DESIGN OF A MULTI-STORY BUILDING IN A CITY CENTRE - A STUDENT ASSIGNMENT

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ABSTRACT

In highly built up cities, more and more buildings have to be erected on relatively small sites. The employment of load bearing masonry structures may be an advantage as the use of small building units enables "just in time delivery". To make students acquainted with the problems related to building in condensed urban areas during their education, two assignments were put together. They mainly deal with the architectural and structural engineering aspects in addition to building physics, daylight entry, sound insulation and absorption, construction technology, detailing etc. Two types of assignment are presented: a 300 hour project and a 90 hour exercise as part of a masonry course. Although the question for both assignments is basically the same, design a medium rise residential/commercial building for a city centre location, their focus is different. The study of the interaction between architectural and structural demands is the main objective of the project. In the assignment, the students put together their own exercise to obtain experience with the procedure of the design calculations for various structural elements such as shear walls, columns and facade engineering.

KEYWORDS: education, shear walls, columns, architectural demands

INTRODUCTION

Construction in city centers

In the highly build up cities of Western Europe it increasingly happens that old buildings or parts thereof are replaced by new ones. Some of the questions encountered in such projects are: a) how will the new building fit or connect to the adjacent existing buildings, b) how are building site problems to be handled as storage can be very limited, and c) how can an entrance to the building site be created. To make students acquainted with these problems of building in condensed urban areas, the following assignment was set up:

> Design a multi-story building on an irregularly shaped small plot in a city centre.
> The building must allow multipurpose activities, e.g. living, working and recreation.

The assignment was made available in project form and as an exercise which made part of a course in structural masonry. An example of both types and some educational experiences are discussed in this paper. The focus is on integration of design, science and technology.

The Department of the Built Environment

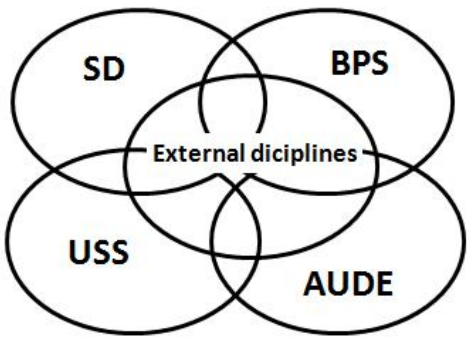
The Department of the Built Environment at Eindhoven University of Technology (TU/e) contributes via its education and research to improving the built environment. Various levels are considered ranging from cities, buildings and building components to the field of building materials. The Department of the Built Environment is one of nine faculties at TU/e. It has eight bachelor degree programs and two master degree programs: Architecture, Building & Planning

(ABP), and Construction Management & Engineering (CME). The Department also conducts research in a broad range of fields in the discipline of architecture.

The Department is primarily oriented towards the technology of building and technological solutions that contribute to the cultural dimension of the built environment. Research and design are scientific in nature and form the foundation of the education. The Department brings almost all construction disciplines together under one roof organized in four organizational units: 1) Architectural Urban Design and Engineering (AUDE), 2) Building Physics & Services (BPS), 3) Structural Design (SD), and 4) Urban Science & Systems (USS), see Figure 1A. Within each unit, scientific architectural research and design are performed and contributions to education are made. The bachelor program, given in Dutch, has a duration of three years. It is aimed at training building engineers to be skilful at multidisciplinary co-operation.

The faculty offers a three years bachelor followed by a two year master. Most (Dutch) students follow both the bachelors and the masters program. The master program is conducted in English.

Students spend about half their time on lectures and related assignments and the other half on projects. This means that the bachelor students do 6 projects during the course of their program.



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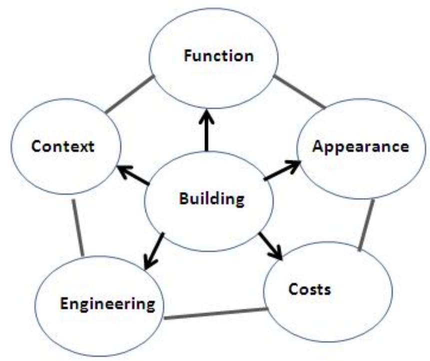

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Figure 1 A. Overlapping disciplines in the Department of the Built Environment TU/e
B. The building as an integrated design.

GENERAL ASPECTS OF THE ASSIGNMENT

In the design assignment two main areas of interest are recognized, i.e. architectural design and structural engineering. Additional aspects like building physics, construction technology and some others are also considered important. The disciplines overlap as shown in Figure 1. In the structural design group the focus will be mainly on structural design but integration with other disciplines is also taken into account. The student's work on the design of the structure focuses mainly on following the load bearing principles and understanding the structural quality of the design and less on exact design calculations. It is very important that the two supervisors, one of architecture (AUDE) and the other of structural design (SD), make sure that integration of the various disciplines, Figure 1B, is applied by the students.

The assignment covers the following areas of interest:

construction; site, location and configuration
building; architecture, height, set-backs, daylight entrance, sound reduction
structure; materials, design, construction

Many other areas of interest are considered implicitly in the design process, e.g. fire safety. For these aspects, rules of thumb are used. In some cases experts in these fields are consulted. Costs are only considered on a very limited level. They are checked on quantities of materials used, complexity of details and building site activity. The building experience of both supervisors is important as they play several roles in the project, e.g. client, customer, colleague designer or opponent.

The specific disciplines represented by the two project supervisors will get the most attention and other disciplines are treated based on their experience. If knowledge is lacking in areas such as planning, logistics or safety- and health planning, other members of the faculty may be consulted.

Problems of building in city centers

Building in a congested city centre has its specific problems: working on small construction sites, finding storage space, keeping traffic moving and scheduling large transports in specific time slots, e.g. at night. These problems require an innovative approach including a location fitting design for the building [1], choice of materials and structural building system. Besides available expertise, good and early communication by the architect with the project developer, structural engineers, services engineers and other stakeholders such as government bodies and owners of neighbouring buildings is essential for all to obtain an optimum product. By touching on all these aspects the students are trained to become more than merely an architect or a structural engineer. Certainly, in the case of urban renewal projects it is crucial to be a team player.

Location of building site in Liège Belgium

Liège is a city in the East of Belgium, close to the Dutch and German border. The river Maas flows through the city. The building site is located along the river in the city centre. Figure 2 shows the location of the building site and surroundings. The plot can be described as relatively narrow and deep, stretching between two streets. The east side of the building looks out over a busy road which is adjacent to the Maas. The west side borders an inner city street. A 10 storey high office building is located just north of the building as shown in Figure 3. On the South side there are three storey, 12 m high, traditional residential houses from the early 1920's. The dimensions of the plot were established from site measurements and photographs, keeping in mind that for educational purposes the exact dimensions are not of vital importance, Figure 2.

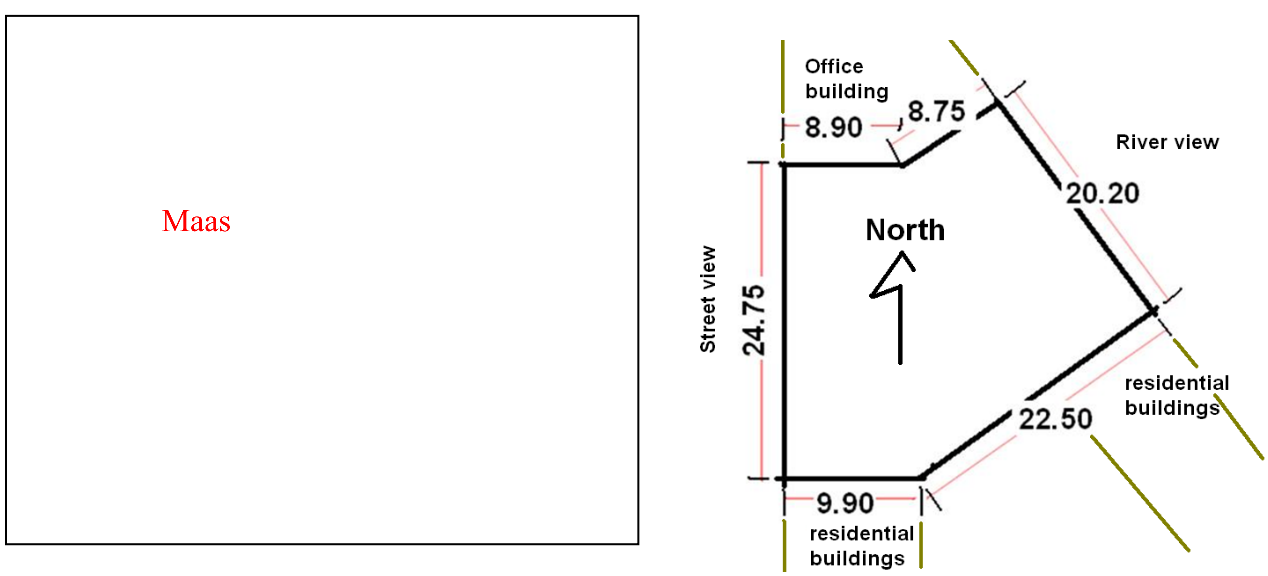


Figure 2 Location of building site in Liege and its dimensions in meters

Figure 3 Photograph of the building site taken from river side.

General set-up of a medium rise building

In a multipurpose medium rise building, the lay-out of specific entrances is one of the most important features. Inside the building, the location of vertical traffic and thus the position of the stairwell and elevator(s) must be considered carefully. Characteristic for a medium rise building of say 10 stories is the presence of a roof section, a mid section with more or less identical floor plans and a lower section including the basement. The bottom stories usually take the whole building plot whereas the upper stories often experience set-backs. In the bottom stories, general functions like offices and shops can be situated as they require easy access by the general public. In some cases, large open spaces are required with load bearing columns instead of shear walls. Then, the load transfer from wall to columns will be part of study [2].

From a functional point of view, a building lay out with general functions at lower levels allows a simple separation of the shopping public from the building residents. If a public function, e.g. a restaurant with river view, is planned at roof level, the separation of vertical transport may cause an additional problem.

Requirements for residential and commercial space

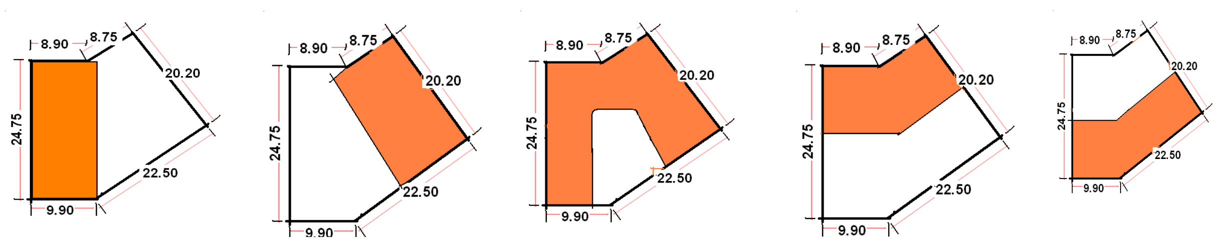
The location of the building site was arbitrarily chosen by one of the supervisors. This type of site and location is typical for Liège and for many cities in Western Europe, e.g. [3], [4] and [5]. The construction problems are typical for this kind of building site as mentioned in section 2.1**.** In addition, the connection with adjoining buildings can be a challenge to the architect.

For residential buildings it is important that sufficient daylight can enter the individual dwellings. For the sizing of window openings, the following window/floor area ratios are suggested: 1/6 for living rooms, 1/10 for bedrooms and 1/7 for kitchens. It is assumed that for sufficiently high windows the light will have a 5 m deep penetration into the area. This leads to an allowable building depth of roughly 10 m if light is able to enter both sides.

Facades with a high sound-load, i.e. facades next to busy roads, require sound insulation. For this project, it can be assumed that modern window frames and glazing systems will perform adequately near roads with heavy traffic.

Although nowadays with mechanical ventilation it seems less important, a good natural air flow through the building is desirable. Therefore, windows and doors should be possible to be opened to create a cross flow of air through the residential and commercial areas.

The requirements for daylight penetration and noise reduction yield several floor configurations for the plot as shown schematically in Figure 4. A view to the south would cause conflicts with the neighbours and is therefore not allowed. A and B either allow a main view on the river or on the city. Combining A and B gives C, a U-shaped floor area with questionable daylight penetration at lower floor levels. D has daylight entrance on the east, south and west sides; the net floor space is perhaps too small. Floor configuration E has its main view on the existing 10 story office building and is therefore not attractive to explore any further.



A B C D E

Figure 4 Floor configurations

THE PROJECT

The project in relation to the educational program

The building design project mainly deals with architectural and structural engineering aspects in addition to building physics, daylight entry, noise control, construction technology, detailing etc. It is offered in the first semester of the final year of the three year bachelor program. By then the students are familiar with working in project groups. They usually start with a group-program during three to four weeks. Much information is collected and shared among its members. Then students start with their own design based on this information. Each week a group session is held with 12 students for half a day in which their progression is presented to the supervisors, but more importantly, to their peers. Results are critically commented on and suggestions for improvement are given. An evaluation session is held after eight weeks. This is a more formal power point presentation to their peers, the supervisors and guests, e.g. colleagues of supervisors. In the second part of the project the focus is on the technical aspects. The design is worked through, including construction details. Because of time limitations the design calculations are limited to the employment of rules of thumb. More detailed calculations are required for an exercise that makes part of a course on structural masonry. This will be discussed later in the paper.

General design requirements

The residential building should have a minimum of 10 apartments of two different types. The standard apartments are for families with children. They have an outdoor space in the form of a terrace, loggia or balcony. The luxurious apartments are for singles. Parking does not have to be considered, enough space is available in the neighbourhood of the building. A second fire escape is required. Additional facilities and functions may be required and the combination of working and living must be possible.

Architectural requirements

Larger residential buildings have the advantage of allowing a profusion of diverse activities. Due to the relatively high density of occupation a basis for several functions does exist and is incorporated in the assignment. A number of questions then arise:

- How do people live together nowadays
- What is the ratio between public, collective and private domain
- What does this mean to the individual dwelling
- To what extent is one free to alter a dwelling according to personal aspiration

Students must develop ideas about these questions and related issues before they start with their design work.

Designing a building is an iterative process that starts with establishing the shape and size of the building as well as the floor layouts taking care of the size and location of the daylight openings. In this phase the designer should, as much as possible, position load bearing walls vertically on top of each other. Students are prompted to the books of Hendry [6] and Drysdale et al. [7].

Structural requirements

The structure of a medium rise building can be made of concrete, steel or masonry but we will focus on masonry in this paper. The first step is to find a logical position of the load bearing walls in the floor lay-out. Therefore, both for the lower and the upper part of the building, floor plans have to be developed in order to obtain a "smooth flow" of the vertical loading. Structural elements that must be recognized are: floor slabs, shear walls, columns and piers. Several types of floor structures are available, but in residential buildings the use of wide plank floors is preferred. This type of floors allows for some control of the transfer of vertical loads to the bearing structural elements since they span in two directions opposed to hollow core slabs which span in one direction. Another advantage is the possibility to extra strengthen parts of the floor instead of using (steel) beams, resulting in a smaller height of the structure.

Then, the design of the shear walls requires determining the individual horizontal and vertical loads. Shear wall design calculations are made for which a spread sheet program is available, Vermeltfoort and Ng'andu [8] based on a matrix method of analysis.

The structure at lower levels, with a more general function, may comprise beams and columns. At higher levels, in the residential area, a system with load bearing walls can be applied. The transition from one system to the other can be a challenge for the students (Vermeltfoort, [2]).
It is important here for students to learn that form and structure harmonize.

Project phasing

The project is carried out in three phases.

1. Site investigation.

The work in this phase is carried out in groups of three or four students. It concentrates on the investigation of the location of the building site and its surroundings, of which a scale model is made, see Figure 5. Often, publications on the project are found in Dutch literature [9], [10] or on web sites e.g. [11], [12]. However, students are encouraged to look for international publications as well, e.g. [1], [3], [4] and [5].

2. Individual preliminary design.
Until the first presentation of individual work to all participating students, the accent is on the development of a conceptual design for the building in relation to architecture and structure, taking into account additional aspects such as its relation to the surroundings, program and functionality. Each student should develop his own vision for this project that allows integration of an appealing architecture with purpose entrances and vertical transport, interior lay-out allowing unobstructed views and a relation with outdoor space. Not in the least, it must pay attention to the constructability of the building. A scale model of the building designed by each individual student is placed in the scale model of the building site for evaluation, Figure 5. A vertical section of the preliminary design is made in which the structural system and method of construction can be demonstrated. These will play an important role in the second part of the project. At least two alternatives must be presented.

3. Salient design calculations.
In discussion with their supervisors the students make suggestions for several important structural components in their design that are considered suitable for detailed design calculations and possible improvement or optimization.

Deliverables
The student finishes the project by submitting the following drawings: view of architectural facades; structural floor plans, a vertical section through the building and details of facades. Furthermore, both an architectural and a structural scale model, in addition to a report on the preliminary site investigation by the group are submitted. Drawings and models should be on a scale to allow easy evaluation of the structural aspects, daylight openings and technical installations. PowerPoint-files of presentations and structural design calculations complete the work.

Figure 5 Scale model of building site, scale model and photomontage of design.

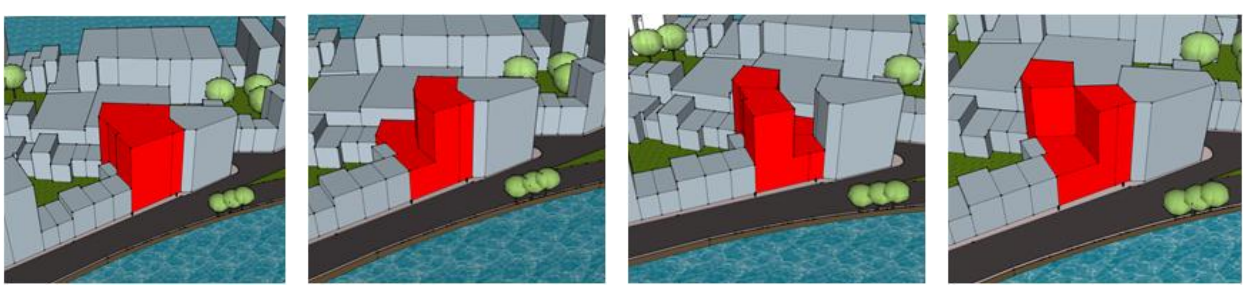


Figure 6 Mass studies in relation to neighbouring buildings, streets and river.

Evaluation of the students performances and their projects.
The evaluation of the students input and projects is done according to the so called 3 P's: process, product and presentation. The process is a measure of the input contribution in weekly sessions, the progress in relation to time and the independent steps taken. The product is the quality of the final design resulting from individual motivation throughout the project. The marks for presentation are based on the quality of the report, drawings and oral presentations.

THE EXERCISE
Structural Masonry Course
The course on structural masonry is an elective and is given in the master program. Most students have followed the bachelors program at TU/e so they are familiar with the design process for buildings. Some students may have done a project similar to the one earlier described in this paper.

The course is a combination of lectures and an exercise. The final grade of the course is based on the marks for the exercise and a twenty minute oral exam. The time needed to do the semester course is estimated to be 90 hours including eight lectures and the oral exam with the remaining hours left for the exercise. During this semester the students can have one or two meetings with the course lecturers.

The lectures on Structural Masonry are given over a period of 8 weeks and are ninety minutes long each. The main topics per lecture are: 1) Structural design of masonry buildings; 2) Experimental determination of material properties; 3) Vertically in-plane loaded walls; 4) M-N-k-diagram for eccentrically loaded walls; 5) Wall-floor interaction and vertically in-plane loaded walls; 6) Overall stability: horizontal load distribution, strength of shear walls, local instability in shear walls, stiffness of shear walls and second order effects; 7) Horizontal out-of-plane loading on diaphragm walls, single leaf walls and cavity walls; 8) Special topics: prefabricated masonry, mortarless masonry infilled walls, deep masonry beams/lintels, reinforced masonry, pre stressed masonry, and crack control.

Course registered students have access to the lecture notes and additional relevant information via the university network called "OASE". The "Manual for the design of plain masonry in building structures to Eurocode 6" is used as reference, [13].

Contents of exercise
The exercise is based on the earlier discussed design project and focuses on the structural aspects of masonry. It is aimed at the employment of the theory from the masonry lectures and at obtaining experience with the procedure of the design calculations for various structural elements such as shear walls, columns and facade engineering. Students are prompted on relevant literature e.g. [14] and [15] and supplied with the necessary information on the architectural aspects and the floor plans. The exercises are personal as they differ in dimensions and floor plan.

The object of the exercise is to derive an optimum structure with a given floor plan. This requires the following design procedure: 1) Establish the maximum number of floors for a given material quality (either CS12, CS20, CS28 or CS36) with a maximum element thickness of 300 mm or

214 mm and, 2) Determine the necessary number of shear walls and their locations in the floor plan.

Like in the contemporary Dutch building practice, all load bearing walls must consist of Calcium Silicate Elements (CASIELs) and the facades comprise clay brick masonry. Information about building with CASIELs from Berkers [16], Vermeltfoort & Ng'Andu [8] and others is made available to students via "OASE".

Code	Strength		Young's Modulus
	Element (MPa)	Wall (MPa)	(MPa)
CS 12	16	8.4	8000
CS 20	20	10.2	1000
CS 28	28	13.6	12000
CS 36	36	16.8	14000

CASIEL hoisted into position, controlled and guided by grooves

Figure 2 Building with calcium silicate elements and main properties [8], [16].

Some design aspects, emphasized in the explanation of the exercise are the following.
1) The gravity loads on the floors are transferred to the walls. The eccentricity of the floor support conditions will cause stress gradients across the thickness of the walls. This effect was discussed earlier by Martens [17], Hendry et al. [6], and Drysdale et al. [7]. The lateral load due to wind on the building is distributed to the individual shear walls resulting in bending and shear stresses along the length of the walls.
2) Shear wall design calculations can be made using a matrix analysis method where the influence of openings on the lateral stiffness is estimated. The method is explained with examples of relatively simple floor plans, Figure 9 and references are made to [8] and [18].
3) The maximum combined stress in each wall determines whether this is acceptable. If stresses are too high, walls can be made thicker, a better quality CASIEL can be used or more rigorously, the length of some of the walls or their lay-out can be altered. The process is then repeated with the new properties and/or structural floor plan.

An example report with explanatory notes is made available to the students. References to this report are allowed. In addition, building code requirements for serviceability loads such as wind forces are allowed to be simplified. The example report also shows the calculation of the lateral load distribution to the individual shear walls using a matrix method of analysis and gives the procedure for controlling the load bearing capacity of the shear walls with the aid of a moment-axial force interaction diagram (μ-υ) as shown in Figure 9.

Working procedure

The working procedure for completing the exercise is as follows. After distribution of the exercise and an oral explanation by the supervisors, the students start to study the architectural drawings of the building and make the preliminary structural drawings. This is followed by a discussion in small groups to select structural elements that are to be subjected to closer study. The design of the shear walls requires that the individual horizontal and vertical loads be

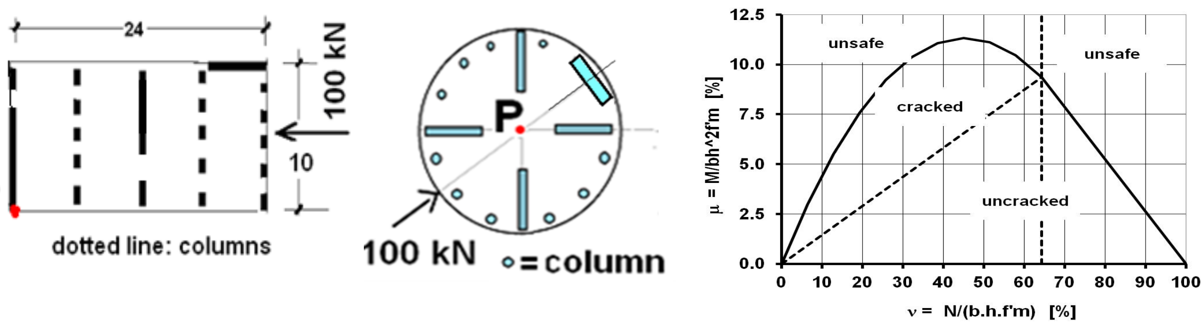


Figure 3: Floor plans used to explain shear wall design and normalized M vs. N diagram (μ−υ-interaction diagram).

determined first. Then shear wall design calculations are made using the available software. The students submit a first draft of a report on paper including a proposal for a structural system for the building and stating their intentions for a closer investigation of several structural components. The supervisor checks whether this report complies with set conditions and indicates possible shortcomings or lack of clarity. The first draft is then discussed individually with the student and plans are made on how to finalize it. An improved final version of the report and drawings must be submitted later.

Grading the exercise

The final grading of the exercise is done by the supervisor and will be based on the final report and an oral exam.

Some of the criteria for assessing the work by the student are:

- correctness of calculations and drawings,
- procedure of structural calculations,
- quality and completeness of drawings,
- lay-out of and use of language in the report and
- keeping of appointments and timing.

The oral exam will take place after the report has been graded. The technical contents of the report can be discussed during the oral exam in addition to various theoretical aspects from the lectures and other course material.

CONCLUDING REMARKS

This paper presents two ideas for making students acquainted with building in highly built up city centers: a semester long design project and an exercise as part of a course on structural masonry.

Main aspects of the project

The project mainly deals with architectural and structural engineering aspects in addition to building physics, daylight entry, noise control, construction technology, detailing etc. The aim is to teach students that form is related to function. The characteristics of a medium rise building on an urban building site, the functionality of a residential building interacting with structural demands and the visual effects of technical details are some of the items that are encountered. The project also allows the training of practical skills such as making drawings, giving presentations and designing structural elements using rules of thumb.

Main aspects of the exercise

In doing the exercise the students learn how to make: a) structural drawings of a building with masonry load bearing walls and columns and, b) structural design calculations to prove that all structural elements have sufficient bearing capacity. Additional facade engineering and building construction detailing are experienced. The students put together their own exercise to obtain experience with the procedure of the design calculations for various structural elements such as shear walls, columns and facade engineering.

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