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The assessment of openings in load-bearing concrete structures

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The aim of this thesis was to examine the assessment of openings in existing load bearing concrete structures. The focus of the study was on identifying the different factors and regulations governing the assessment of openings in different structural components.

As a first step, an extensive literature review was conducted. The aim of the literature review was to map out the existing guidelines and regulations for designing openings in concrete structures. After the literature review, senior engineers were interviewed about their best practices regarding the matter, and this information was also incorporated in the work. Additionally, the work process of the assessment was further demonstrated by an actual assessment case study.

As a result, the thesis compiles existing guidelines and regulations, which can be used to facilitate the assessment process. The compiled information can be used by structural designers to better understand the different aspects of the assessment process. Additionally, a general work process of the assessment of openings in load bearing concrete structures was created for the use of the client of the thesis.

Keywords	concrete, openings, renovation, load bearing structure

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Tässä työssä tutkittiin kantavien betonirakenteiden jälkikäteen tehtävien reikien tarkastelua. Työn tavoitteena oli kerätä tietoa yhteen eri betonirakenteille olemassa olevista ohjeistuksista ja toimintaperiaatteista sekä reikien suunnitteluprosessista.

Ensimmäiseksi työtä varten suoritettiin laaja kirjallisuuskatsaus. Katsauksen tarkoituksena oli kartoittaa jo olemassa olevia ohjeistuksia ja säännöksiä jälkikäteen tehtävien reikien tarkasteluun liittyen. Tämän lisäksi työtä varten haastateltiin kokeneita rakennusinsinöörejä heidän tavoistaan tarkastella kantaviin betonirakenteisiin tulevia reikiä ja näitä haastatteluista saatuja tietoja on myös sisällytetty työhön. Työn aikana kerättyjä tietoja käytiin myös läpi tarkemmin esimerkki rakenteeseen tulevan reiän tarkastelun avulla.

Opinnäytetyön lopputuloksena saatiin selvitettyä reikien tarkasteluun liittyvää ohjeistusta, joka on myös esitetty työssä. Kerätty teoria ja ohjeistukset helpottavat suunnittelijaa ymmärtämään reikien tekoa eri rakenteisiin ja nopeuttavat suunnittelijan työtä. Lisäksi työn tuloksena luotiin yleinen reikien suunnitteluprosessi työn tilaajan käyttöön.

Keywords	concrete, openings, renovation, load bearing structure

Contents

1 Introduction

New openings in existing load-bearing concrete structures are very common and often challenging to implement. The importance of well made opening plans are of higher importance in renovation projects as the existing structures drastically limit the placement of new openings [1,45]. In many cases, the spaces are rearranged and their use changes, which means that the HVAC systems are modified as well. The placement of HVAC ducts and pipes might change; important bearing walls must be removed and new openings for light wells and staircases are planned between floors. All this means that the new openings to the structures must be planned accordingly.

A structural engineer is responsible for these changes to the building's structure. The cost of making a new opening in existing structures makes up a significant portion of the total building cost. [2,520.] By controlling the placement, size and number of new openings it is possible to achieve a substantial positive effect on the load bearing capabilities of the structures, the economy and the total cost of a project. [1].

The planning of the openings requires a close cooperation between the various parties and designers involved in the project. The structural engineer is usually responsible for guiding the planning already from the initial steps of the project. The structural engineer must evaluate the building and highlight all possible and most favorable locations for new openings to the other designers, and to the customer to minimize making costly openings in the load-bearing structures of the building.

The thesis is done for the needs of the renovation department of Wise Group Finland. The company seeks to unify and streamline the design process. Currently the company does not have any general instructions for the assessment of openings in existing concrete structures. The aim of the thesis is to draw up a general design process for planning and designing openings. Additionally, the thesis compiles the instructions regarding assessing the openings, which would assist the designers in the independent assessment and design of openings and perforations in load-bearing concrete structures. In addition to this, a couple of the Wise Group's more experienced structural engineers were interviewed about the work. These interviews aimed at gathering their ways and processes for assessing and designing the openings.

Making new openings in existing lightweight partition walls and other non-load-bearing structures is usually easy and does generally not require any accurate structural consideration or calculations. Load-bearing structures, on the other hand, are much more challenging and often require a broader consideration and calculations, as the effects of openings are usually not just local, but may span broader in the structures. In many cases, making small openings in load-bearing structures is possible and quite easy, but as the size and number of the openings increases, their effects on structures grow broader, which requires a more precise review of the effects.

The first chapters of the thesis discuss the necessary initial data the designer needs to obtain before a successful assessment can take place. The importance of initial data, such as plans, drawings and calculations as well as original values for design loads and design standards is covered in chapter 2. Chapter 3 discusses the current condition and previous modifications of structures and chapter 4 further explains the importance of structural surveys in the absence of original plans. Chapter 5 gives a brief summary of the first chapters and discusses the verification of the load bearing capacity of structures after the necessary initial data is obtained.

After this the thesis clarifies how the practices differ between the assessment of openings in various concrete structures and discusses the different aspects a designer must take into account when designing openings. Chapter 6 compiles various guidelines and instructions regarding the subject by structural components. In renovation projects the typical load-bearing concrete structures that need to be penetrated are beams, walls and slabs. In addition, the basic design guidelines for openings in beam and slab structure, hollow core slab, Nilcon U-slab and double tee slab are included as they are also encountered in renovation projects from time to time. After this, in chapter 7 the thesis presents the most common situations and general ways of reinforcing structures with openings. In the last part of the thesis in chapter 8, the assessment process is demonstrated further with the help of an assessment case example.

2 Initial data

As in all kinds of renovation projects, also before the assessment and design of new openings in structures, the designer must have the necessary initial data about the structures at hand beforehand. The following chapters describe the necessary initial data.

2.1 Original drawings

The planning and implementation of a renovation requires a thorough knowledge of the structures. The repairs should always be done within the limits and terms of the structures. New plans should also consider the current condition of the structures, as well as the design methods and regulations of the time the building was built [1]. This is especially valid for designing new openings as without the necessary knowledge of the structures and their current condition, it is not possible to safely plan the modifications.

The original construction plans and drawings of a building are usually archived. The location depends on the date when the building was built. The information included in the plans are for example the structure types, measurements, steel reinforcements, existing openings in structures and original structural design calculations. [1.]

Frequently in renovation projects, obtaining initial information can be challenging as the availability and quality of the original plans varies from building to building. Of some buildings, it is possible to find a wide variety of original and accurate construction drawings, while of others there are only the minimum amount of master drawings to be found, which the local construction supervision has required. [1,36-37.]

The original plans can be searched from the building control and other archives of cities, the archives of engineering offices and the archives of the property owner or the property management company [3]. In most cases, the most extensive collection of plans can be found in the archives of the maintenance company. Therefore, the designer should reach out to these bodies already at the initial steps of the project. In addition to the original plans it could be useful for the designer to use literature in general, for example, to check commonly used building structures and other information of the era of the building.

The assessment of new openings is done on the basis of the original structural plans. The more comprehensive the set of original plans available, the more accurately and safely the designer can establish the structural model and check the used design criteria. As the Finnish Construction Engineer Association's guide on renovation, RIL 174-4 states, the original drawings often give good directions for the design, but one must be careful not to blindly trust them. Therefore, the accuracy of the original drawings should be confirmed in all projects if possible. Usually, the older the building is, the less one can count on the building being built according to the plans. In many cases the structures have been modified during the construction period or afterwards, without updating the drawings to their current state. [1.]

The first challenge of a review process is often incomplete initial information. It can be challenging for a designer to be able to ensure the functionality and safety of the structure, if the initial information is incomplete or not available. The worst examples include situations where the structures have been modified or new openings have been made during the lifetime of a building without any documentation of the changes. [1,37.]

For this reason, it is of utmost importance to always verify the accuracy of existing plans to find out the potential risks in good time before doing any detailed analysis or design of openings. If the original plans are not available or are incomplete, the current state of the structures can be examined best by a site visit and, if necessary, further testing such as opening the structures. The condition of the structures and building surveys are discussed in more detail below in chapters 3 and 4.

2.2 Calculations

The best knowledge of the carrying capacity of the structures can normally be found in the original structural design calculations. It is usually possible to identify which calculation standards and regulations have been used. As RIL 174-4 states, too often these calculations are not available, and if they are found, they are often quite limited. For example, many of the building plans of the early 1900's do not include any calculations, such as specific design loads or calculation criteria. Often only the measurements of the structural components such as columns and beams and their moments and reinforcements are presented in the calculations. [1,37.]

If the calculations are not available, it should be possible to assess the material properties and carrying capabilities of the structures by using common materials properties and calculation standards of the building era. [1.]

2.3 Design load standards

It is also important to establish the loads the structures were originally designed for. Making modifications and new openings always affects the properties of load-bearing structures, so before more precise assessment can take place, the designer must find out the original design criteria of the structures. [1,56.]

If the drawings do not show the used design loads, and the original calculations are not available, it can be assumed that the structures have been dimensioned with the loads defined in the calculation standards of the building era. According to RIL 174-4, there have not been any serious structural damages caused by the used calculation standards in Finland. Therefore, it is safe to assume that the renovations can be planned applying the calculation standards of the building era. Of course, the design process must take the current condition and possible underlying flaws in the structures into account. [1.]

The loads defined in the calculation standards of the building era can only be used in cases where the loading conditions of the structures do not change. The Finnish Ministry of the Environment has published a decree (477/2014) in 17th of June 2014 on the design of load-bearing structures. Subsection 10 of the decree defines the process as follows:

> In the planning and execution of building repair and alteration work and of changes in the intended use, the properties and conditions of a building and its structures shall be taken into account and, for special reasons, clarification of these shall be provided, and the possibility of an increase in loading on the structures shall be determined. For partial alteration of structures, it shall be ensured that the alterations to the structural system do not affect the fulfilment of requirements, in accordance with section 4 of this Decree. When the repair and alteration work in buildings or changes in the intended use do not cause an increase in the loading on structures, but the condition of the structures is such that the strengthening of them is required, the regulations valid at the time of the construction of the building and the best building practices in effect at that time may be applied. When the repair and alteration work in buildings or changes in the intended use do cause an increase in the loading on structures, sections 2 to 5 of this Decree shall apply in the design and execution of load-bearing structures with regard to new structures and structures to be strengthened. [4.]

According to the decree the possible increase in the loading on the structures must be evaluated. Even if the loads on structures are increased, the technical requirements of the subsection 3 of the decree must still be met. The essential technical requirements for load-bearing structures and bracing are met if these are designed and executed in accordance with the Eurocodes and the relevant national standards issued as Ministry of the Environment decrees. In addition, the structural designer must take the construction site conditions into consideration. According to the decree, the regulations valid at the time of the construction can only be used for the evaluation of existing structures if the loading conditions remain unchanged. If the loadings change, the design must be done according to the Eurocodes and the national standards. [4.] The experienced structural engineers interviewed for this thesis confirmed this and told that they follow these guidelines in their own planning work.

The allowed loads have decreased and increased throughout the years. In his master's thesis from 2016, J. Martin summarizes the changes and compares them to the current Eurocodes. [5.] The comparisons are shown in figures 1 and 2 below.

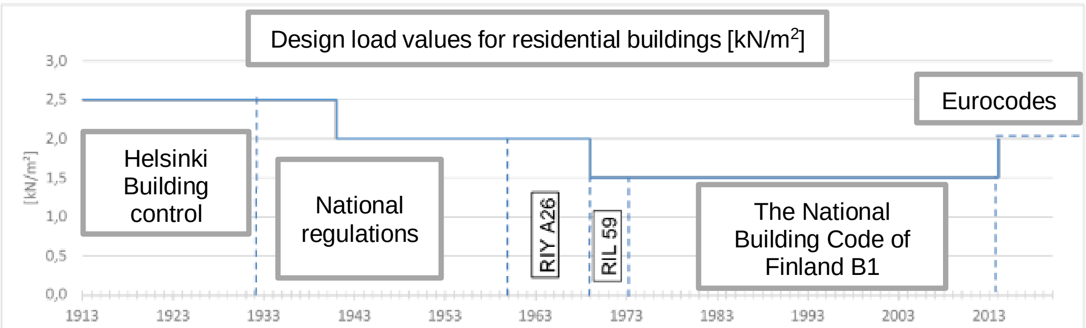

Figure 1. Used design loads for residential buildings 1913-2015. Modified from Martin [5].

There were no uniform design load standards in Finland in the beginning of the 20th century. The first national design load standards were issued in 1932 and they have been increased and decreased over the years. The Finnish Ministry of the Environment issued the National Building Code of Finland B1 in 1973 decreasing the design loads. The National building Code was updated in 1978, 1983 and 1998. In 2013 the Eurocodes came into effect, increasing the values again. [3.]

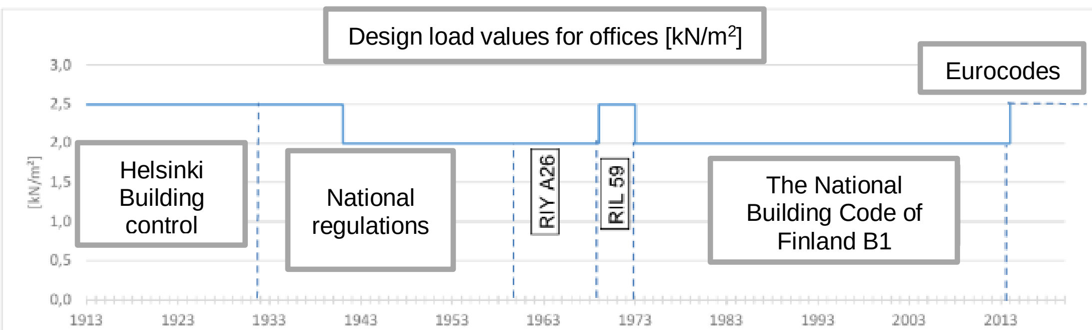

Figure 2. Used design loads for office buildings 1913-2015. Modified from Martin [5].

The graphs show the changes in values of the used design loads for residential and office buildings throughout the years. If the original drawings and calculations do not show the used design loads of the structures, it should be safe for the designer to assume that the structures have been designed for the used design loads of the construction era. It must be noted that the different design loads cannot be compared directly as they are as also the calculation standards have changed along the years.

If the design loads cannot be confirmed, the designer must move to the next level, which is to determine the true nature of the structure, the quality, and loads the actual operational structure is carrying. [1.] The effects of the condition of the structures are discussed in the next section.

3 Condition of the structures

3.1 Damages and their effects

The cause of damages to concrete structures can often be revealed by a simple visual inspection. Common damages are for example, water and frost damage, which usually occur in outdoor concrete structures. Manufacturing and design errors and defects that suggest an overloading of the structures must always be examined further. Usually the most challenging structures to examine are foundations and other hidden concrete structures. [1.]

In reinforced concrete structures, the shape, size and location of the cracks reveal a lot about the cause of the damage. In bent concrete structures, such as concrete beams, it is common to find small and steady cracking, which, however, only affects the appearance of the structure. If individual larger cracks occur, it is usually a clear sign of capacity overloading of the structure. These types of cracks can be caused by the inner forces of the structure or too high loading conditions, and always require a closer examination of the structures. [1.]

Manufacturing and construction defects are the most common causes for structural damages and lower the load-bearing capacity of reinforced concrete structures. The bearing capacity is affected most by mistakes in the compaction of concrete and incorrect location of reinforcements inside the finished structure. A common problem is the settlement of the steel reinforcements at the top section during the pouring of the concrete, which in turn affects the properties of the finished structure. The most common design flaws are inadequate anchorage of the reinforcement bars, neglection of the inner forces of the structure in calculations, and improper reinforcement design of corners and joints of the structure. [1,102.]

3.2 The effect of repairs on structures

The older the building is, the more likely it is that the building is not constructed in full accordance with the original plans. The worksites have often implemented the plans rather freely and many of the details have been designed during the construction period and implemented with the building techniques of the era. The result is often adequate and even good, and follow good building practices as the decisions have been based on long experience and vast knowledge of building construction techniques. [1,57.]

However, this is the single largest risk for renovation planning and construction as some of the decisions might have been flawed and thus affect significantly, for example the bearing capacities of structural components. In renovations and alterations such solutions may cause serious hazards if they are not detected in time. It should be noted, however, that these factors are quite difficult to find in existing structures. In many cases, the structures are covered with surface structures and thus potentially hiding the damages. [1,38-39.]

4 Structural surveys

In the absence of original plans, the necessary information can be gathered by structural surveys. The condition and bearing capacity of existing concrete structures can be determined with the necessary initial information:

- the dimensions of the structures (cross-section area, span, beam division, loading and support structures)
- the material properties of concrete and steel reinforcements
- he location, the quantity and the quality of the reinforcements. [1.]

When dealing with existing concrete structures it must be noted that the location of the steel reinforcements might differ quite significantly from the original drawings. It is also possible that unplanned reinforcements have been used, or designed reinforcements have been left out entirely. Additionally, it must be considered that also the quality of the materials used, such as steel, and the construction workmanship varies from building to building. For this reason, the structures are always treated individually. [1,40.]

If the strength properties of the concrete are not mentioned in the original plans, they can be determined by taking test pieces. The test pieces must be taken from such a place that does not affect the normal function of the structure. [1,40] From the test pieces it is possible to determine the compressive strength properties of the concrete by a standardized test where the test piece is loaded until it breaks. The compressive strength determined by this test is 0.85x the test strength. [6,35.]

In bent structures, such as beams, the compressive strength of concrete affects the compressive and shear strength of the cross section of the beam. The compressive strength of concrete has a less significant effect on the bending capacity of the structure, as it is normally assumed that the steel reinforcements transfer almost all the tension forces created by the bending moment. [6,54]

If the strength properties of the concrete cannot be determined from the original plans and more in depth structural surveys are not feasible to execute at the time, it should be quite safe to use the lowest strength class of the era in preliminary calculations. The preliminary calculations are not the most accurate ones, but could be used at the initial stages of the assessment to give an idea of the properties of the structure at hand. [1.]

A concrete cover meter can be used to determine the location of steel reinforcements inside a concrete structure. All cover meters operate electromagnetically. Electric currents in a coil in the search head generate a magnetic field that propagates through the concrete and interacts with any buried metal, such as reinforcing steel. The interaction causes a secondary magnetic field to propagate back to the head where it is detected. The received signal increases with increasing bar size and decreases with increasing bar distance, or in other words the concrete cover thickness. A more modern Hilti Ferroscan scanner can even pinpoint the rough quantity and quality of the reinforcements inside a structure. [7,28]

A concrete cover meter is a fairly easy method to investigate the existing reinforcements without damaging the structure, which is its definite advantage [7,28]. Even in cases where the original plans specify the details of reinforcements, the use of a cover meter before any actual modifications take place would be advisable to ensure the accuracy of plans. For example, in beams and slabs the cover meter can be used to give an idea of the location of the important tension reinforcements at the bottom of the structures.

If the position of the steel reinforcements cannot be determined with necessary accuracy with non-destructive methods, it is possible to carry out a structural opening. For example, in cases where there are several similar beams, it is possible that the end of a beam is opened with a drill to reveal the reinforcement bars. This usually allows for an easy measurement of the dimensions and positioning of the reinforcements. [1.] The information could then be used to determine the bearing capacity of the beam. At this point it might be also easy to take a sample of the concrete to determine its properties, such as compressive strength, as discussed above. [1,40.]

If the load-bearing capacity of structures cannot be determined with the means mentioned above, the last option might be a test load of the structure. Test loadings can mainly be done for bent structures, such as beams, and they must be done according to a plan created by a structural engineer. [1,40.]

5 Verification of the load-bearing capacity of structures

As seen above, the bearing capacity of a structure can be determined when the necessary initial information of the structure is known. If the loading of the structures does not increase in the renovation, but it is still necessary to assess the capacity, the calculations can be done according to the standards of the construction era as was discussed in chapter 2.3. above.

However, structures may have to be modified to the extent that the distribution of loads change. Also, changes in the use of space makes it necessary to assess the load-bearing capacity if the changes also influence the distribution of loads. As was discussed above in chapter 2.3., in case the loads change or increase, the structure must be assessed using the current Eurocodes. The bearing capacity can be determined from the original drawings and calculations, but in case these plans are not available, the crucial information can be gathered with the help of structural surveys as shown in chapter 4. [1,40.]

A more in depth assessment is possible after the load-bearing capacity of the structure is verified and all the necessary information is obtained. The placement of openings depends on the guidelines of the structural component. The guidelines for various structural components are discussed in the next chapter.

6 Instructions by structural components

The challenge for the assessment and design of openings in existing concrete structures is the lack of specified instructions and regulations. The literature review of the thesis, did not reveal any clear and specified instructions for openings in existing concrete structures. The design of openings in new concrete structures can be done according to guidelines shown in The Finnish Concrete Association's guide BY 210 on Concrete Structures, and the surroundings of openings can be reinforced accordingly. Literature review also revealed that many guide books include instructions on the design of openings in new structures. Making openings in existing structures requires a different approach and an adaptation of the instructions and regulations for new structures. The guidelines for new structures, which can be applied for existing structures as well are presented below. Also, ways and processes gathered for the thesis during interviews with experienced structural engineer of the company are included here.

The need for new and mapping out the existing openings in structures is done prior to the assessment of new openings. In renovation projects the typical load-bearing concrete structures that need to be penetrated are beams, walls and slabs. For this reason, most of the guidelines and instructions presented in the following chapters discuss them. In addition, the basic design guidelines for openings in beam-slab-structures, hollow core slabs and double tee slabs are included, as they are also encountered in renovation projects from time to time.

6.1 Bearing wall

Walls are plate structures, which are supported from the bottom edge of the plate, whose main loading occurs in the direction of the plate causing compression stress. A structure is classified as a wall if its cross-section width b is larger than four time its height, that is $b > 4h$ (figure 3). Vertical structures outside this definition are defined as columns. [8, 89.].

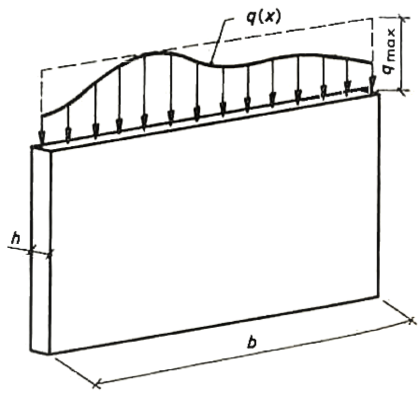

Figure 3. The distribution of loads in a wall. Reprinted from RIL 125 (1986) [9,362].

Another type of a wall is a beam wall which is a type of a concrete beam. The Eurocode 2 defines a beam as a structural component, whose span is at least three times the height of its cross section and beams with a shorter span are regarded as a beam walls. [13.]

New openings in load-bearing concrete walls are common in renovation projects. The use of the spaces is usually altered during renovations, which requires new openings for walls and windows. In outer walls the most common openings are for new windows and in inner walls for doors. New window openings can often be placed favorably in regards to the bearing capacity of the wall, but the openings for doors are often located near the supports of the walls and this always requires a more precise assessment of the effects on the wall. [9,376-377.]

The vertical transition of the loads from the top floor to the foundations must be considered when planning new openings in existing load-bearing walls. All the structures from top to bottom must be included, and the whole wall reviewed as a single unit. The location and size of existing openings must be confirmed prior to the design, and the new openings must be planned on the basis of the current situation. If there is an opening above a new planned one, it might be necessary to strengthen the structures above and below the openings to allow the loads to transfer safely to the structures below.

An opening in a bearing wall may change the distribution of forces considerably and the effects of the opening depend on its location and size. Outside the compression zone, highlighted in figure 4 below, it is possible to place openings quite freely without affecting the load-bearing capabilities of the wall. [9,376-377.]

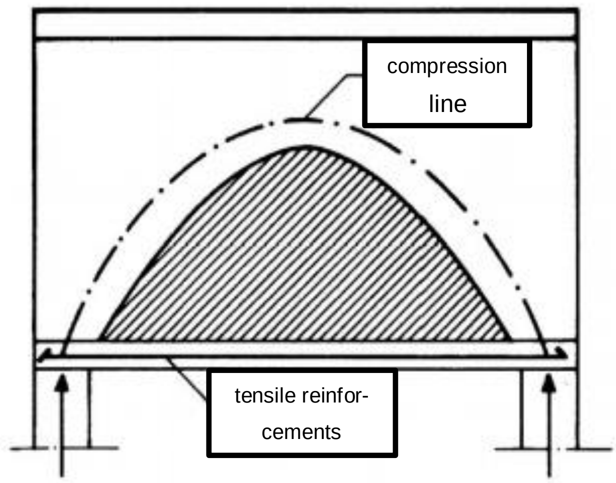

Figure 4. Placement of openings in bearing walls. Modified from RIL 125 (1986) [9,376-377].

The areas of walls that are the most important for the bearing capabilities of the wall are the supports, in which no openings are allowed. In figure 5 below the supports are marked as b_S and the areas with no openings are defined.

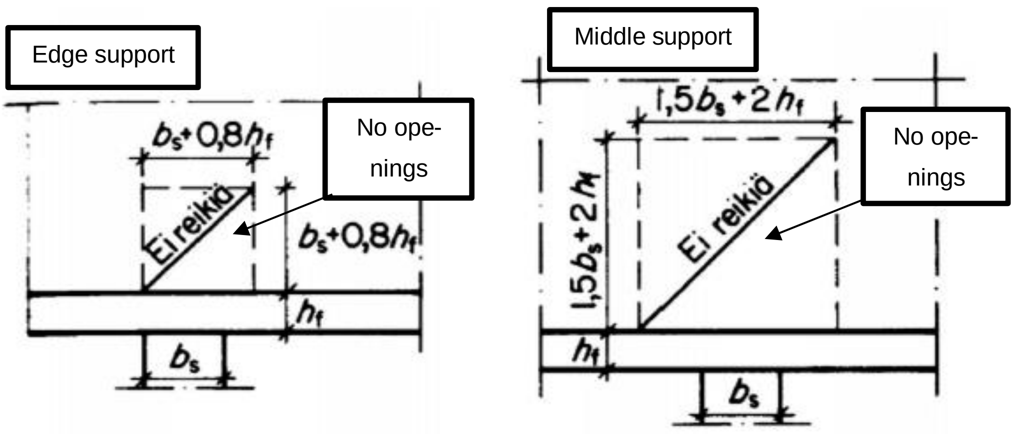

Figure 5. Areas of walls where no openings are allowed. Modified from RIL 125 (1986) [9,376-377].

According to RIL 125 Design of concrete structures, if an opening breaks the compression line its effect on the bearing capacity of a wall has to be determined. A small opening, larger side $< h_{ef} / 6$ ($h_{ef} = effective\ height\ of\ the\ wall\ beam$), can be accepted even inside the compression zone, but only if the compression stresses can be distributed to both sides of the opening. This requires more precise structural calculations and design. [9,366;9,377.]

The force distribution of a wall can be studied for example with the strut-and-tie method (STM) where the order of forces in different parts of the wall can be determined. The STM is a reinforced concrete structure design method in which the structural components are idealized as truss models which are composed of axially loaded members. The concrete functions as the compression bearing member, struts and the steel reinforcements function as tension bearing members, or ties. The members join in nodes, the force balance of which must be secured. [8,430.] An example of a strut-and-tie model can be observed in figure 6 below.

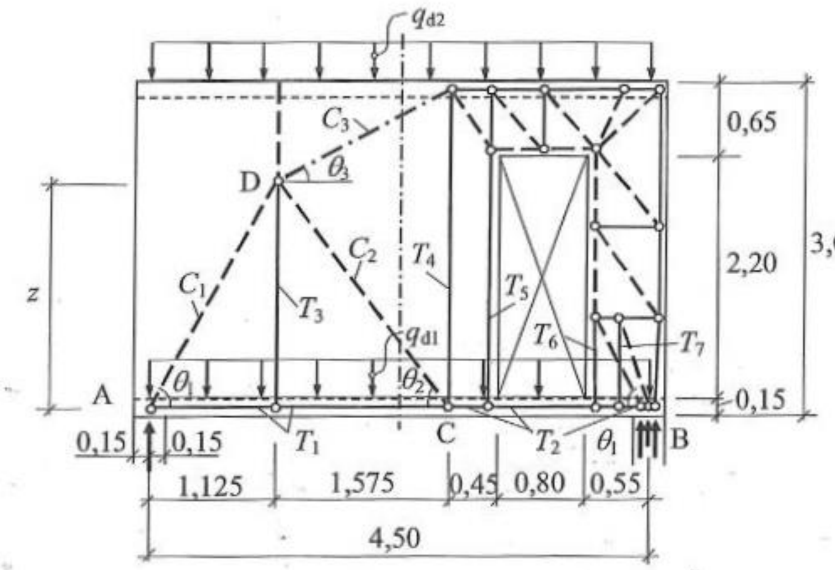

Figure 6. Example of a strut-and-tie model of a wall with an door opening. Reprinted from Handbok till Eurokod 2 (2010) [10].

Figure 6 is reprinted from Swedish Concrete Associations Guide book to Eurocode 2 from 2010, which has in depth examples on the usage of the STM [10]. The Finnish Concrete Association’s guide BY 210 on Concrete Structures has similar content about the strut-and-tie model with good instructions of its use with examples on pages 430-443 [8].

Many times, making openings in existing load-bearing walls also requires the strengthening of the structure. The most common solutions to strengthen the openings of wall structures are presented in Chapter 7 below.

6.2 Slab

A concrete slab is the most common type of load-bearing concrete structures. Concrete slabs are plate structures, where the thickness is small compared to that of other structures, and whose load is mainly perpendicular to their plane. For this reason, slabs are treated as two-dimensional structural components. Concrete slabs can be divided in categories based on their load-bearing direction and support system. There are one-way slabs, two-way slabs and column slabs. [9,293.] The different slabs are shown in figure 7 below.

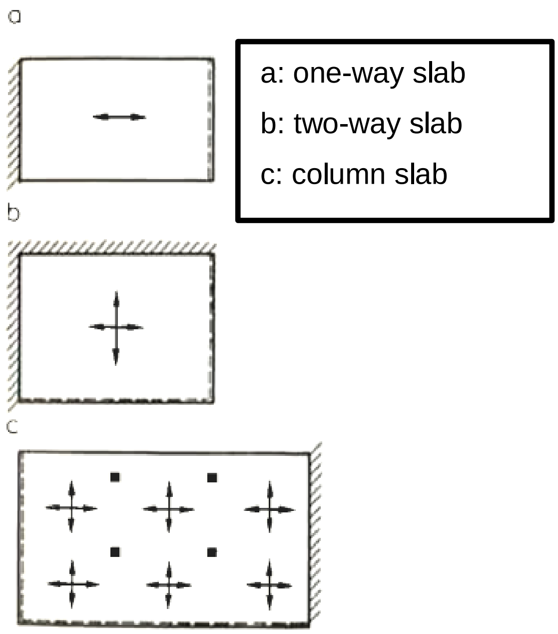

Figure 7. Different concrete slab types. Modified from RIL 125 (1986) [9,293] .

The Finnish Concrete Association's guide BY 210 on Concrete Structures guides that as the bending only occurs in the direction of the longer span of the slab in one way slabs, the force distribution can be determined in the same way as with similarly supported beam structures. [8,389] For a two way slab where the bending moment occurs in both directions, the force distribution of the slab can be approximated with a method of dividing the slab into two diagonal beam sections [11,14].

The most common reasons for new openings in concrete slabs are for example openings for heating, ventilation and air conditioning installations, and new stairwells and lightwells between floors. Especially new HVAC installations might require new, larger openings in renovation projects, as often the existing openings might not be large enough to fit the updated modern or additional installations.

Making openings to the slab parts under high stress should be avoided. According to the yield line theory, these parts in uniformly loaded two way slabs are located along the yield lines. Yield lines and their transformations are illustrated in figure 8. No openings should be placed directly to the areas of the slab where these yield lines develop as this affects the behavior of the slab and the distribution of the yield lines. [11;25.]

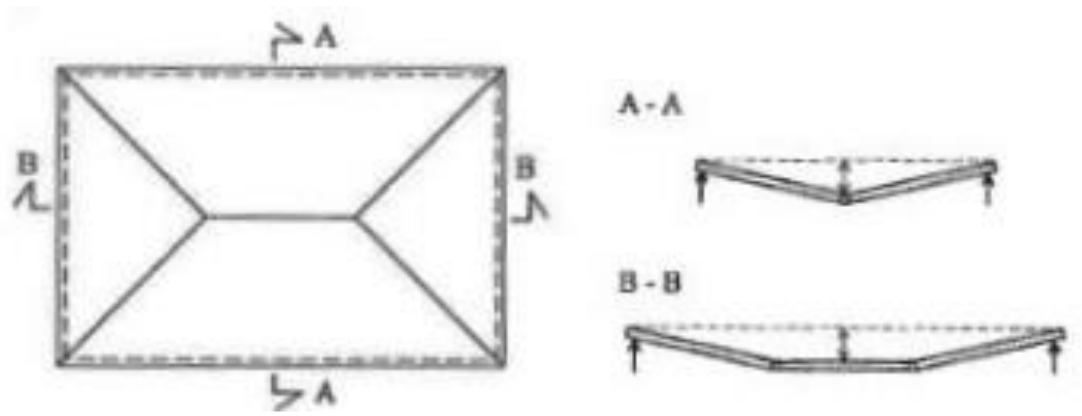

Figure 8. Yield lines and transformations on yield lines in a two-way slab. Modified from Nykyri (2016) [11,32]

An opening is classified as small if the larger side of a rectangular opening or the diameter of a circular opening is at most one fifth of the shorter span of the slab. Determining the effects of small openings with calculations is not needed, it is enough to place a half of the amount of steel reinforcements that is cut by the opening in the slab to both sides of the opening. [11,86;25,139] The principle is shown in figure 9 below.

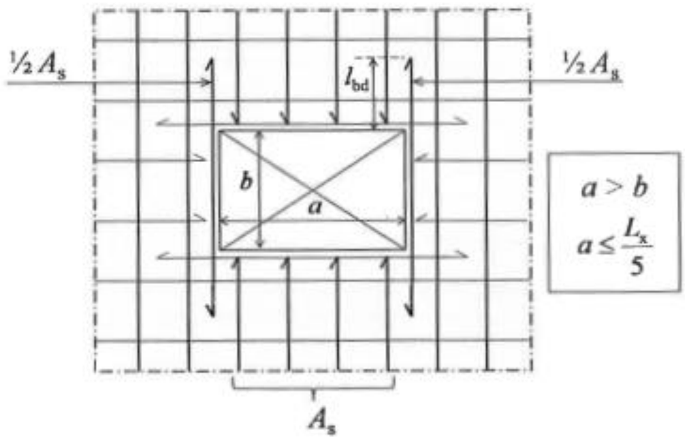

Figure 9. Additional reinforcements around a small opening in a slab. Reprinted from Nykyri (2016) [11,86].

The interviewed experienced structural engineers confirm this practice of placing the reinforcements to the sides of an opening and it can be applied to openings in existing concrete slabs as well. However, every situation must be assessed individually and the possible strengthening need must be determined. An example of the practice can be seen in chapter 7.

The effects of large openings, to the other adjacent slab zones must be checked as large openings usually affect the continuity of slab structures, thus affecting the bearing capacity as well. The effects of large openings in concrete slabs can be determined with the help of the strip method presented in the BY 210 guide by The Finnish Concrete Association. [8,394.] An example situation of the use of the strip method in a slab with an opening is presented in figure 10 below.

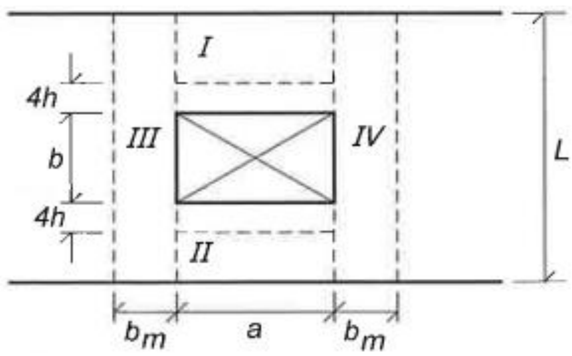

Figure 10. Examination of a large opening in a slab with the strip method. Reprinted from Leskelä (2006) [8,393].

In the BY 210, the slab is divided to strips I, II, III ja IV around the opening. The strips III ja IV function as supports for the loads transferring from the transverse stirps I ja II and they are dimensioned accordingly. The sides of the transverse strips function as support beams for the loads from their respective strips. [8,394.]

According to BY 210, when applying the strip method, the width, b_m of the strip can be chosen as

$$b_m = (0{,}8 - \frac{b}{L})\,L,\; 4h \leq b_m \leq L/4$$

where $b =$ length of the shorter side or the diameter of the opening,

h = height of the slab,

L = shorter span of the slab. [8,394.]

and the design moment for width unit of the strip is

$$m_{x,ed} = \left[0{,}125 + 0{,}19\ \frac{a}{L}\ (\frac{2b}{L})^2\right] p_d L^2$$

where b = length of the shorter side or the diameter of the opening,

a = width of the opening,

p_d = design load. [8,394.]

Additionally, BY 210 guides that the transverse strips I ja II sides are dimensioned as support beams with width $4h$. The instruction adds that the Eurocode 2 regulates that the free sides of the slabs must be equipped with corner reinforcements, which must be surrounded by stirrups as is shown in figure 11 below. The reinforcements of the side strips work as corner reinforcements in this case. [8,394.]

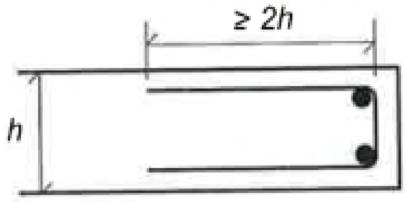

Figure 11. Reinforcements of the free edge of a slab. Reprinted from Leskelä (2006) [8,394].

In existing concrete slabs, the effects of the opening and the magnitude of forces in the slab can be determined with the help of the strip method. After these are known, it is possible to examine the capacity of the remaining reinforcements in the slab in the modified situation and to determine the need of additional strengthening of the slab. [8.]

The designer has a great advantage of knowing the strip method. It is an efficient and relatively quick way to examine simple slab structures. When the force distribution of the structure is known, all the linear equations derived in the basic theory of statics are solved. However, more complex structures must be analyzed by a numeric approximation system. The most efficient one has proven to be the Finite Element Method, which is usually shortened as FEM. The FEM is a method for numerical solutions of field problems. In the FEM, the structures with complex geometry are divided in to a finite number of elements, which in turn are simple in their geometry. The elements are reconnected at nodes and the results are calculated in each node using mathematical interpolation. The results are presented as a set of simultaneous algebraic equations. [12.]

The computerized calculation analysis tools based on the FEM are called Finite Element Analysis programs. The experienced structural engineers interviewed for this thesis advised that currently it is better to examine more complicated slabs with the help of FEA structural analysis software such as Autodesk's Robot Structural Analysis software. FEM programs are computational tools for engineering analysis, which make the analysis of the structures faster and easier, simultaneously lowering the risk of calculation errors as opposed to manual calculation methods. [12.]

The FEA software allows modelling the designed structure, and the planned opening can be placed in the structure. The effects of the opening on the structure can be determined with different load combinations and situations. The software makes the calculations and presents the results in easy-to-understand graphical and numerical forms. For example, in slab structures the magnitudes of different forces in different parts of the structures can be observed from the graphical interpretation of the results. This could allow a more precise design of the reinforcements around an opening, as the moment distribution in the slab is known. [25;26] An example of a graphical interpretation of the results can be seen in figure 12 below.

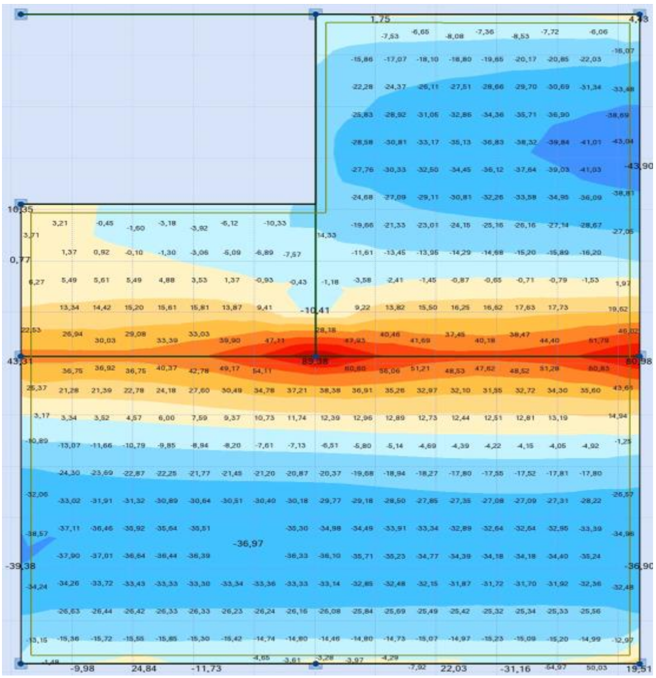

Figure 12. Example of a FEA analysis results of a concrete slab with an opening in a graphical form.

The bending moment in a slab structure is often not distributed equally around both sides of an opening and one side might gather more, thus needing additional reinforcement to be able to carry the loads [11]. The various locations for the opening can be determined as the computer model of the structure allows the designer to examine the effects of the opening on the structure by moving it in the model. This can be a useful way to examine alternative solutions to the problem at hand.

6.3 Beam

Openings are common in beam structures, and especially in renovation projects new openings in beams are required as the space around the existing structures is often quite limited. For instance, when renovating the ventilation ducts, the new upgraded main ducts are usually placed in the lowered ceiling of the corridors, but the branching side ducts often require openings through load-bearing structures such as concrete beams. Eurocode 2 defines a beam as a structural component, whose span is at least three times the height of its cross section. Beams with a shorter span are regarded as a beam walls. [13.]

The effect of openings on the bearing capacity and deformations of a beam depend on the size and the location of the openings. If the location is chosen wisely, it is possible to place quite large openings on beam structures without affecting the bearing capacity. However, even small openings placed in an unfavorable location can drastically lower the strength of the beam structure. [9.] For this reason, the size and location of the openings must be planned precisely. In existing concrete beams, particularly important factor to consider is that the new opening should cut as little of the reinforcement steel as possible, as these are crucial for the beam’s bearing capacity. [6,54.]

Openings can be made in beams provided that the openings are located sufficiently far from the upper surface of the beam so that the compression zone remains sufficiently high. This way the opening does not affect the bending capacity of the beam. [8.] The compression zone and the placement of openings in regards to it is shown in figure 13 below.

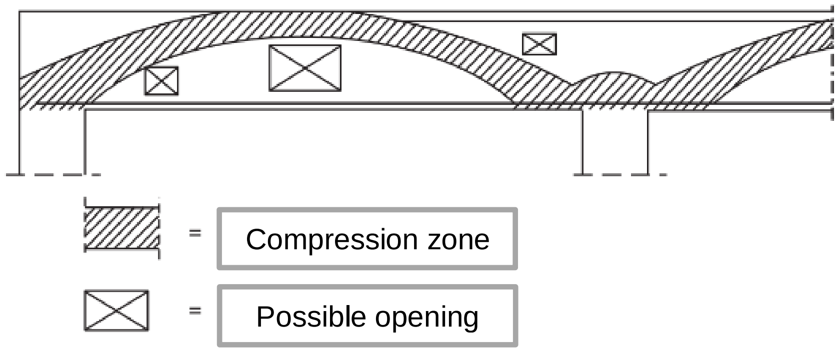

Figure 13. Placement of openings in beams. Modified from Leskelä (2006) [8,384].

The height of the compression zone in beams under bending stress can be calculated with the following formulas:

Relative moment:

$$\mu = \frac{M_{Ed}}{b \cdot (d)^2 \cdot f_{cd}}$$

where	$M_{Ed} =$	design bending moment,
	$b =$	the width of the cross-section,
	$d =$	effective height of the cross-section,
	$f_{cd} =$	design value of compressive strength of concrete. [8.]

After the relative moment is known, the height can be determined with the following simple formula:

$$\beta = 1 - \sqrt{1 - 2 \cdot \mu}$$

Respectively, the distance of an opening from the bottom surface must be sufficient, to accommodate for the tension reinforcement, and to have an adequate concrete cover on both sides of the steel bars. Additionally, the cross-sectional area of the bottom part, the tension zone, must fulfill the requirements represented in figure 14 below, $A_c \geq 2b_{min}^2$, which assures that the temperature of the steel stays under the design limit in case of a fire. [8;14,165.]

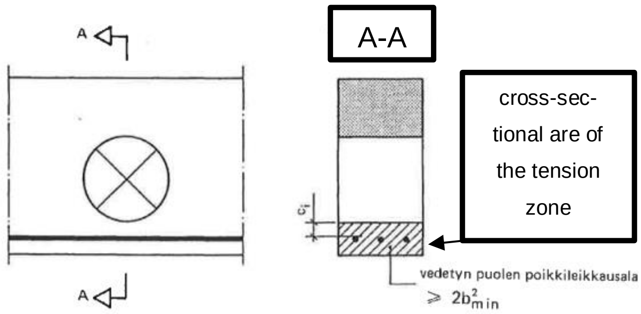

Figure 14. Requirements for cross sectional area of the tension zone. Modified from BY 50 (2012) [14,165].

Additional aspects to note when designing openings in beams:

- tensile reinforcements must be left intact as they are crucial for the bending capacity of a beam.
- the placement of openings in high shear force areas such as close to the supports must be avoided if possible.
- the beam must not contain any openings near the supports at the distance equal to the effective height d of the beam (see figure 15)
- it is recommended to place the openings in the middle third of the beam span where the shear force is the smallest.
- the advised distance of the opening from the top surface is at least $0{,}3\times h$. It is advisable to calculate the height of the compression zone more precisely.
- the ends of slotted beams should not have openings for a distance of one meter from the ends. [8,384;23]

Round shaped openings are preferred as stress tends to accumulate to the edges of straight angled openings causing cracking in the concrete. Rectangular openings in length direction are used only in exceptional cases and even in these cases, the edges of the opening should be rounded to avoid unnecessary cracking. [15,291.]

When working with existing structures, it is advisable to check if the steel reinforcements are lapped inside the structure. This is quite common in older, longer spanned beam structures as in these kinds of structures the reinforcement extensions might be located in the same area of the beam. These areas of beams must be identified and no openings should be placed near them if possible as this allows the reinforcements to work as intended and does not affect the bending capacity of the beam. [6,54.]

6.3.1 Small openings

BY 210 defines that openings whose length is $l_h \leq 0{,}6h$ and height is $h_h \leq 0{,}3h$ can be excluded from the dimensioning if they are located outside the compression zone of the beam. The instructions add that the edges must be equipped with adequate reinforcements as seen figure 15 below, to avoid local cracking in the concrete. [8,385-386.]

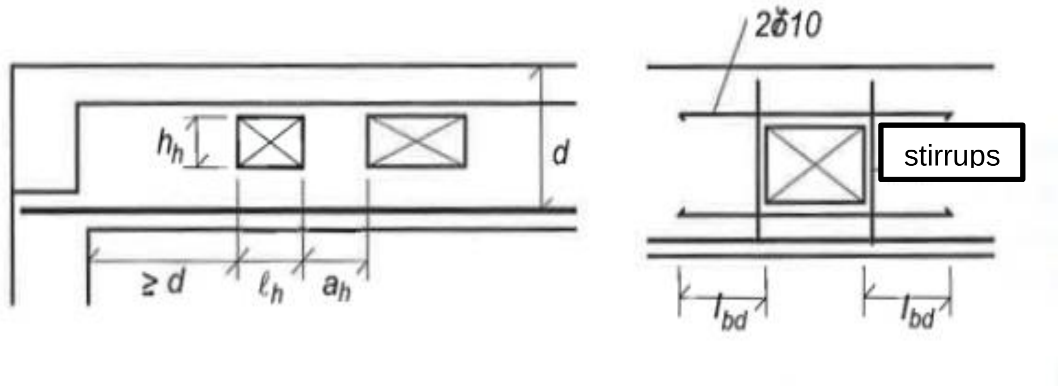

Figure 15. Placement of small openings and additional reinforcements. Modified from Leskelä (2006) [8,384].

In practice this is not possible for small openings in existing beams as placing the reinforcements is challenging. In case strengthening is required, the openings must be strengthened for example with external steel members. [1,146-147]

The instructions in BY 210 add that the character of small openings changes if the length of the web a_h between two openings is smaller than the height h_h of the openings. This kind of situation must be regarded as one big opening, whose length is $2l_h + a_h$. BY 210 adds that the sufficient shear capacity of the sections above and below the opening should be secured in any case. [8,384.]

According to [6,149-150] the shear capacity of a concrete cross-section, $V_{Rd,c}$, can be calculated as follows:

$$V_{Rd,c} = \max(V_{Rd,c\,min}; V_{Rd,c^0})$$

$$V_{Rd,min} = 0{,}035\, b_w\, d\, k^{3/2} \sqrt{\frac{f_{ck}}{MPa}}\, MPa$$

where	$b_w =$	width of web,
	$d =$	effective height of the cross-section,
	$f_{ck} =$	characteristic compressive strength of concrete,
	$k =$	height factor. [6,149-150.]

The height factor, k , can be calculated with the following formula:

$$k = 1 + \sqrt{\frac{200\ mm}{d}}$$

The effective height of the cross-section, d , can be calculated with the following formula:

$$d = h - c_{nom} - 1{,}1\ \emptyset_h - \frac{1{,}1\emptyset}{2}$$

where	$h =$	height of the cross-section
	$c_{nom} =$	concrete cover,
	$\emptyset_h =$	diameter of stirrups,
	$\emptyset_h =$	diameter of tensile bars. [6,149-150.]

The shear capacity, $V_{Rd,c}$, of the concrete cross-section is adequate if the shear strength is larger than the design shear force V_{Ed} at that point. [6,149-150.]

6.3.2 Large openings

In regards of large openings BY 210 advises that if the length of the opening is $l_h > 0{,}6h$, its effects on the durability of the beam must always be assessed more precisely. The effect of the opening on the beam's deflection, and in case of a continuous beam, also the effect on force distribution of the beam must be examined if the opening fulfills the following condition

$$(\frac{Io}{I})(\frac{l_h}{L}) \leq 0{,}1$$

where

I_o = moment of inertia of the beam's cross-section,
I = moment of inertia of the cross section on the compression side above the opening,
L = span length of the beam. [8,385-386.]

Additionally, according to BY 210, the moment of inertia I_0 of the cross-section can be calculated using the same width b_0 of the compression side as in other stiffness assessments of the structure. This can be written as $b_0 \leq \sum b_{ef} + b_w$. At the point of the opening, the width of the compression side is assumed to be smaller as the opening affects the effective width of the cross-section $b_{0,h} \leq 2\, h_{h_c} + b_w$. In case the opening reaches the bottom of the slab above the beam, the width can be $b_{0,h} = 0{,}5 l_h$, but at least $b_{0,h} \geq 2h_s$. [8,385.]

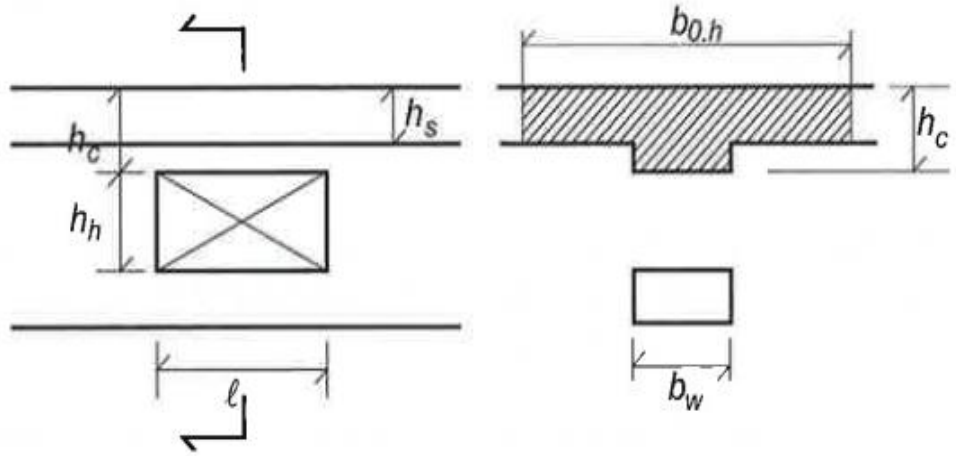

Figure 16. The effective width of the compression side above the opening. Reprinted from Leskelä (2006) [8,384].

The openings that do not fulfill this condition are classified as large, and their effect on deflection and force distribution of the beam must be examined further. The local force examination can be done according to the instructions in BY 210 page 385, which demonstrates a mechanical approximation model, but only if the following conditions are fulfilled:

- no openings are located inside the length d from edge of the support
- the length of the opening is $l_h \leq 2h$.
- the size of the opening fulfills the condition $(\frac{Io}{I} - 1)(\frac{l_h}{L})^3 \leq 0{,}1$.
- the length of the web between openings is $a_h \geq h_h$. If $a_h \leq h_h$, the openings must be regarded as one long opening. [8,385.]

The local force distribution at the spot of the opening can be examined by dividing the beam in two equal parts at the spot of the opening. [8,385.] The principle is shown in figure 17 below.

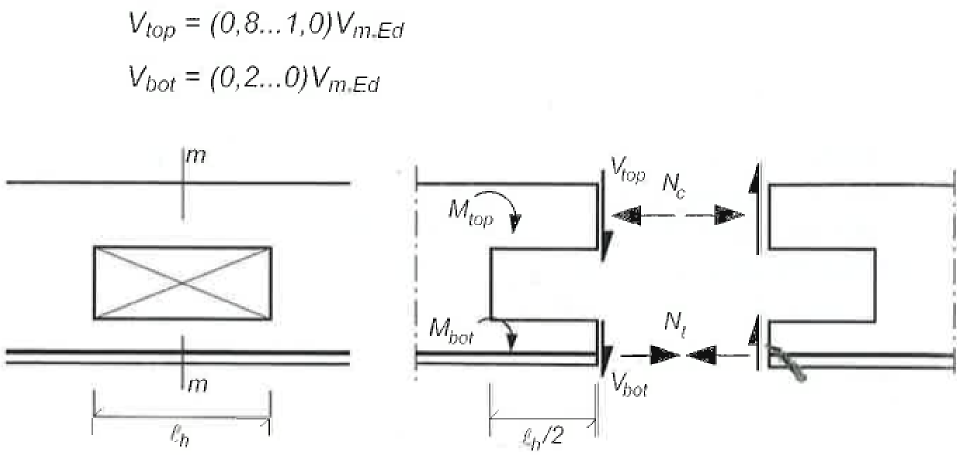

Figure 17. Force distribution at the point of the opening. Reprinted from Leskelä (2006) [8,386].

Additionally, BY 210 guides that the upper and lower sections of the beam around the opening are dimensioned to shear forces V_{top} ja V_{bot}. The instructions add that if possible, the upper part of the beam, the compression side, takes the whole shear force because the stiffness of the tension part is significantly lower due to cracking under bending stress. [15,295] The interviewed experienced structural engineers confirm this practice, and from the information gathered during the interviews, it is advisable to check the following aspects when assessing the effects of openings in concrete beam structures:

- the effective height of the compression zone in the ultimate limit state.
- the minimum concrete cover of the tensile reinforcements. If the reinforcements are untouched the bending capacity remains unchanged.
- the initial placement according to the previous conditions. The center third is the most favorable location.
- the shear strength capacity of the upper section above the opening. A good practice, especially near the supports, is to place the opening in a such way that the whole shear force is transferred through the upper part of the beam.
- the compressive strength of the upper section above the opening. The cross-section is smaller above the opening, which means that the same compression force is transferred through a smaller cross-sectional area than before.

If the opening can be implemented according to these conditions, the structure does not need strengthening in most cases. However, every situation needs to be evaluated individually to confirm the load-bearing capacity. In new concrete beams and structures, it is possible to reinforce the areas around the openings but in existing structures this is practically impossible with the use of traditional steel reinforcement bars without also adding concrete around them. [22,88.]

In cases where the opening has a crucial effect on the bearing capacity of the existing beam and the beam needs to be strengthened, the strengthening can be done by using exterior supports such as steel profiles bolted on the sides of the beam. [1,146-147.] This can be a useful method in cases where multiple openings must be made in the same beam, thus lowering its bearing capacity too much. The strengthening can also be achieved by adding steel reinforcements and concrete on the outside of the beam, thus increasing its cross-sectional area. [22,88.] Different strengthening methods are discussed further in chapter 7.

As mentioned above in the chapter 1, planning the openings in existing structures requires a close cooperation between different designers. In beam structures, it is always advisable to check with the HVAC designer if for example the needed large opening can be divided to several smaller ones. This is often possible and it could allow lighter design solutions and it might also reduce the costly need of strengthening the structures as well. In cases where a larger opening is divided to smaller ones, the distance between the openings must be larger than the height of both openings, $a_h > h_h$, as mentioned above in this chapter. [8,384.]

When several openings are required, or the beam requires strengthening, the force distribution around the opening can be examined with the help of the strut-and-tie model introduced in chapter 6.1. [8]. This allows the determination of different forces around the opening and as the forces are known, the dimensions of the strengthening supports are placed accordingly.

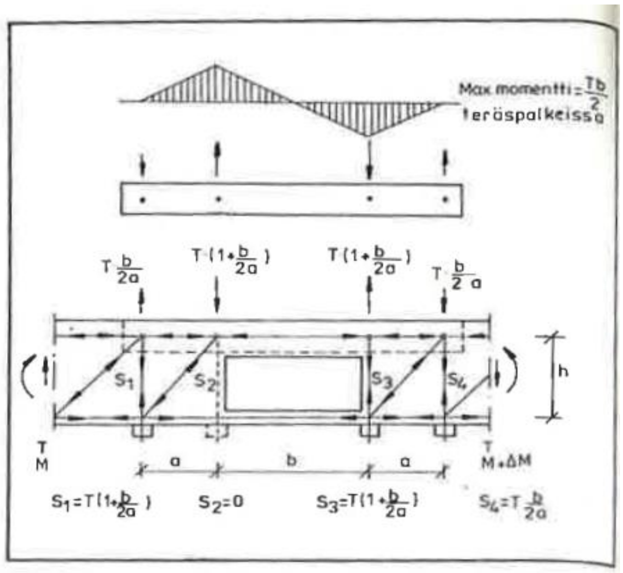

Figure 18. Examination of the force distribution in a beam using the strut-and-tie model. Reprinted from Hero (1988) [1].

6.4 Beam and slab structure

The single most common form of subfloor in Finland in the early 1900s was the beam and slab structure. It consolidated its position by the beginning of the 1920s, and was used until the early 1950s. [3.] The beam and slab structure consists of reinforced concrete beams, with a thin reinforced concrete upper or bottom slab attached to the beams, which makes it a kind of composite structure of concrete beam and slab. The floor structure on top is usually made of timber or reinforced concrete. The empty space between the beams is often filled with organic and inorganic construction waste to function as sound insulation inside the structure. [3.]

It should be noted that the bottom slab is generally quite thin and sparsely reinforced. According to the Helsinki Building Inspection regulation of 1929, the beam division must not exceed 1.2 meters if the thickness of the bottom slab is 40 mm. Before this, slabs even as thin as 30 mm have been used. The typical reinforcement in the slabs has been a minimum of 5 mm thick bars with 200 mm spacing. [3.]

The beams are often equipped with longitudinal reinforcement located only at the bottom and the stirrups were U-shaped open stirrups shaped. Due to the open stirrups, the beam is usually not capable of withstanding more torsion stress than the properties of the concrete allow. Additionally, in older buildings with beam and slab structures, part of the tensile reinforcements on the bottom of the beam might have been bent upwards near the end of the beam. This was done for two reasons. Firstly, the bent reinforcements transfer the tensile stress from the top part of the beam near the supports and secondly, the reinforcements work as a shear reinforcement on the diagonal sections together with the stirrups and the concrete. [3.]

As in typical concrete beams, making openings in the areas near the supports must be avoided. Favorable locations for openings are the center thirds of the beams and the sections of slabs between the load bearing beams. The guidelines and regulations for typical beams can be applied when designing new openings in existing beam and slab structures. Different types of beam slabs are illustrated in figure 19 below. [3;5.]

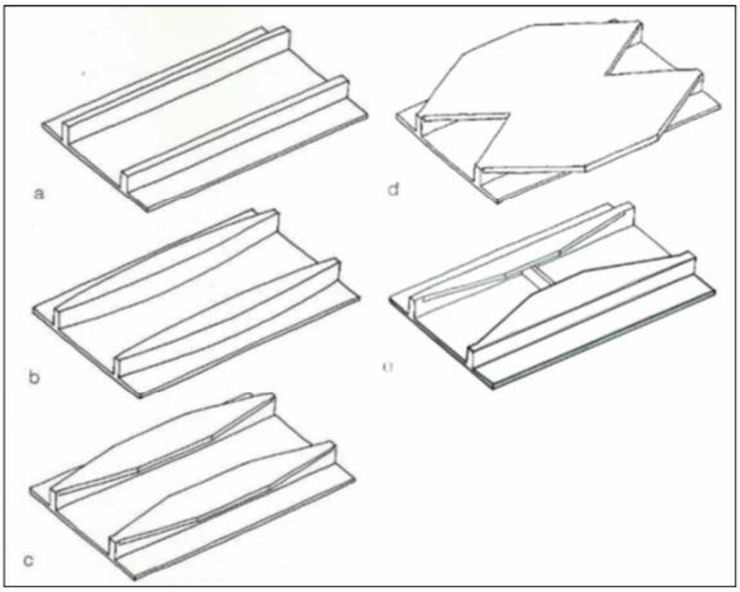

Figure 19. Typical forms of beam and slab structure. [3.]

It should be noted that some beam and slab structures are flanged on the top of the beams for increased load-carrying capacity. No openings should be made in these flange areas. The flanged structure types are examples c, d and e shown in figure 19. [3;5]

6.5 Hollow core slab

Hollow core slab is a reinforced concrete element type which is used for load-bearing building elements as base floors, intermediate floors and roofs. Hollow core slabs are the most common concrete element structures in Finland. They are precast slabs made of prestressed concrete where the steel wire ropes act as tensile reinforcements. The slabs have tubular voids extending the full length of the slabs, which make them substantially lighter compared to typical concrete slabs. Hollow core slabs are single spanned and simply supported structures. [8,685.]

The most common types of hollow core slabs used in Finland are shown in figure 20 below.

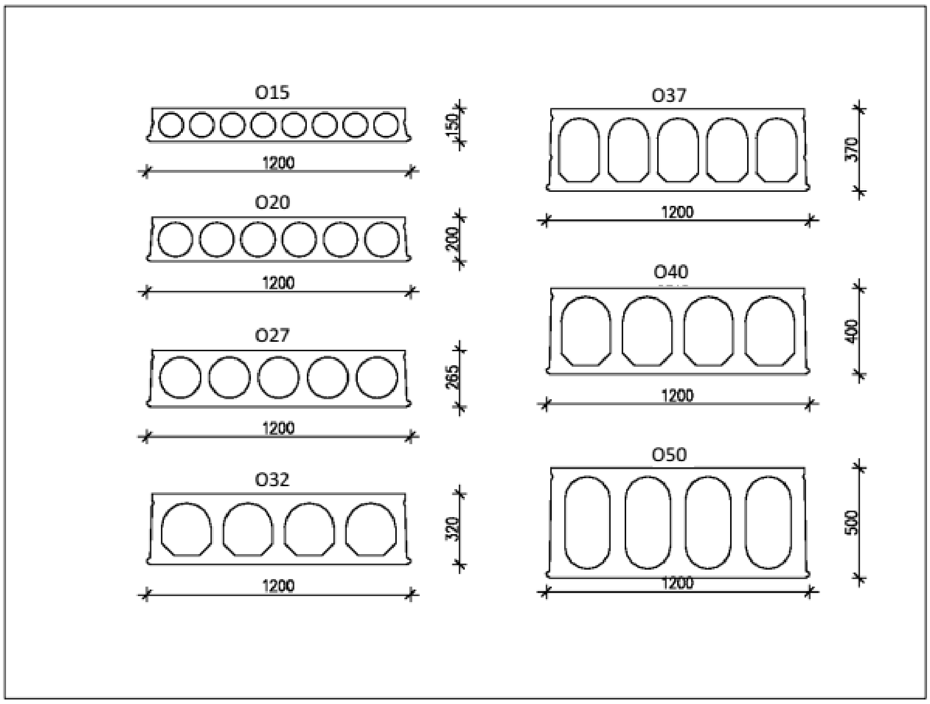

Figure 20. The typical hollow core slab type used in Finland. Reprinted from Parma (2013) [16]

Due to the wide variety of hollow core slabs and their fast installation time their use has diversified and they are used as load-bearing structures in buildings from residential buildings to industrial warehouses and offices. For this reason, hollow core slabs are quite common in renovation projects, and new openings must be examined and planned from time to time. [8,685.]

From 1970 to 1980 two commonly used hollow concrete slabs in Finland were the Variax 5 and Variax 6 slabs, with five and six void hollow tubes, respectively. For example, the Variax 5 slab was manufactured as versions with 4, 6, 8 or 10 steel rope wire reinforcements with different bearing capacities. The number of reinforcements depended on the intended use and loads of the slab. [17,370.] Table 1 below illustrates the correlation between the number of reinforcements and the moment capacity of the slabs.

Table 1. Variax 5 hollow core slab moment capacities. Modified from RIL 115 (1986) [17,370]

Steel rope reinforcements	Allowed moment, kNm/m
4 Ø 12,7 mm	45,1
6 Ø 12,7 mm	67,6
8 Ø 12,7 mm	90,5
10 Ø 12,7 mm	113,0

Guidelines regarding openings in Variax hollow core slabs are similar to the guidelines for the current, modern slab types, which are presented in the next chapter. If the hollow core slab under assessment is a Variax type slab, it is advisable to check the more precise instructions, which can be found in the recommendations by Finnish concrete union and its instructions. [18.] Instructions for openings in hollow core slab are presented in the following paragraphs. The openings in hollow core slabs can be divided into small and larger openings by their size.

6.5.1 Small openings

It is possible to make new small openings in a sealed hollow core slab. The size of the openings is demonstrated in the figure 21 below. There can be a maximum of three small openings in a slab with five hollow voids, and two openings in a slab with 4 voids in the same cross-section of the slab. A cross-section is defined as the distance between the inner edges of two openings. The distance between the inner edges must be under 2500 mm. [19.] The placement of openings and the definition of the cross-section can be seen in figure 21 below.

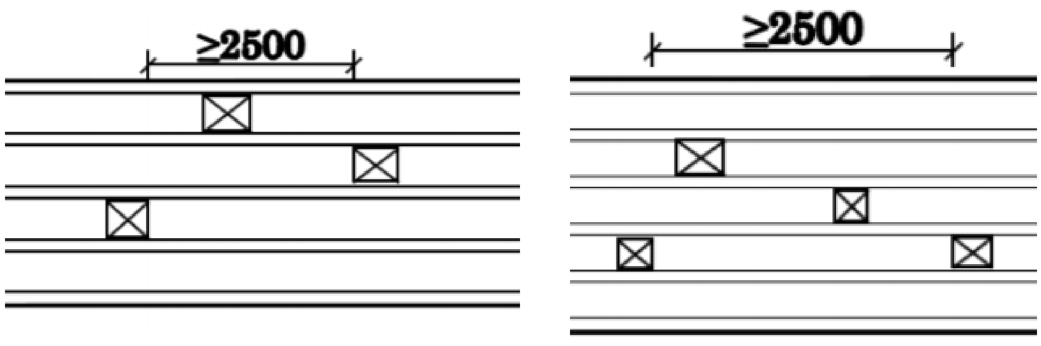

Figure 21. The placement of small openings. Reprinted from Betoniteollisuus r.y. (2012) [19].

Openings that cut the webs (concrete between the voids) of the slabs are classified as large and they always affect the bearing capacity of the slabs. If the opening dimensions are so large that the slab webs need to be cut, the design of such openings must be conducted by a structural engineer with adequate experience on steel wire rope reinforcement design [19]. This thesis does not include an in depth analysis of hollow core concrete slabs and their design, but nevertheless the basic instructions about large openings and aspects that the designer must consider when working with them, are included.

6.5.2 Large openings

The first thing to do when making large holes in already installed hollow core slabs is to examine the original structural drawings. It is especially important to find out which loads the slab system is designed for and which type of steel wire ropes have been used in the slabs. The bearing capacity of the slabs needs to be confirmed before the opening is considered, and it must be remembered that large openings usually require cutting the tensile reinforcements of the slabs, which has a drastic effect on the bearing capacity of the slab [19].

If large openings are required, the location, size and quantity of the reinforcements of the adjacent slabs must be determined. The original structural plans are the best place to find the information, but in case the drawings are not available, the reinforcement can be located with the use of electromagnetic concrete cover meter, as described in chapter 4. The moment capacity or the bearing capacity of the steel wire rope reinforcements can be found in the tables in the original design instructions. [19;20.]

If the opening does not cut the whole slab, it can be assumed that the loads are transferred to the adjacent slabs via jointing concrete, but only when the adjacent slabs have extra moment capacity left. Additionally, it must be noted that the adjacent slabs must also have steel wire ropes in the outermost webs as these are crucial if the slab with the opening is supported by them. For example, the older Variax 5 hollow core slabs were manufactured with different moment capacities and reinforcement quantities, and the slabs with 4 hollow voids could have the only reinforcements located evenly in the center of the slab. For this reason, the slab type, the reinforcements and the moment capacity must be examined before the assessment and planning of the openings. [19.]

Making openings near the supporting beams reduces the shear strength properties of the slab significantly. For this reason, areas where the structures join and where the shear stress is at its largest, such as near the supporting beams or walls, no openings should be made. [19,55.] However, if the opening cannot be placed elsewhere, the bearing capacity of the slabs must be determined, as a cut slab will transfer its load to the adjacent ones, thus increasing the magnitude of the loads in the support regions [17]. For a safe distribution of loads in the structures, the whole changed situation of the slab system must be examined.

If the opening is placed too close to the support and the web is cut, the remaining part of the slab transfers the same loads to the supports, which means that the same forces effect on a smaller surface area, thus increasing the shear stress. [17.]

6.6 Nilcon U-slab element

Nilcon-precast case-slab element is a U-shaped load-bearing precast concrete element structure, which was briefly manufactured and used in Finland at the end of the 1960’s. The slab consists of prestressed outer beams with a thin concrete slab between them. Inside a Nilcon slabs there is a mineral wool insulation, and rising shins were used over the beams, which supported the thin concrete top slab. The structure is illustrated in figure 22 below.

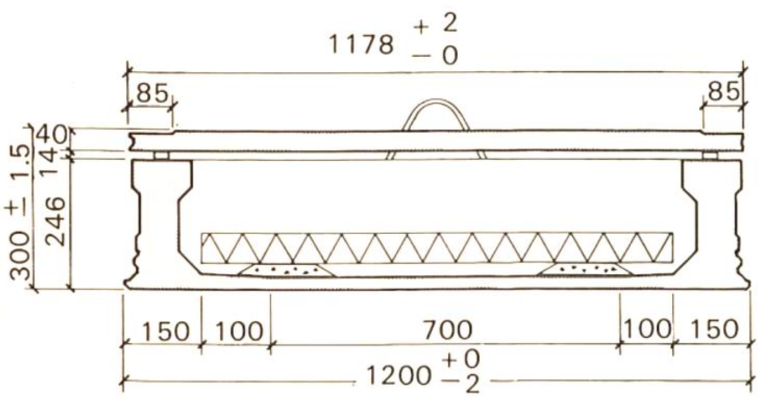

Figure 22. Structure of the Nilcon U-slab element. Reprinted from BES suositus 1979. (1979) [17]

Regardless of the brief manufacturing period of the slab structure, it was quite widely used at the end of the 1960’s, and occasionally one is faced with building systems where it has been used. According to the original design instructions of the U-slab element, openings can be placed quite freely in the top and bottom concrete slabs as long as their size is at most 300x300 mm [18]. Larger openings require more in-depth assessment as with hollow core slabs.

6.7 Double tee slab

Double tee slabs are prestressed concrete elements which allow long spans in the structures. They are mostly used in commercial buildings and warehouses where ample free space inside is needed. Double tee slabs are manufactured with a wide variety of dimensions, which vary from manufacturer to manufacturer. Small openings are allowed in double tee slabs and they can be placed quite freely if they are located on the slab portion of the structure. [21.] An example of the placement guidelines is shown in figure 23 below.

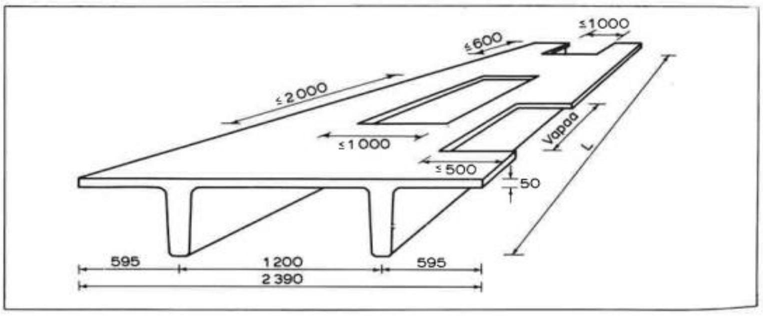

Figure 23. Placement of openings in double tee slabs. Reprinted from RIL 125 (1986) [9,370]

As can be seen in figure 23, no openings should be placed in the edge areas or in the beams of the structure. If the beams need to be pierced, the new opening must be round in shape and located over the tension reinforcements at the bottom part of the beam. [24.] Larger openings require more in depth analysis of the situation.

7 Strengthening of structures

In many cases, making new openings and other modifications in concrete structures makes it necessary to strengthen the structures. The strengthening of structures is defined as increasing the bearing capacity of the structure compared to its original stage. [22,87.]

Normally, when a structure is strengthened, this cannot be achieved by increasing the strength of the existing material. The most common options are, instead, adding a material with better strength properties to the structure, or increasing the cross-sectional area of the structure. Special attention needs to be paid to the distribution of loads and the proper cooperation between the existing and new structure. By strengthening the structures it is possible to achieve, for example decreases in deflections, redistribution of loads and reduced cracking of the structures. [22,87.] The example drawings included in the following chapters are from Wise Group Finland’s existing projects.

7.1 Opening beam

Concrete walls with openings can be strengthened with a reinforced concrete beam or a steel beam. The most common openings in walls are for new doors and windows. The structural engineers interviewed for this thesis advised that the most commonly used solution to strengthen a door opening is to cast a reinforced concrete beam over the opening. A large enough opening is cut to the wall to ensure adequate space for anchoring the steel reinforcements. Steel beams are a viable option in larger openings for their easier installation process. The elastic properties and generally larger deflections of steel beams must be considered when using them in strengthening [1].

Additionally, the effects of the opening on the total stiffness of the wall structure must be determined. Often the sides of the openings must also be strengthened in order to assure that adequate stiffness of the wall with the opening is achieved. The more precise need for strengthening must be assessed individually according to the size of the opening, its location and loads of the wall. [1.] Figure 24 below illustrates the strengthening of a wall opening with steel beam and columns.

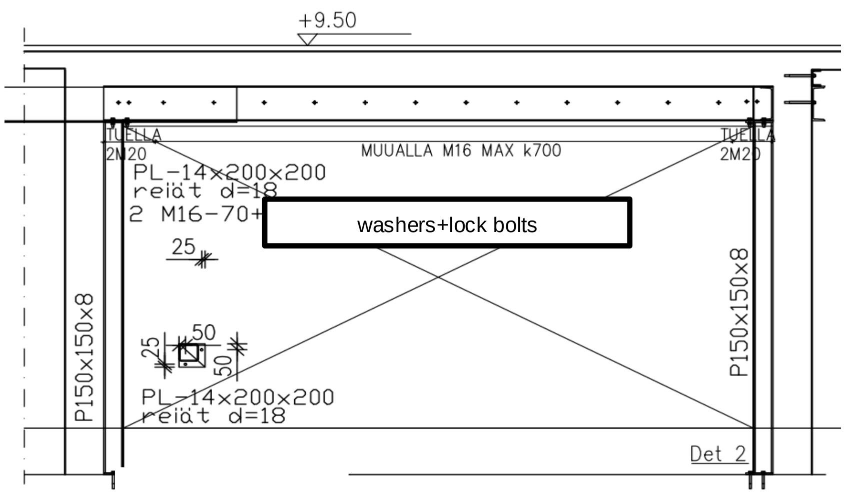

Figure 24. Example of strengthening of an opening with a steel beam and columns.

In the example above, columns are used to stiffen the sides of the wall opening. It is to be noted that if columns are used, the proper distribution of vertical loads to the structures below the opening must be assured. The concrete or steel beam is dimensioned for the loads it is required to carry. Additionally, the beam should be brought far enough over the edge of the opening to ensure the proper distribution of loads to the load-bearing structures below the opening. [1.]

7.2 Additional concrete

Concrete structures can be strengthened by adding more reinforcements and concrete to the tension or compression side of the structure. The added reinforcements and concrete must always be connected to the existing one with mechanical connections. The most commonly used option is to use welded connections or steel bars, which are taken through the existing concrete. [22,88.] Normal steel reinforcement bars and nets are used, but in case the adequate concrete cover cannot be guaranteed, stainless steel bars must be used. Adding concrete is an efficient option to add more capacity to the structure but it requires enough space around for installation. Additionally, it is important to assure proper cooperation between the existing and new concrete, which means that the shrinkage of new concrete must be taken into consideration as well [22,88]. An example of this method can be observed in figure 25 below.

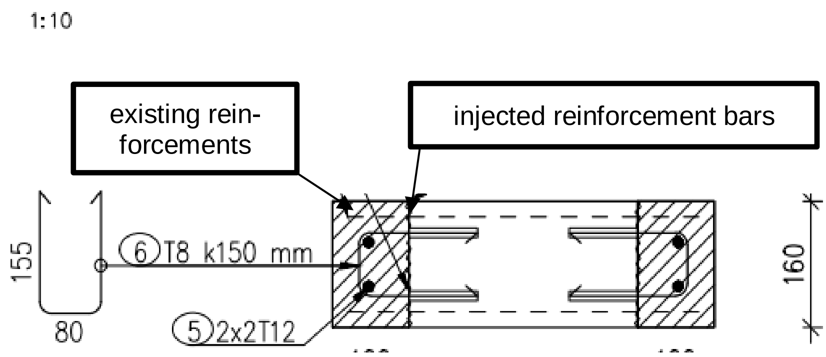

Figure 25. Increasing capacity by added concrete and reinforcements.

Openings in concrete slabs can be strengthened with the method explained in chapter 6.2. In this method, the amount of steel reinforcements cut because of the opening is transferred on both sides of the opening. The general procedure is explained below.

An opening is cut to the slab with a diamond saw or a pneumatic hammer. In existing slabs with openings, the opening must be cut larger than the finished one as this allows adequate space for steel reinforcements. The reinforcements are anchored to the existing slab with the necessary anchorage lengths after which concrete beams surround the opening. [11,86.] Figure 26 below illustrates the added reinforcements around an opening in a slab.

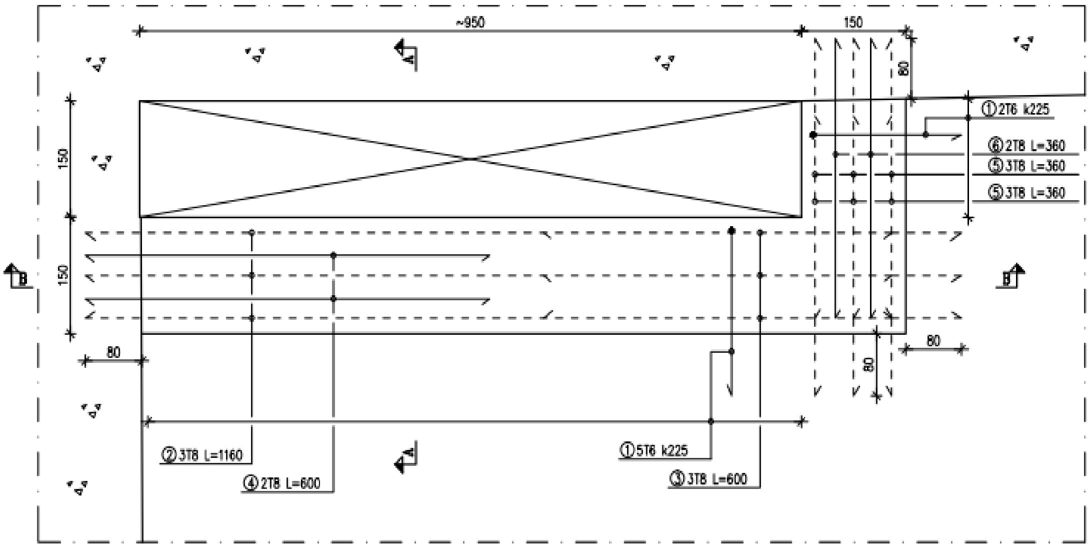

Figure 26. Example of strengthening of the slab with an opening.

The supporting of the slab must be examined individually depending on the need, but generally it is advisable to support the slab from below before cutting the opening [1]. This allows the work to be done safely.

7.3 Strengthening with steel

Using reinforced concrete beams can be challenging at times for their large amount of work needed. Often the same result can be obtained by using steel beams and other profiles. The most common option is to locate a new steel beam, such as a HEB or IPE-profile above the structure to be strengthened. In this way, all loads are transferred with the steel beam and distributed to the load-bearing structures below. In this method, the beam must be installed before the existing structure is demolished or an opening is cut to it. [1,146-147.] Figure 27 below shows an example where the above slab and wall are supported with a steel beam bolted to the wall above the opening in a situation where the wall underneath is demolished.

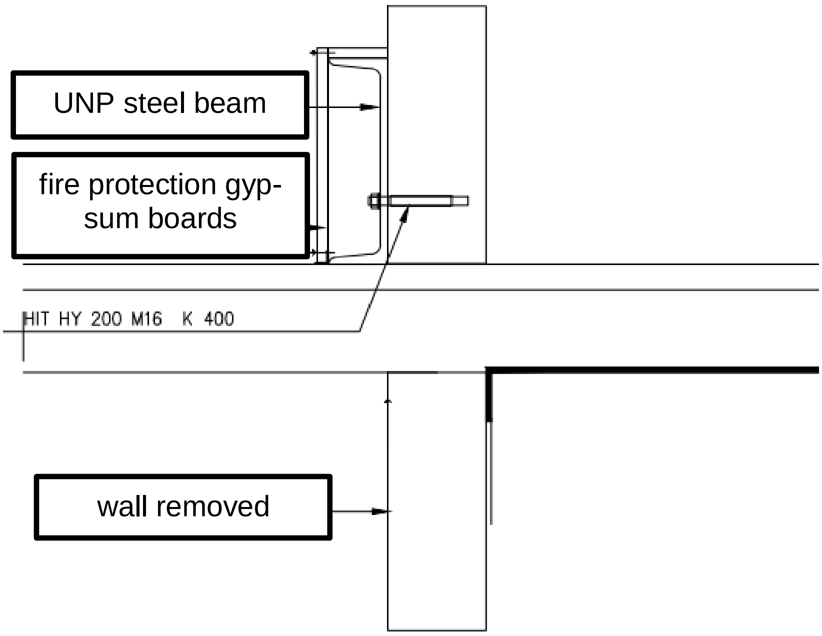

Figure 27. Example of UNP beam strengthening above a structure.

If it is not possible to implement an option like the one in figure 27 due to the limited space above the structure, the steel profile can be bolted to the side of the structure as well. U-shaped UNP profiles are a viable solution in these cases. The UNP-profile is bolted to the side of the structure thus transferring part of the loads to it and increasing the overall load-bearing capacity of the existing structure. When mixing concrete and steel structures, the different stiffness of the materials must be taken into consideration. The more elastic steel beam must be wedged according to the loads before bolting it securely to the concrete. In use the loads can be divided in relation of the stiffness of the different materials. [1,146-147.]

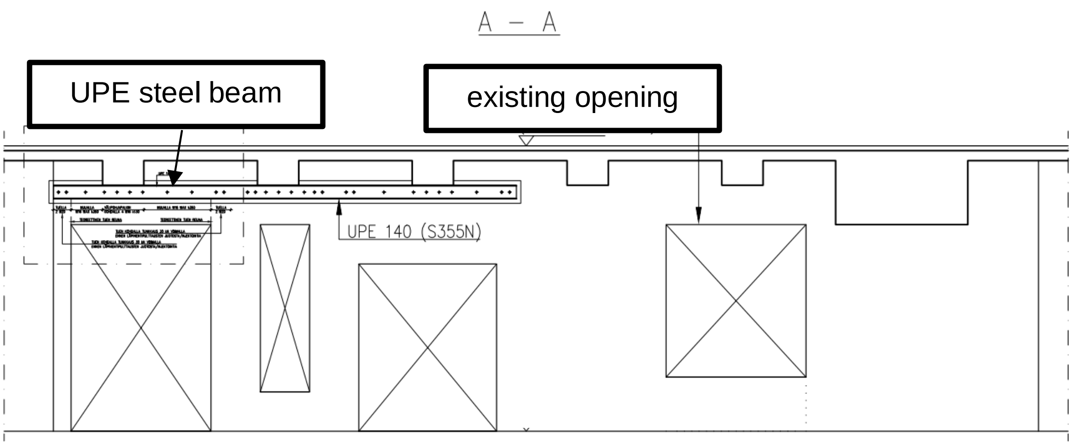

Figure 28. Example of strengthening of an opening in a bearing wall with steel beam.

The easiest option is to install a new concrete or steel beam directly on top of the existing concrete beam, or in case of slabs, directly underneath it if there is adequate space for it. Adequate fire protection must be remembered when using steel structures. The easiest way to achieve fire proofing is by casting concrete over the steel beam, with fire protection gypsum boards or by using fire protective paints. [1,146-147.]

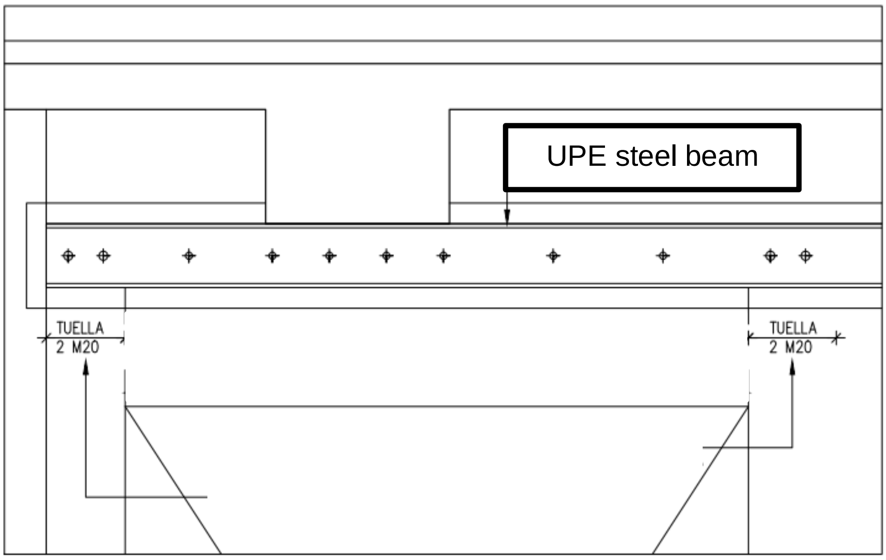

Figure 29. Example of strengthening of an opening in a bearing wall with steel beam.

The most common method to support a concrete slab is to add a support to the middle of it. Reinforced concrete or steel beams, placed underneath the slab, can be used as a support. RIL 174-4 notes that a steel beam is usually not stiff enough in order to be considered as a fixed support, but yet stiff enough to change the bending moment distribution of the slab. At the point of the new center support, the bending moment might change its value from positive to negative, which might cause cracking in the top surface of the slab. These kinds of cracks lower the shear capacity of the slab, but they can be avoided by cutting a groove to the top surface of the slab at the point of the support. [1, 146-147.]

7.4 Adhesive bonding strengthening

Additionally, it is possible to use different adhesive bonding techniques in the strengthening of structures. In this method, a strong material is glued to the exterior surface of the structure to increase the tensile or shear capacity of the structure. The most used materials are steel and more commonly carbon fiber parts. The gluing is achieved by epoxy resin based glues and the glue can be spread to one surface or alternatively to both. [22,88.]

7.5 Strengthening of hollow core slabs

Openings in hollow core slabs can be strengthened with supporting concrete beams or steel supports, which are installed between the slabs. The adequate moment capacity and the fact that the existing steel rope reinforcements are in the outermost webs must be confirmed before the implementation of the supports as mentioned in chapter 6.5. [17].

In hollow core slabs, the opening must be cut slightly larger than the final beam as this allows adequate space for the installation of the reinforcements. The reinforcements are set in place and anchored to the adjacent slabs. Small openings can be cut to the adjacent slabs for the anchoring of reinforcements of supporting beams and the reinforcement installed inside the slabs. After the reinforcements are in place, the concrete of the beam can be cast. For safety reasons the supporting of the slab system from underneath must be carried out before the opening is cut. [19.]

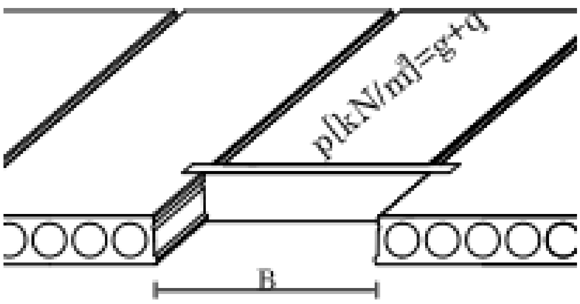

Figure 30. Supporting a cut hollow core slab with a steel beam. Reprinted from Parma (2013) [16,26]

Furthermore, the shear capacity of hollow core slabs under high shear stress areas such as near the supports, can be increased with a technique where the hollow core voids of the slabs are filled with concrete. [19.]

8 The assessment process

The thesis has so far presented the different aspects of the assessment process individually. In the following chapter the process is opened further with a help of an example assessment of an opening in an existing load-bearing concrete structure. The flow chart of the general assessment process created for this work can be found in attachment 1. The assessment process is based on the information gathered during the literature review, the interviews and the actual assessment of an opening carried out during the example case. The specific assessment processes and instructions created alongside the thesis are not published.

The subject of the example assessment is a load bearing concrete slab of a 1960's office building. The building is a former office building which is being transformed into educational use. A large opening is planned to be implemented to the load-bearing concrete slab between the second and third floor of the building, to increase the amount of natural light in the hallway of the second floor. The aim is to perform a preliminary assessment to determine the feasibility of the opening and the need of strengthening, which has a direct effect on the total costs of the project. The calculations presented in the example are based on the initial information gathered from the original structural plans and on the current Eurocode standards.

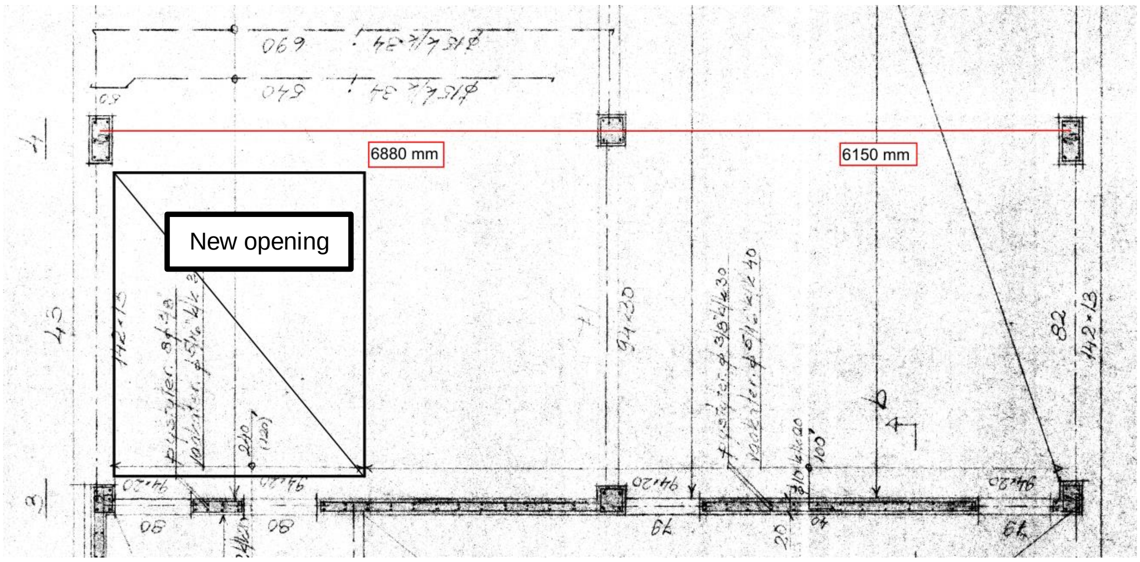

Figure 31. The location of the new opening in the concrete slab.

Figure 31 above illustrates the original structural plan of the slab and the location of the new opening. The structure is a one-way load-bearing concrete slab, which is supported by beams in the middle and on both ends. The opening is classified as large as its width is larger than 1/5 of the shorter span of the slab, which means that the effects of the opening on the slab must be examined further. Additionally, as the opening is classified as a large opening and alters the slab, it means that the assessment and design must be carried out according to the current Eurocodes, as mentioned in chapter 2.3.

As discussed in chapter 2, the first step of any assessment is obtaining the initial information of the building. In this case, the original plans of the building were plentiful and most of the necessary initial information was obtained from the city archives. The information included the structural system, material properties, reinforcements of the slab and beams, as well as the used design load loads and standards. The most important information is listed below:

- Thickness of the slab, $h = 0{,}23\ m$
- Concrete, Type B-concrete K200, which equals C16/20
- Steel reinforcement v40, designing strength $f_{yd} = 348 \frac{N}{mm^2}$ $(when,\ f_{yk} 400 \frac{N}{mm^2})$
- Distributed load for the slab, $Q_1 = 500 \frac{kg}{m^2} = 5 \frac{kN}{m^2}$
- Weight of the slab, dead load, $g = 0{,}23\ m \times 25 \frac{kN}{m^3} = 5{,}75 \frac{kN}{m^2}$

As all the initial information was obtained from the original plans, there was no need to perform any additional structural surveys at this point of the assessment process.

The next step of the assessment was to establish a structural model of the structures. The slab is a one-way slab, which means that its force distributions could be determined in a same way as for a simply supported beam structure. [8,389.] The slab spans across the entire building and is supported from the ends by wall beams and approximately from the center by another beam line, which serves as a center support. The center support divides the slab into two different zones, zone 1 and zone 2. The original structural model is presented in the figure 32 below.

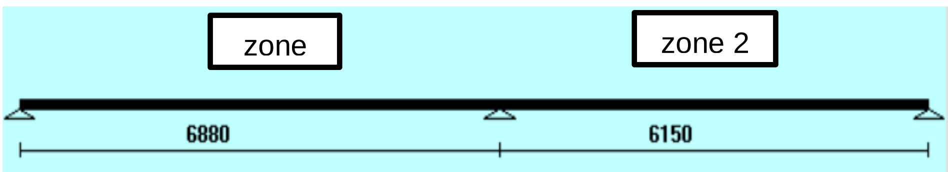

Figure 32. Structural model, original situation.

The new opening cuts the zone 1 of the slab in half, thus turning it to a cantilever with the length of 3300 mm. The original structural model is presented in figure 33 below:

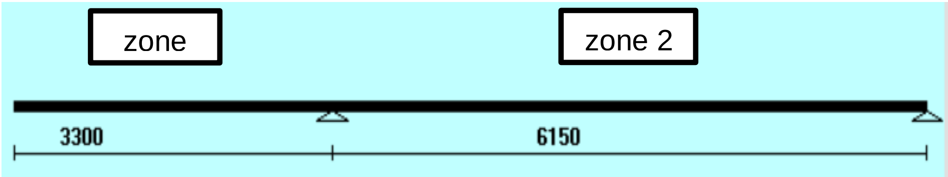

Figure 33. Structural model, modified situation.

The structural models were created with PUPAX5 software, which allows the user to determine the elastic internal force distributions needed in the dimensioning of cross-sections of beam and slab structures. The software produced the following results for the slab in both the situations, presented in table 2 below.

Table 2. The moment distribution of the slab in different situations and slab zones.

Situation	Momentti, kNm	in zones	
	zone 1	support	zone 2
Original	56,57	-75,83	43,23
With opening	0	-76,83	51,13

As can be observed from table 2, when the opening is added to the slab, the bending moment of the slab zone 2 grows quite significantly ($7\ kNm$). Consequently, the next step was to investigate whether the existing reinforcements of the slab zone 2 were adequate in the altered situation and if their moment capacity was exceeded.

According to the original drawings, the slab zone has one 12 mm steel reinforcement bar at the bottom of the cross-section at every 150 millimeters. The moment capacity of the steel reinforcements was determined by an excel sheet calculation based on the Eurocode guidelines. The moment capacity of the reinforcements can be seen in table 3 below.

Table 3. The moment capacity of the steel reinforcements in the slab zone 2.

Situation	Capacity, (kNm)	Moment, (kNm)	Usage level
Original	48	43,23	90,06%
With opening	48	51,13	106,52%

As shown in table 3, the bending moment capacity of the slab zone 2 is exceeded in the altered situation with the opening. From this it can be assumed that if the opening is cut to the slab zone 1, the original reinforcements in the zone 2 are not sufficient. The slab needs strengthening which allows the bending moment to be contained within the limits of the properties of reinforcements. However, there is always a certain level of uncertainty when assessing existing structures. It is always advisable to consider the age and possible defects of the structure, when reviewing the results.

The large size of the opening and the uncertainty of the initial calculations encouraged an assessment of the effects of the opening on the slab more precisely. For this, a model was created in FEA software called Autodesk Robot Structural Analysis. As the initial need for supporting the slab had been established, the next step was to determine how the cantilever part of the slab would behave in the new situation. A structural model was created in the software and all internal force distributions of the slab determined. According to the calculations, the bending moment for the slab zone 2 in the new situation was approximately $37\,kNm$, around 28% smaller to the moment calculated with PUPAX5 software. One of the reasons for this difference is the higher level of accuracy of the FEA analysis. The graphical results of the bending moment distribution in the slab in the new situation with the opening and in the situation where the opening is supported with concrete beams from below, calculated with Robot-software can be seen in figure 34 below.

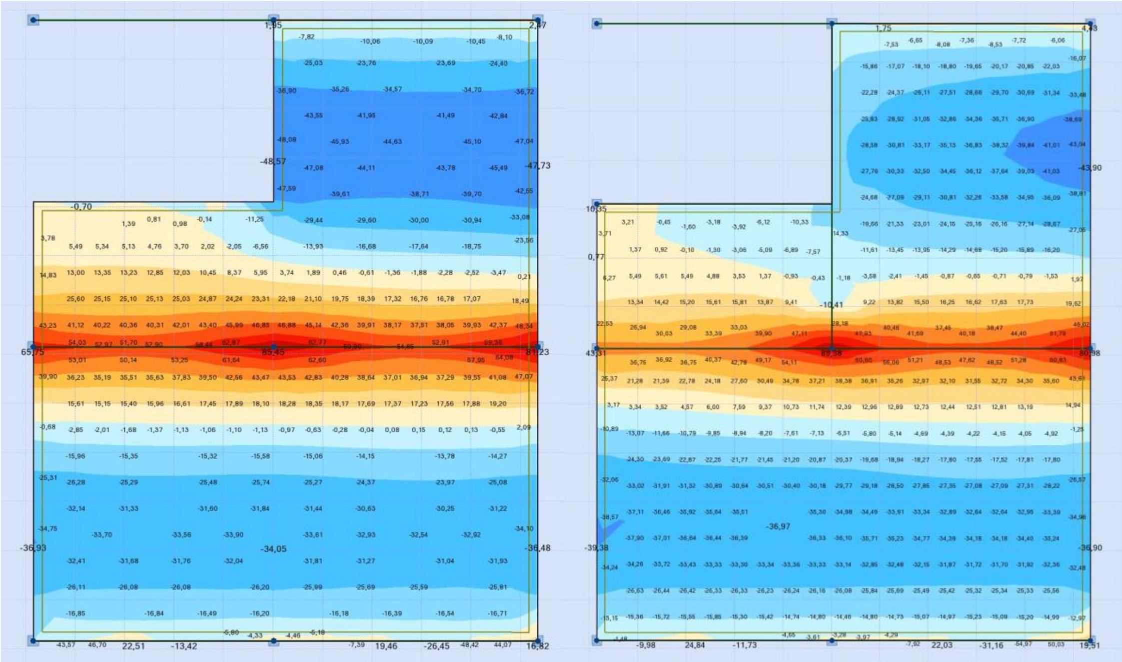

Figure 34. Graphical representation of the moment distribution in the slab.

According to the results of the analysis, the deflection of the cantilever portion of the slab in long term loading condition remained inside the allowed limits as well but only when supporting concrete beams were added to the sides of the opening.

As the strengthening need was confirmed, two reinforced concrete beams were added to the sides of the opening. The supporting is achieved by two beams, a primary beam which is anchored to the columns, and a secondary beam which is anchored to the primary beam and the bearing wall on the other end. In the preliminary assessment stage the cross-section of the reinforced concrete beams was approximated and a 300x500 mm ($b \times h$) cross-section was chosen as a basis for the assessment. The suggested support beams and their locations are illustrated in figure 35 below.

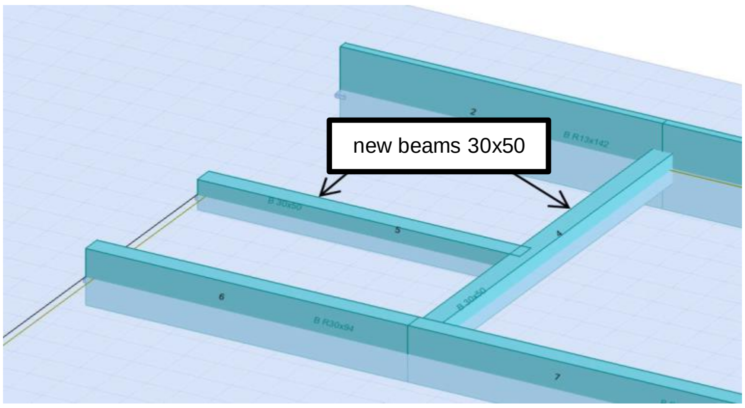

Figure 35. The location of the support beams around the opening.

The internal forces of the support beams were determined with the FEA model. The beams are loaded with their own and the slabs weight, as well as the distributed load of $5\ \frac{kN}{m^2}$.

The design bending moments for the support beams are

$M_{Ed} =\ 90.79\ kNm$ for the primary beam and
$M_{Ed} = 16.30\ kNm$ for the secondary beam.

The functionality of the chosen cross-sections was determined by the excel calculation sheet based on the Eurocodes in attachment 2. The dimensioning calculation confirmed the functionality of the cross-section, and the initial tension reinforcement was confirmed to be four 16 mm steel reinforcement bars, with a 72% usage factor.

The assessment confirmed the feasibility of the opening, but it was determined that it is possible only if additional supporting beams are placed underneath the slab. A more precise cost estimate can be executed with this information, which allows the client to decide whether the opening will be included in the project or not. More precise planning of the opening and supporting beams can be done once the confirmation of its realization is granted.

9 Conclusions

Wise Group Finland Oy did not have any instructions or an assessment process for the assessment of openings in existing load-bearing concrete structures. The aim of the thesis was to compile the existing instructions and guidelines for various concrete structures and to define a general assessment process and workflow for the designers. The thesis discusses the necessary information the designer needs to obtain before a successful assessment can take place. In addition to this, the thesis compiled the most important instructions and guidelines regarding openings in concrete structures, and collected so called silent knowledge as the experienced designers of the company were interviewed about their processes and habits. This information is embedded in the instructions of different concrete structure components.

During the literature review of the thesis it was noted that a large amount of instructions and guidelines exists for new concrete structures. However, they rarely even mention existing concrete structures. It should be noted that the reason for this is most likely the fact that a successful renovation design requires the knowledge of designing new structures as well. Here, the interviews and discussions with other more experienced structural designers proved valuable, as many of the interviewees had a long experience on structural design. One of the most important aspects that emerged from the thesis project is the importance of the knowledge of different structural systems and concrete design in general. The knowledge helps the designer to assess and design openings and alterations to existing structures more safely and with long lasting results, as the designer can take all variables into account.

Since the thesis was able to compile the instructions and the general assessment process, it could be considered a success. The compiled instructions and guidelines and the general assessment process serve as a first guidance for a designer in the assessment of openings in existing concrete structures. The specific nature and the quantity of variables when assessing openings meant that it was a challenge to compile general instructions that would work in every situation. For this reason, the instructions and general assessment process should not be used as they are in every case but rather as a manual and as a start to the assessment. Every opening should always be assessed individually, and modifications should always be done within the limits and terms of the structures.

As further study, it would be useful to develop the assessment process and to create more specific instructions and guidelines for different building components. Additionally, researching other building structures as well, such as masonry structures would be useful as they are common load-bearing structures in older buildings. It would also be useful to continue the assessment of the slab structure used in the example for this thesis, particularly with the dimensioning of the supporting concrete beams as this would complete the assessment process from the initial steps to the completed plans for supporting the planned opening.

Overall, the thesis was a superb learning opportunity and the aims set in the beginning of the work were accomplished successfully. The example assessment of the thesis was an excellent opportunity to carry out an actual assessment and to use the knowledge gained from the literature review and interviews of the thesis. Additionally, with the help of the example I was able to familiarize myself with the actual implementation and the processes and aspects of the assessment itself, which will be valuable knowledge considering further studies and work life.

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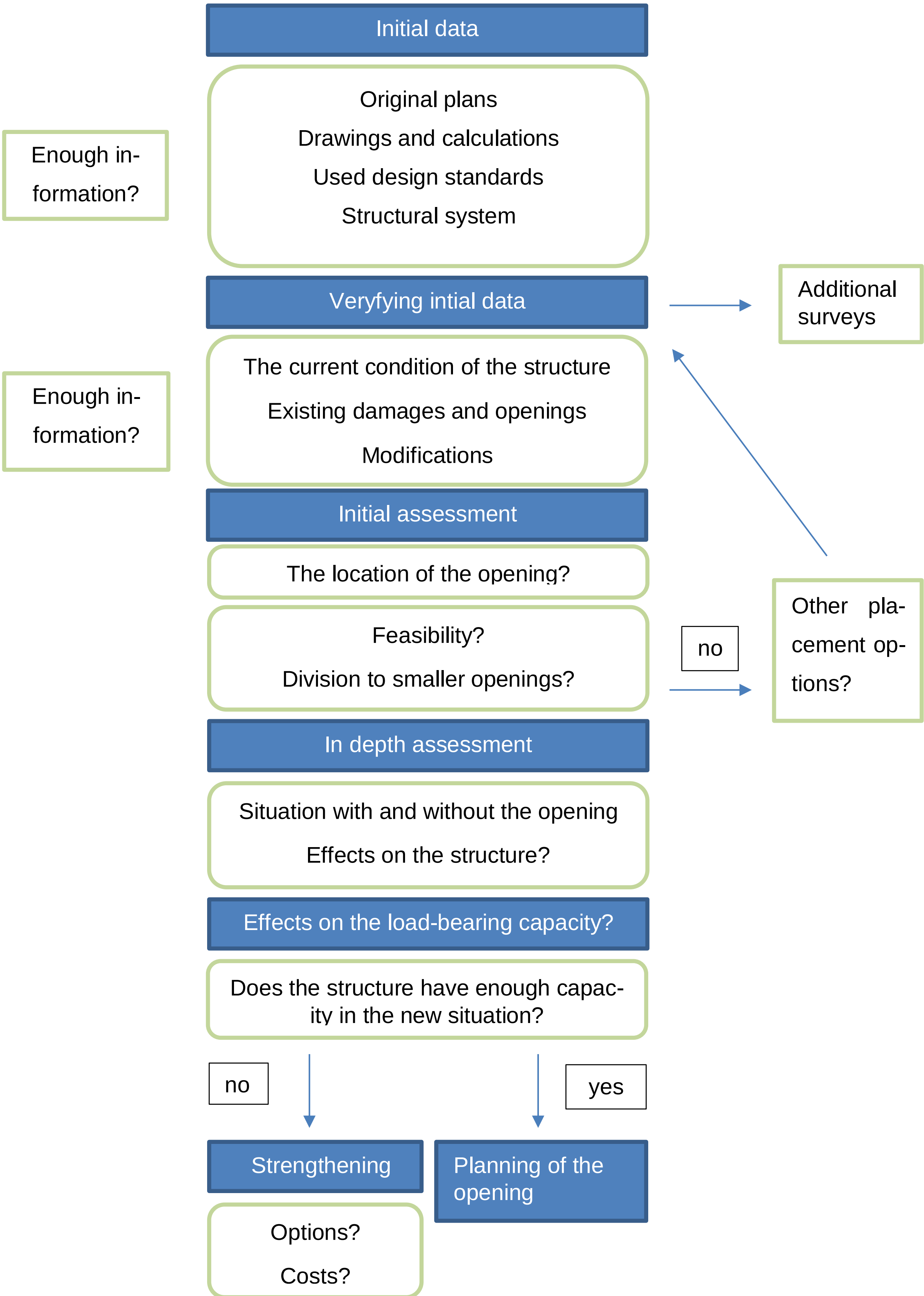
General assessment process



Dimensioning of support beams

	Projekti:	Example assessment Support beam	pvm 13.4.2017 laat. Kve	N:o sivu

Dimensioning of beam cross-section
Support beams

Lähtötiedot

Betonin lieriö	30	MN/m2	MN/m2 Valittu betoni **C30/37(K37)**
Md=	0,1	MNm	Murtorajatilan mitoitusmomentti
M,Eqp=	0,06	MNm	Pitkäaikaisten kuormien mitoitusmomentti
Vd=	0,06	MN	Mitoittava leikkausvoima
b=	0,3	m	
d=	0,469	m	=h-25-6
h=	0,5	m	
c=	25	mm	laskennallinen betonipeite (= teor. bet.peite - sallittu poikkeama)
cmin=	25	mm	betonipeitteen vähimmäisarvo (= nimellisarvo - sallittu poikkeama)
wkp=	0,3	mm	Pitkäaikaisen halkeamaleveyden perusarvo (ks. taulukko ohessa)
fiiv=	1,6		Betonin virumaluku
Es=	200000	MN/m2	Teräksen kimmokerroin
Ecm=	32837	MN/m2	Betonin sekanttimoduuli
Ec,eff	12629	MN/m2	Betonin tehollinen kimmokerroin
fck=	30	MN/m2	Betonin lieriölujuuden ominaisarvo 28 vrk ikäisenä
fcd=	17,00	MN/m2	Betonin puristuslujuuden mitoitusarvo
fcm	38	MN/m2	Betonin keskimääräinen puristuslujuus 28vrk ikäisenä
fctm=	2,90	MN/m2	Betonin keskimääräinen vetolujuus
fyk=	500	MN/m2	Teräksen myötölujuuden ominaisarvo
fyd=	434,78	MN/m2	Teräksen laskentalujuus

Teräsmäärä murtorajatilassa

Asmin=kt*b*h*fctk/fyk=	212	mm2
Asmax=0,04*Ac	6000	mm2
myy=Md/(fcd*b*d^2)=	0,08914236	
beeta=1-(1-2*myy)^0.5=	0,09351488	
z=d*(1-beeta/2)=	0,44707076	m
Asmt=Md/z/fyd=	514	mm2
Asvaad=	514	mm2

Tulokset

Teräsmäärät

Asmin=	212	mm2	SFS-EN 1992-1-1 mukainen minimiteräsmäärä
Asmt=	514	mm2	murtorajatilan vaatima teräsmäärä
myy=	0,089		suhteellinen momentti

Yhteenveto

Vaadittu teräsmäärä:

Avaad=	Asmt=		514 mm2						
=fii	16	3	kpl	0	0,000	0		=	0

Valittu teräsmäärä:

As=		804 mm2					
=fii	**16**	4	kpl2	**k=**	**0,075**	m	
Muvast=		0,152 MNm	omega=	0,1462	myyvast=	0,1355	

Halkeaman leveys pitkäaikaisille kuormille

wksallpitk=	0,30	mm	sallittu halkeamaleveys
wkpitk=	0,11	mm	lask. halkeaman leveys
sigs=	180	MN/m2	Käyttörajatilan teräsjännitys

Leikkausraudoittamattoman rakenteen kestävyys
VRdc= 0,0720 MN
Vd<VRdc Ei vaadi leikkausraudoitusta, OK