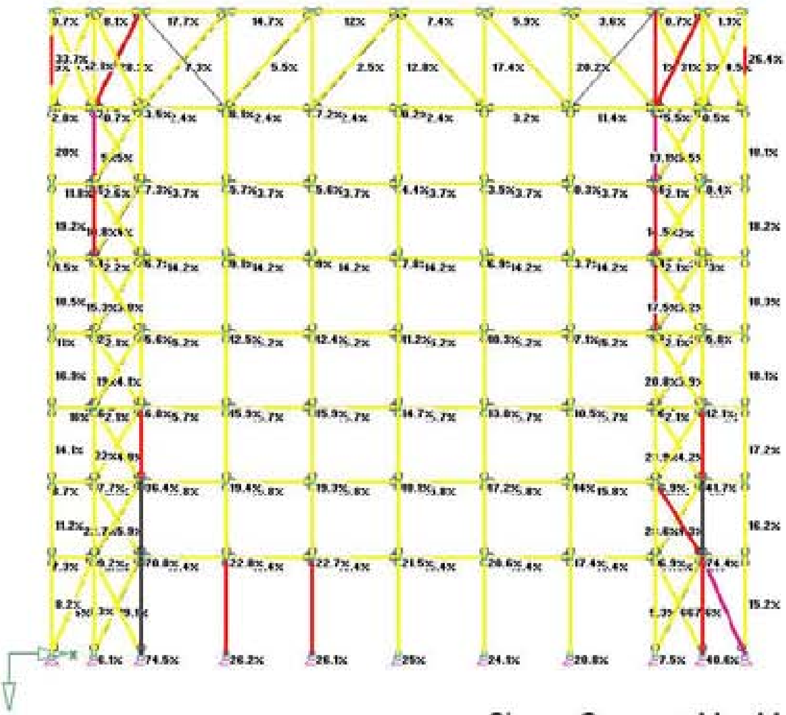
Max u = 96.61 mm < H/300

Timber stress analysis



Sigma Ten. + M   Max = 62.7%

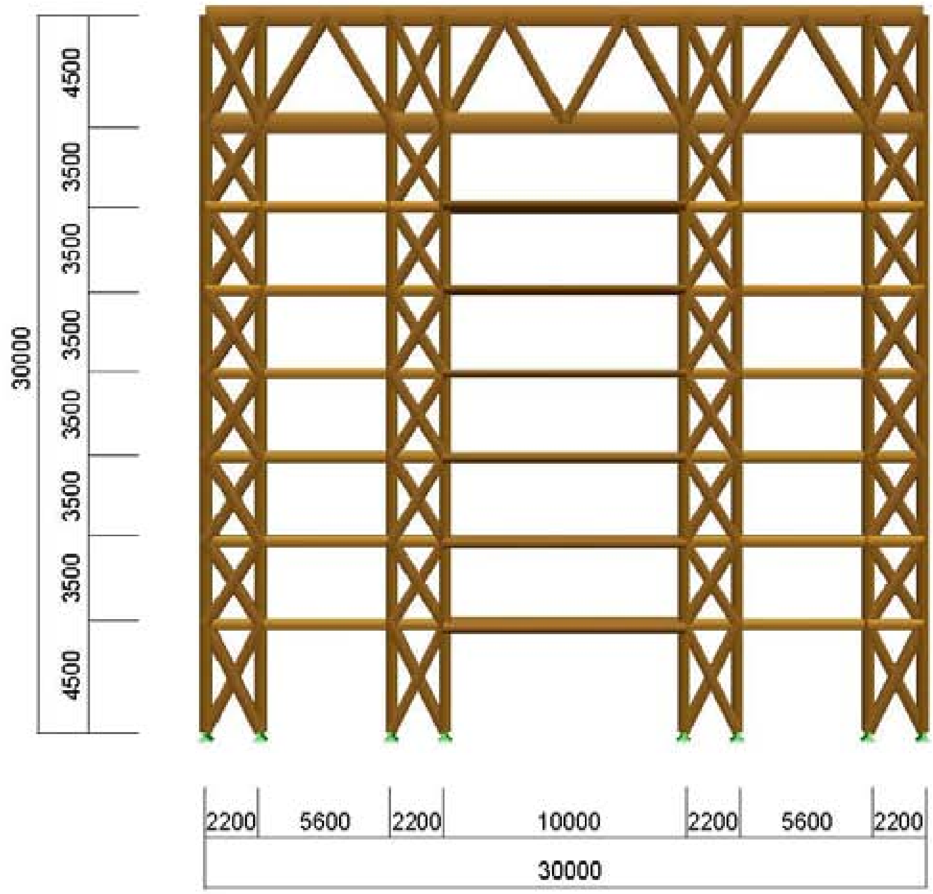
Timber stress analysis



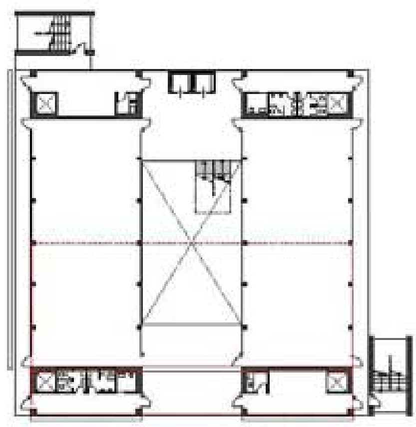
Sigma Comp. + M   Max = 74.5%

5.4. Frame analysis 3

Truss frame X direction, wind load



Calculation model



Load

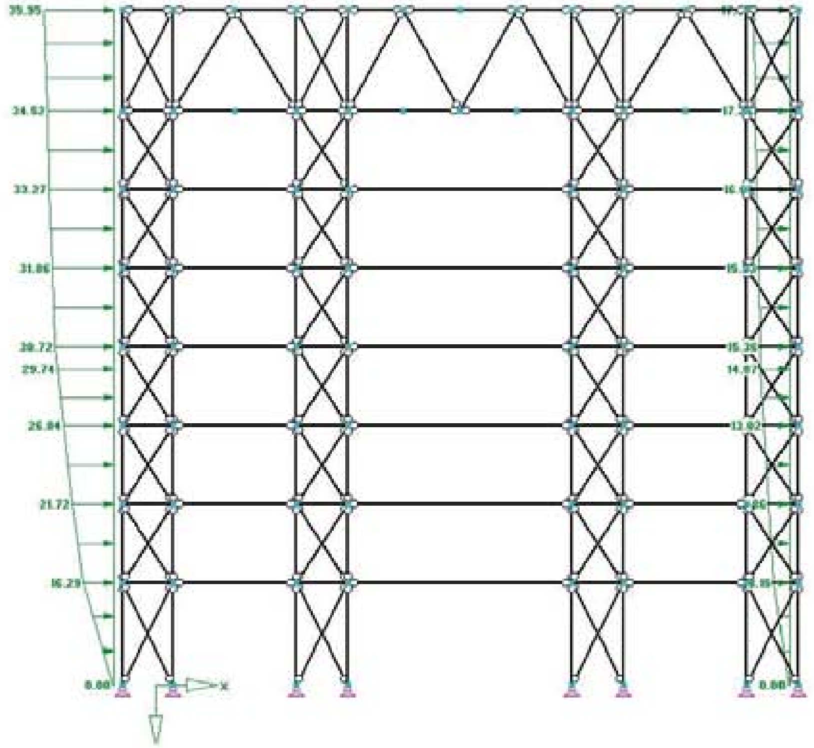
Dead load: g = 1.5 kN/m²

Live load: p = 3.5 kN/m²

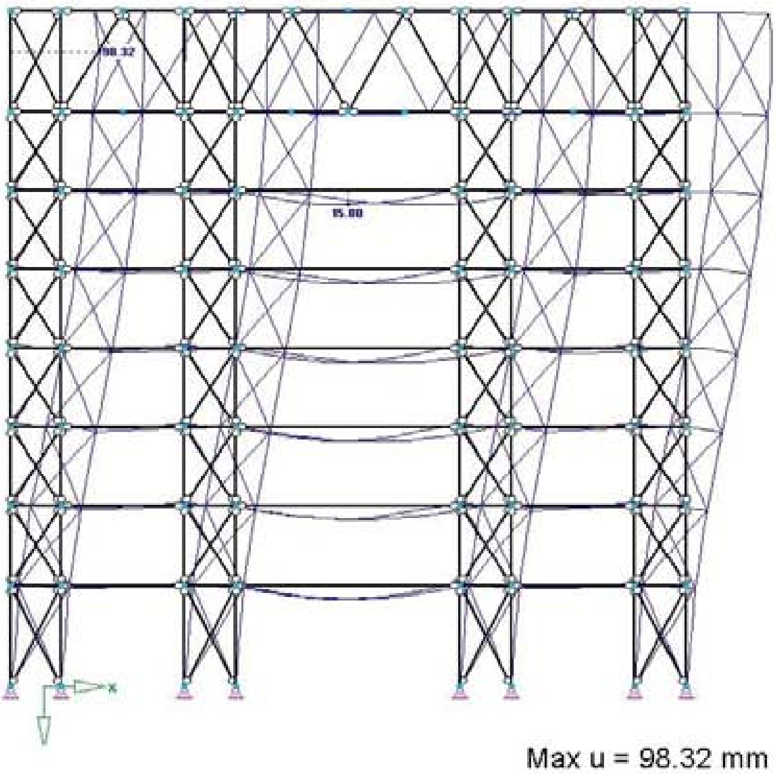
Wind load LK3: 1g + 1.5w

Profile	Material
Truss member 450 x 450mm	BS14, S13
Hut truss 450 x 450mm	BS14, S13
Hut truss beam 450 x 800mm	BS14, S13
Floor panel 305 x 2000mm	BS14, S13

Wind load

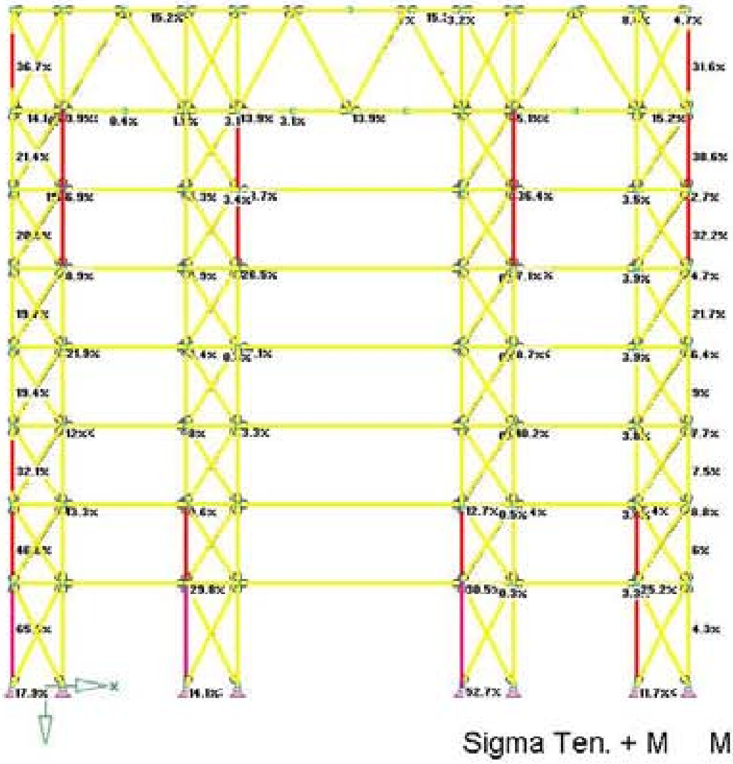


Deformation



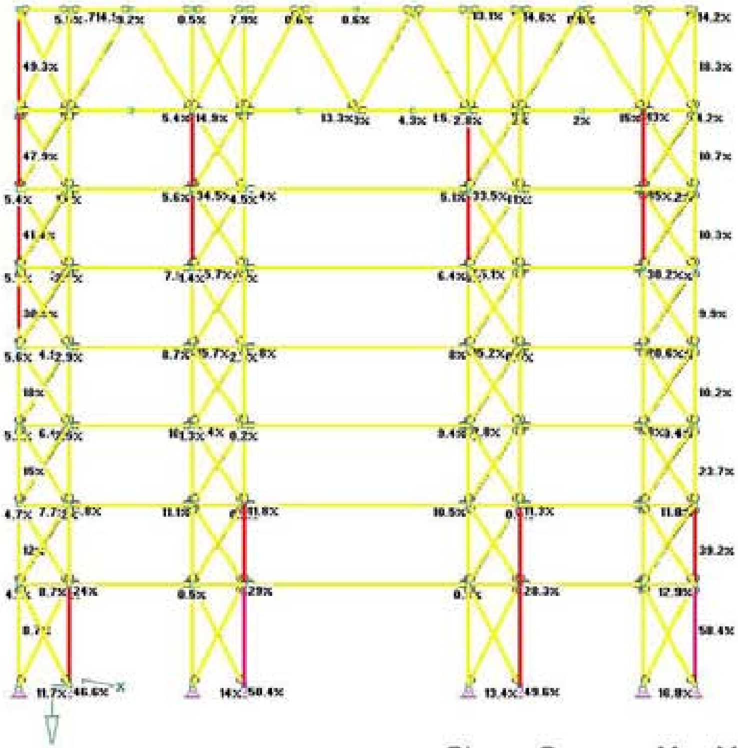
Max u = 98.32 mm < H/300

Timber stress analysis



Sigma Ten. + M Max = 65.6%

Timber stress analysis



Sigma Comp. + M Max = 58.4%

Conclusion

The present work is intended to study the feasibility of wooden multi-story building in urban area by means of considering the issue of fire safety. The basic studies of fire protection measure, smoke control and evacuation measure is presented. And conceptual proposals are derived from the studies. The fire-resistive structure and smoke control atrium chimney and evacuation planning presented are applied for a building example. The structural calculation of wind load and load of fire case show that the fire-resistive structure presented is realizable.

Some topics are not included in the thesis and needed to discuss in the next step. In the thesis, the atrium chimney is designed from the equation concerning only inlet, outlet and height of the atrium chimney. However, in order to utilize natural ventilation, air transfer between the rooms and the atrium affects the air pressure of the atrium chimney. Therefore, exact calculation of air pressure must be considered. In the structural calculation, only wind load are taken into account as a horizontal load. Calculation of seismic force must be considered in the next step. And economical consideration is also a controvertible topic. For instance, comparison between the wooden building and other materials can be discussed.

Concerning fire protection, there are already many studies and researches have been carried out in the field of building physics and engineering. This studies and proposals are intended to develop the topic in the field of architecture design and structural design. In this way, new measure of fire safety design is made possible. It hopefully expands possibilities for use of wood as a building material, and contributes to the sustainable society.

References

[1] Building Guidance Division & Urban Building Division, Housing Bureau, The Ministry of Land, Infrastructure and Transport (MLIT) National Institute for Land and Infrastructure Management of MLIT Building Research Institute. *The Building Standard Law of Japan*. The Building Center of Japan. 2004.

[2] J.Natterer et al. *Timber construction manual.* Birkhaeuser, 2004.

[3] K.Ikeda. *The Kenchiku Gijutsu. 666.* Kenchiku Gijutsu. 2005. 92-99.

[4] J.Yamaguchi et al. *Development of Fire Resistance Wooden Structure Σ Wood.* Report of Obayashi Corporation Technical Research Institute 70. 2006.

[5] Y.Hasemi. *Kajiba no saiensu –Mokuzou ha hontou ni kaji ni yowaika.* Inoue Shoin. 1988.

[6] Y.Hasemi et al. *Compatibility of Solar-assisted Natural Ventilation and Smoke Control in an Atrium Building.* J.Environ.Eng., AIJ, No. 569, 1-6. 2003.

[7] Y.Minegishi et al. *Zone Modeling and Parametric Study of Ventilation Performance of a Smoke Control Compatible Solar-assisted Natural Ventilation System in an Atrium Building.* J.Environ.Eng., AIJ, No. 580, 1-7. 2004

Acknowledgements

I would like to express my sincere gratitude to my supervisor, Univ. Prof. DDI. Wolfgang Winter for providing me this precious study opportunity as a Master's course student in his institute.

I especially would like to express my deepest appreciation to my supervisor, Univ. Ass. Dr. Yoshiaki Amino for his elaborated guidance, considerable encouragement and invaluable discussion that make my thesis of great achievement and my study life unforgettable.