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Design of Densely Reinforced Concrete Walls and Columns

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<p>The purpose of this thesis was to define the origin of the value for maximal reinforcement area for reinforced concrete walls and columns, and to create a useful design instruction for the design of densely reinforced structures. Also, the thesis aimed to provide a clear picture of possible applications of dense reinforcement for cast-in-situ structures and to define factors which need to be considered during the design and construction processes.</p> <p>A significant part of this research was based on interviewing experts at structural design companies as well as at construction sites. In addition, the thesis was based on literacy research of previous and current structural design norms.</p> <p>The information that retrieved from interviews and studies explained the origin of maximal reinforcement area value and the problems occurring in densely reinforced concrete structures.</p> <p>This knowledge can be applied in structural design process to minimize the possibility of mistakes occurring, as well as to develop the efficiency of structural design and construction implementation processes. In addition, a unique structural guide for the design of densely reinforced concrete walls and columns was created.</p>	
Keywords	reinforced concrete, densely reinforced concrete, design of densely reinforced concrete.

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List of Abbreviations

A_s = Reinforcement area

A_c = Cross-section area of concrete

$A_{s,vmax}$ = Maximum area of vertical reinforcement

$A_{s,vmin}$ = Minimum area of vertical reinforcement

$A_{s,hmin}$ = Minimum area of horizontal reinforcement

$A_{s,v}$ = Reinforcement area of vertical reinforcement

b = Width

c/c = Centre-to-centre

d = Diameter

d_v = Vertical reinforcement rod's diameter

EN = Eurocode

f_{yd} = Reinforcing steel yielding strength

h = Height; width; smallest width of the column

NA = National Annex

N_{ed} = Normal force design value

n = Amount of grouped rebars

RIL = Finnish Engineering Union

$S_{v,max}$ = Maximum centre-to-centre of vertical reinforcement

$S_{h,max}$ = Maximum centre-to-centre of horizontal reinforcement

$S_{cv,t,max}$ = Maximum centre-to-centre of transverse reinforcement

\emptyset = Diameter of the rebar

1 Introduction

Eurocode is the European standard for conducting structural design processes. Additionally, Eurocodes require that countries have their own additional regulations which are called National Annexes. In Finland, the Ministry of Environment (Ympäristöministeriö) is responsible for the National Annex for buildings. The Finnish Standard Association SFS develops, publishes and controls the national standards.

Eurocode 1992-1-1 regulates reinforced concrete structures and gives the basic rules and concepts for construction. Finnish Engineering Union has an instruction for concrete works implementation, it is called RIL 149-1995. Eurocode 1992-1-1 states the maximum value of reinforcement in concrete walls. However, it is not explained why this value cannot be exceeded and how the coefficient of the maximum value is calculated. Currently, when designing a reinforced concrete wall or column, it is recommended to not exceed the maximum value of the vertical reinforcement area. (2.)

In special situations reinforced concrete wall or column structures are needed to carry large loads when certain properties of the wall/column (such as width) cannot be increased. Eurocode 1992-1-1 gives a limit for the reinforcement area in a concrete wall or column that cannot be exceeded. However, there are situations where it is impossible to change the properties of the structure such as cross-section area. In these cases, an engineer needs to design a structure with the given properties. This thesis studies these situations, and examines the origin of the maximum value, as well as factors which affect it.

2 Theoretical Background

2.1 RIL 149-1995

According to RIL 149-1995, a concrete structure is considered densely reinforced when special methods are needed for formworks, casting and vibration. It means that ordinary working principles will not allow the structure to gain full bearing capacity nor work properly as it is designed to, due to difficult implementation at the construction site. For example, ordinary methods in a densely reinforced concrete structure to compact the concrete will not work properly, and the concrete will not locate correctly around the rebars. This leads to cracking of concrete at places where it is not strong enough and the structural design age will be decreased. (1.)

Dense reinforcement problems can appear in any type of structures, such as columns, walls and beams. However, dense reinforcement usually appears at connection between structures and in bending structures. In columns or walls, dense reinforcement is rarely seen. However, a structure will often have dense reinforcement in connection areas with other structures such as columns with slabs, or walls with slabs. In columns, the amount of concrete mass used is small, the speed of casting is usually high, which leads to an unequal distribution of aggregates and concrete mass that finally may lead to cracking. (1.)

In thin reinforced concrete walls, the same problem happens as in other densely reinforced concrete structures. Due to a tight reinforcement net, aggregates are separated from cement and get stuck between rebars. Ultimately it leads to unequal distribution of concrete mass. In reinforced concrete walls openings have dense reinforcement. (1.)

2.2 Maximum Reinforcement Area Value

The main task of columns and walls is to transfer loads of upper structure elements to the foundation. Columns and walls are compressed structures where tension occurs due to large moment forces. Concrete has high compression strength capacity when reinforcement resists well tension in the structure that happens due to moment forces. In vertical structures, it is possible that second order bending occurs, which needs to be prevented to keep the structures stable. Reinforced concrete columns and walls are similar structures and can be calculated with the same formulas. The vertical reinforcement of a wall, however, needs to be checked additionally.

2.2.1 Vertical Reinforcement

Vertical reinforcement shall be checked for minimum reinforcement area, symbols are $A_{s,vmin}$ for walls and $A_{s,min}$ for columns. Secondly, maximum value of reinforcement area shall be checked, symbol are $A_{s,vmax}$ for walls and $A_{s,max}$ for columns. S_{vmax} - Distance between rods shall be calculated. (2.)

According to Eurocode 1992-1-1, the recommended maximum value of vertical reinforcement is 4 % of the cross-section of a column or wall. (12.) The following formula is given:

$$A_{s,vmax} = 0.04 * A_c \quad (12.)$$

However, in the Finnish NA the maximum value is 6 % of the cross-section area, it is larger than in Eurocode. It means that when designing reinforced concrete structures in Finland, the formula is the same but with 6 %. (12.)

$$A_{s,vmax} = 0.06 * A_c \quad (12.)$$

Eurocode also gives the minimum value for vertical reinforcement, 0.2 % of the cross-section area. (12.) The following formula is given:

$$A_{s,vmin} = 0.002 * A_c \quad (2.)$$

Also, minimum reinforcement area can be calculated with the following formula:

$$A_{s,vmin} = 0.10 * \frac{Ned}{F_{yd}} \quad (2.)$$

For the minimum reinforcement area allowed in reinforced concrete structures, the Finnish NA has the same value as EN 1992-1-1. (12.)

The maximum distance between the vertical rods can be calculated with the formula:

$$S_{v,max} = \min(3h; 400 \text{ mm}) \quad (2.)$$

2.2.2 Horizontal Reinforcement

Horizontal reinforcement is calculated differently for walls and for columns. In walls, horizontal reinforcement are bars which go all the way through the wall. In columns they are stirrups. In vertical structures, horizontal reinforcement prevents buckling of a vertical rebar. If a vertical rebar in a column starts to buckle, the stirrup does not allow it. It also involves other vertical bars in preventing the buckling. In walls, when a vertical rod is under load and starts to buckle, horizontal reinforcement does not allow it, and also involves other rods to resist the force. However, it is important to place a horizontal reinforcement closer to the edge than a vertical reinforcement. Figure 1 shows the correct and incorrect locations of horizontal and vertical reinforcements. If a vertical reinforcement is located on the outside, a transverse reinforcement should be applied.

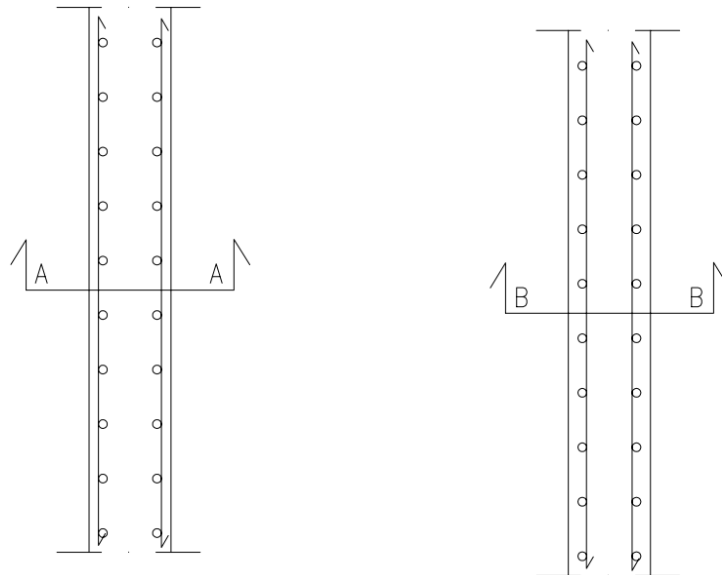


Figure 1. Plan view of wall reinforcement.

In the left drawing, reinforcement is located correctly, the horizontal reinforcement is outside and the vertical reinforcement is inside. It is not preferable to locate reinforcement as it is in the right drawing, where the vertical reinforcement is outside and the horizontal is inside. In this case transverse reinforcement is required.

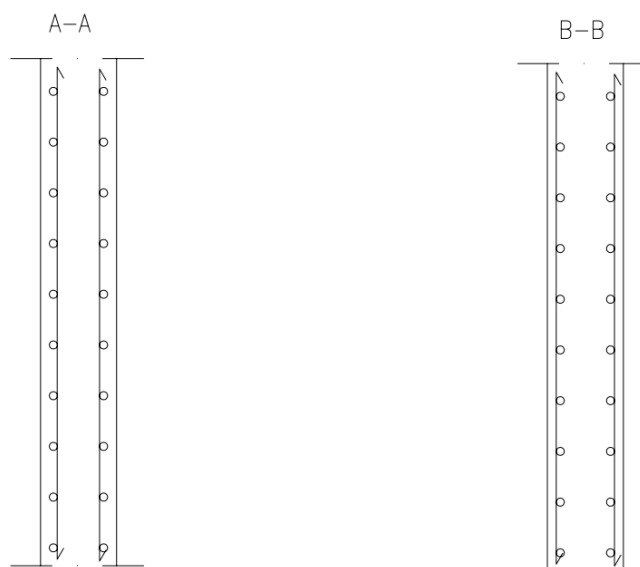


Figure 2. Sections of the reinforced concrete walls.

2.2.3 Transverse Reinforcement

Transverse reinforcement prevents buckling of vertical reinforcement in columns or walls. However, transverse reinforcement is not always needed. It is necessary to put only when vertical reinforcement is outside of horizontal reinforcement. (2.) Figure 3 shows the plan view of the wall when vertical reinforcement is located outside and transverse reinforcement is applied.

When vertical reinforcement is outside of the horizontal one, at least 4 units of transverse reinforcement must be used per square meter. However, it is not needed when a reinforcement net is done by welding and the maximum diameter of a rod is 16 mm and concrete cover is at least 2 x diameter. (2.)

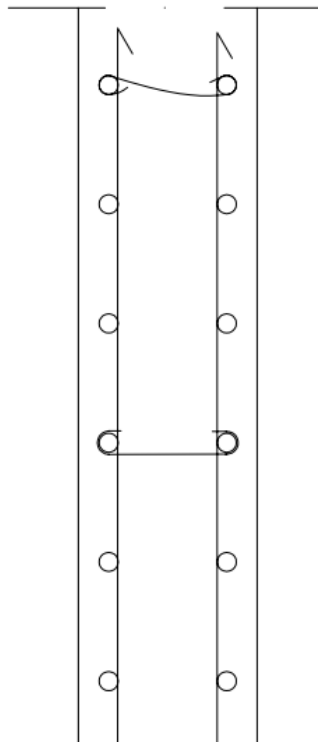


Figure 3. Transverse reinforcement.

The distance between transverse reinforcements is calculated with the formula:

$$S_{cv,t,max} = \min(15 * \phi_v; 400 \text{ mm}; h)$$

The center to center distance decreases in the connection area of the structures with other structure. Distance should be less or equal to $0.6 * \text{maximum centre-to-centre distance of transverse reinforcement}$. (2.)

2.3 Reinforcement Overlapping Maximal Value

According to the standard EN1992-1-1 FIN NA, the maximum value of reinforcement area is 12 % of cross-section area in overlapping reinforcement areas. It is calculated with this formula:

$$A_{s,vmax} = 0.12 * A_c \quad (12.)$$

However, 12 % is a very big value, often the structure is not going to function properly if 12 % is used.

3 Maximum Reinforcement Area Value

EN1992-1-1 gives a recommendation value for the maximum and minimum area of reinforcement. Moreover, it mentions that the maximum value can be presented in the National Annex. As mentioned above, the Finnish NA sets the maximum value for area of reinforcement larger than does the EN1992-1-1. However, the method of calculation, reasons and factors that affect it are not mentioned. (11.)

The maximum values of reinforcement areas in columns and walls are not supported by any theoretical factors. For this research no calculations which can show how the 6% value was gained could be found. Therefore, it is possible to say that the reinforcement maximum area value is a practical value that was presumably gained through tests, experience and other factors which are going to be considered further.

3.1 Economical Factors

Densely reinforced concrete structures require a lot of work at the construction site and to implement densely reinforced concrete structures is very challenging. Additionally, a long time is spent to install the rebars in the correct positions in narrow structures, where concrete pouring and vibration works are difficult. Furthermore, in densely reinforced structures concrete does not cast equally and workers need to concentrate to ensure that it mixes as equally as possible. (9.)

Additional problems occur in the overlapping area. All the work costs money and materials, especially if many steel rods are needed. This is why, it is not economical to create densely reinforced concrete structures. Project engineers can consider substituting reinforced concrete columns by composite or steel structures. However, it is not possible to substitute it by any other wall material. (9.)

3.2 Safety Factor

Vertical structures mainly are compressed and deflected. In compression, concrete mainly resists the compression and reinforcement prevents the deflection. The main

goal of vertical structures is to transfer the loads of the building from the roof to the foundation. (9.)

6% of the cross-section of a structure for reinforcement is a large reinforcement area. For example, in a wall with a width of 300 mm, reinforcement area, which is 6 % of cross-section area, would be 32 diameter rebars with 80 mm centre-to-centre distance. From a safety point of view, it is dangerous to use structures with such a relation between loads, cross-section and reinforcement. It is dangerous to utilize structure close to 100 % of its capacity due to great forces and moments. The value 6 % is another safety value-coefficient which shows that the structure may not work properly. This safety factor gives us an option to increase the cross-area and consequently decrease the stresses. (9.)

The safety factor can be referred as creep of concrete, that it is dangerous to have such a relation loads to capacity structures all the time under large stresses. Since one part of a column or wall is always in tension and another is always in compression, deformation increases, the moment grows and risks of the structure collapsing grows respectively. Creep must be taken into account in the design phase as well as to figuring out what type of loads affects the structure. If the permanent load is the main load and also the largest load, the designer should understand that the structure is going to be under high stresses all the time, which can cause creep. In the case if live load is the main, the situation is not dangerous since the structure is not always under stresses. The designer should always take into account what type of loads affect the structure. (9.)

3.3 Implementation at Construction Site

Another reason why the 6 % reinforcement area cannot be exceeded is the difficulties it would cause with implementation at the construction site. 6 % is a high value and if it is exceeded, it means that the rebars are very close to each other. This means that pouring the concrete equally becomes challenging and vibration works cannot be done properly. Thus, the concrete does not obtain the required properties between the rebars, meaning that the structure will not work properly. (8.)

It is possible to group the main reinforcements to get more space between rebars. However, not more than 3 rebars can be grouped. Moreover, if reinforcement is grouped, the reinforcement area of the grouped rods is decreased. The reinforcement area of grouped reinforcement can be calculated with the following formula:

$$\varnothing_n = \varnothing * \sqrt{n} \leq 55mm \text{ (11.)}$$

For example, a bunch of 3 rebars with a diameter of 32 mm covers 55 mm equivalent reinforcement area. A bunch of 2 rebars with a diameter of 32 mm covers a 45 mm reinforcement area. Therefore, the total reinforcement area can be calculated with the following formula:

$$A = \varnothing_n^2 * \pi/4$$

A bunch of 3 rebars with a diameter of 32 mm, when \varnothing_n is 55 mm, covers 2375 mm² reinforcement area. Grouping improves the conditions, but not significantly.

4 Comparing National Codes

4.1 Russian Code - SP, SNIP

The Russian construction code is called SP (previously SNIP). Section SP 63.13330.2011 covers the basic regulations for reinforced concrete structures, basic rules. The maximum recommended value for maximum reinforcement area is 5 % of the cross-section area. However, the code states “without an adequate reason this value can not be exceeded”. Therefore, if the situation requires that the value is exceeded and it is reasonable, it can be exceeded. In reinforcement overlapping the area which can be used is 10 % of the cross-section area. (4.)

The regulation SP 52-103-2007 states that the value of reinforcement in the cross-section area cannot exceed 10 % in any location. (5.) The minimum value for reinforcement is 0.1 % of the cross-section area. (6.)

The Russian code does not provide a formula to calculate the maximum reinforcement area value. However, it states that the maximum reinforcement is defined through tests in a laboratory. The results show that over 10 % reinforcement does not increase the bearing capacity. A higher value can only make the situation worse, and cause installation problems at the construction site. (6.)

Another idea is that, 5 % is a “check-point” which allows engineers to see if calculations of reinforcement are correct and if the structure is effective from an economical side to use as much reinforcement. Also, the Russian code states that if the initial data is correct and the calculations are done properly, the reinforcement area should not be a higher value than 5 % of cross-section area. If the value is higher, the initial data the structure should be changed as width or height. (6.)

According to SP, reinforced concrete structures where shear force cannot be born only by concrete, stirrups with centre to centre not larger than $0,5 \cdot$ smallest width of the column or 300 mm must be installed. Rebars should have durable anchoring at both ends, either due to overlapping or welding, in order to have a durable connection. According to the Russian code, overlapping reinforcement is applied to rebars with a diameter less than 40 mm. (4.)

4.2 German Code – DIN EN 1992-1-1/NA/A1:2013-04

In German National Annex, the values are similar to those in Eurocode 1992. The minimum required diameter of vertical reinforcement for columns is 12 mm. The minimal area of reinforcement is calculated by the following formula:

$$A_{s,vmin} = 0.15 * \frac{|NEd|}{F_{yd}} \quad (3.)$$

Chapter NDP ZU 9.5.2 (3) states the maximum area of reinforcement, as 9 % of the cross-section area, thus a value of 0.09 is used. This value is applied for every area of the column, both the main reinforcement as well as reinforcement overlapping. (3.)

According to DIN 1992-1-1/NA:2013-4, for the requirements are similar reinforced concrete walls. Minimum reinforcement area value is calculated the same way as for reinforced concrete columns, with the following formula:

$$A_{s,vmin} = 0.15 * \frac{|NEd|}{F_{yd}} \geq 0.0015 * A_c \quad (3.)$$

For slim walls or if: $|NEd| \geq 0.3fc * A_c$, the formula that should be used is:

$$A_{s,vmin} = 0.003 * A_c \quad (3.)$$

The maximal value for the main reinforcement area is 4 % or 0.04 of cross-section area. In reinforcement overlapping area it is allowed to use double value, 8 % or 0.08 of the cross-section area. (3.)

4.3 US Code – ACI 318-14

According to the American code the maximal reinforcement area shall not exceed 0.08 or 8 % of cross-section area for nonprestressed columns and for prestressed which compressive stress is less than 1.55 MPa. The minimal reinforcement area must not be less than 0.001 of the cross-section area. The value of maximum reinforcement area is considered practically. This value allows for concrete to consolidate around the rebars and engineer to design a column the way it was tested. The 0.08 value applies to all

parts of the column, including reinforcement overlapping areas. Therefore, vertical reinforcement cannot exceed 0.04 or 4 % of the cross-section area. (7.)

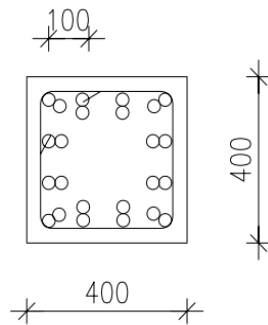


Figure 4. Overlapping reinforcement in the column.

As mentioned above, the overlapping area can have 8 % of the cross-section area. However, ACI 318-14 gives a drawing that shows that the bars in the overlapping area from lower or higher level shall be bent inside the column, as can be seen in figure 4. This provides clear spacing between the rebars. (7.)

ACI 318-14 gives the minimum reinforcement values for vertical and transverse reinforcement in table (11.6.1, page 169). The maximum reinforcement area value is not stated in the chapter R11 – Walls. Possibly, the maximum reinforcement area value is the same as for columns, 4 % for vertical reinforcement and 8 % for reinforcement overlapping. (7.)

5 Reinforcement Overlapping

Reinforcement overlapping is a difficult area in reinforced concrete structures. According to the Finnish NA, the maximum area of vertical reinforcement can be 0.12 of the cross-section area. (11.) However, it is hard to implement this in a structure. 12 % is too large a value and it will result a continuous row of reinforcement rebars, as it can be seen in the column in figure 5. In this case, concrete will not fill the space between the rebars and, obviously, the concrete will not function properly. It is crucial that the structural engineer remembers the reinforcement overlapping area. Also, each overlapping reinforcement area should be evaluated carefully and care should be taken that a minimum distance between rebars is kept.

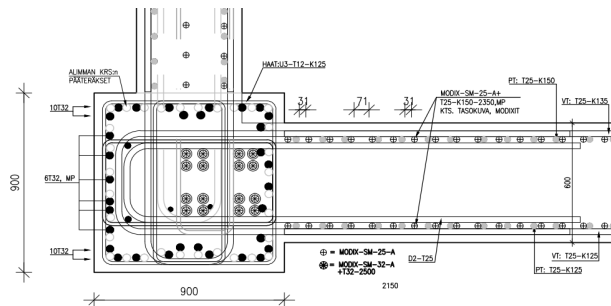


Figure 5. Continues row of reinforcement. (14.)

It is a recommendation to model the reinforcement overlapping area with a BIM program or manually to assess the structure to ensure enough space between the rebars. (9.) Since space is limited in densely reinforced concrete structures, it is possible to use reinforcing bar couplers. This will decrease the space which is needed for overlapping. Couplers are from 10 to 50 mm diameter rebars, with additional space needed for muffs.

Reinforcement welding is an extremely difficult process and it is not recommended as a solution for reinforcement overlapping. In the Finnish construction field there are not very many welders. It is difficult to find and employ a welder quickly to work at construction site. Reinforcement welding requires additional tests. A welder needs to make a sample connection which is sent to a laboratory where it is studied for a long period of time. All steps take a lot of time as well as money. Therefore, it is not recommended to use reinforcement welding in big projects. It is much easier to use another solution. (9.)

6 Casting, Shrinkage and Vibration Works

6.1 Concrete Mass

RIL 149-1995 mentions that in densely reinforced concrete structures the process of choosing concrete mass requires additional attention. It is very important to consider the flexibility, aggregate properties and coherence of the concrete. Usually the best result is achieved with liquefied concrete that easily gets through dense reinforcement. However, the vibration works requirements are the same as for ordinary concrete, despite the use of liquefied concrete in dense reinforcement structures. The main advantage of liquefied concrete is that it goes between the rebars and settles equally. (1.)

Concrete is mixed in a truck and while it is waiting to be poured in the form, it is necessary to add a liquefier so that it casts easier. A liquefier slows down the reaction between the cement and water, which in high and thin structures helps to cast properly. Despite the liquefier, liquefied concrete keeps its properties and functions as well as ordinary concrete. (1.)

For liquefied concrete, the formwork must be strong and able to hold the pressure. In densely reinforced concrete structures more vibration works are done than in regular structures. Thus, the formwork must be stable and not let the concrete to leak from the formwork. (1.)

Aggregates should be of approximately the same size and distributed equally in the structure. If the aggregates are too small they will drop down to the bottom, which will lead to unequal distribution. If the aggregates are too large, they will get stuck between the rebars which does not allow the concrete to fill the formwork properly. In densely reinforced concrete structures, the maximum size of aggregates can be 0.85 of the distance between rebars of the same direction. (1.)

Concrete aftercare ensures the correct quality of the structure according to the norms, for example in a period of 10 days, quality control might be performed every 3rd day and any necessary action or adjustment can be undertaken. The action might include keeping the temperature difference minimal throughout the whole structure. Due to a chemical reaction between cement and water, the temperature in the structure can be

as high as 60 degrees Celsius. It is necessary to install insulation to avoid high temperature difference in the structure because it can cause cracks. According to the codes, the allowed temperature difference is 20 degrees per meter. (1.)

Shrinkage does not depend on the density of reinforcement, it happens of itself and depends, for example, on the cement, the size of aggregate, the chemical elements, the amount of water. Thus, densely reinforced concrete structures are subject to usual shrinkage. The higher the concrete strength, the more shrinkage occurs. Since higher concrete strength, means more cement and water and when the water leaves, shrinkage happens. In this case, it is possible to use sulfate resisting cement which has a low water-to-cement ratio and is suitable when high durability of concrete is needed. It is as strong as regular cement but the shrinkage is smaller. (10.)

Self-compacting concrete is another suitable option for densely reinforced concrete structures since it is difficult to perform vibration works in thin reinforced concrete walls. Self-compacting concrete saves working time and has the same bearing capacity and properties as ordinary concrete. Although, the price of self-compacting concrete is higher, it compacts itself and no worker is needed to vibrate the concrete. However, the speed of casting is high which means that the loads for formwork are large. Casting pressure from self-compacting concrete can be from 5 kN/m^2 to 10 kN/m^2 . This pressure is too high for usual formwork. (10.)

6.2 Casting

During the casting process, the concrete mass generally is not allowed to fall more than 1 meter. Pipes can be used ensure a low drop height. A pipe is put down into the structure between the rebars to a suitable level, and the structure is cast. This method is broadly used to cast reinforced concrete structures. In densely reinforced concrete structures it can be challenging. If the structure is thin and the reinforcement is dense there will not be enough space for a pipe to be put in. This is why this method is not suitable for densely reinforced structures. (1.)

Another option is to make a hole in the formwork and pour concrete through the hole to avoid high fall. For example, if a wall is 3 meters high, a hole can be made at the 1 meter level and concrete can be poured. (1.)

In densely reinforced concrete structures it is important to control the speed and the quality of casting. The speed should not be too high to allow for proper vibration works. Pumping is too fast for dense reinforcement, there is not enough time to perform vibration works correctly. In high structures, such as columns or walls, the height can be too large, meaning that not all parts of the structure are necessarily vibrated. Densely reinforced concrete structures should be cast first to have enough time to control the casting and to fix problems if necessary. Generally, regular casting height is used. However, it is necessary to take into account how vibration works are going to be done. (1.)

6.3 Vibration Works

For reinforced concrete, a mechanical vibrator is the most suitable since it is efficient and provides a high-quality result. Sometimes mould vibration is used to vibrate the structure. (1.)

In densely reinforced concrete there is not much space between rebars, which is why a smaller diameter of the rod should be used. Sometimes, rods get stuck between rebars and it is impossible to get them out. Therefore, there should be enough equipment and tools available at construction site to save time of the construction process. Also, casting or vibration works can take more time than originally planned. Therefore, the labour resources should be sufficient to allow for an increase of the number of workers in a certain place to keep the process going. (1.)

Vibration should be done at a distance of 8 x diameter of rod, and in densely reinforced concrete this distance should be even smaller. The vibration time should be from 5 to 10 seconds. Incorrect or lacking vibration works leads to a decrease in the bearing capacity of the structure. Therefore, it is important to perform vibration correctly. The recommended vibration time is 800 s/m³, and speed 4m³/h. (1.)

7 Examples of Densely Reinforced Concrete Structures

7.1 Reinforced Concrete Column

An example of densely reinforced concrete structure is a reinforced concrete column 900 mm x 900 mm, which has 32 rebars with 32 mm diameter and centre-to-centre 100 mm. Therefore, maximum reinforcement area value is 6 % of the cross-section area, as mentioned in chapter 2. In this case, in the column are 32 rebars with 32 mm diameter, which makes is 3 % of reinforcement area of the cross-section. As can be seen in figure 6, the reinforcement is freely located, and there is enough space between the rebars. Anchors located in the column from the connecting wall as well as additional vertical bars to strengthen the anchoring.

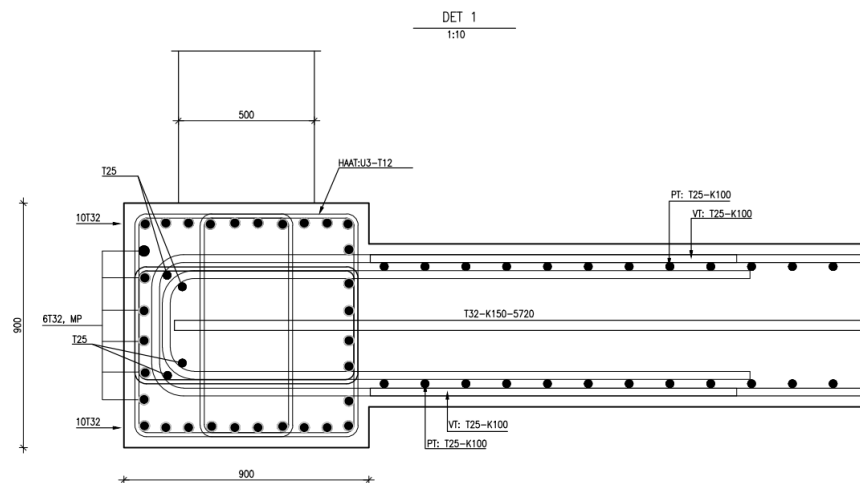


Figure 6. Main reinforcement of the column. (13.)

According to the drawing in figure 6, the structure seems functioning properly. However, the picture changes in the reinforcement overlapping area as can be seen in figure 7. The main vertical reinforcement is doubled, which makes a continuous row of rebars, or in other words, a column of rebars. According to EN1992-1-1, the reinforcement overlapping areas can be 8 % of the cross-section area, or according to Finnish NA, it can be 12 %. However, in this case the overlapping reinforcement area is 6 % and the structure does not function properly since there is no access for concrete between the rebars. The situation gets worse since additional anchors and muffs are located inside the column which worsen the vibration works capability.

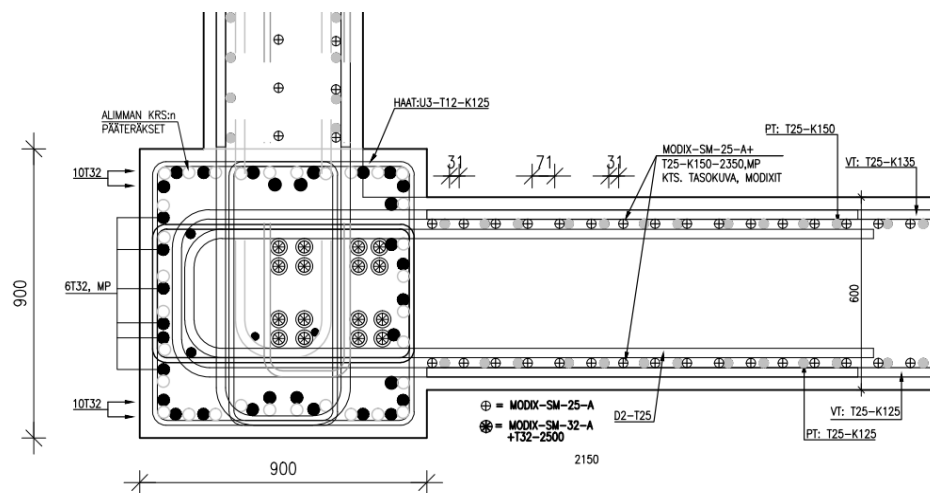


Figure 7. Reinforcement overlapping area of the column. The main reinforcement makes a row of rebars. (14.)

In this case, there is an alternative for how the structure can be done. The main reinforcement of the upper or lower column could be bent inside. Thus, it would not be a row of rebars, but rather one reinforcement would be near the edge as can be seen in figure 6 and the bent rebars would be inside, next to the other rebar.

7.2 Reinforced Concrete Wall

The next example is a reinforced concrete wall with 350 mm width. In the structure there is an overlapping area with rebars from the lower level, there are rebars with 25 mm diameter and centre-to-centre is 125 mm. The main reinforcement is 2 rebars of 32 mm diameter with 150 mm centre-to-centre. The rebars are doubled, located next to each other. In this area the reinforcement area is 8,5 % of cross-section area, in the overlapping area, the maximum reinforcement area allowed is 12 % of the cross-section area. Additionally, stirrups of various length and type support the main reinforcement horizontally.



Figure 8. Installed reinforcement. (15.)

Figure 8 is a photograph of the wall when the rebars were installed. The reinforcement is extremely dense. Some areas have rows of main reinforcement rebars from 50 to 100 mm. When there is such a long row of reinforcement, the structure is not going to function as it does with 1 or 2 rebars together. The drawing of the reinforcement area of the column can be seen in figure 9.

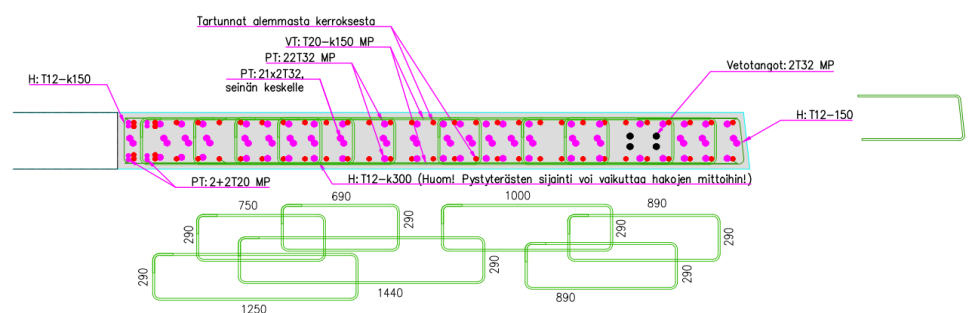


Figure 9. Reinforcement overlapping area in the wall. (16.)

In this case, the main reinforcement from the lower level could be done with a larger diameter, for example 32 mm. This would reduce the amount of rebars in the wall and there would be more space for vibration works and for the concrete to get between the rebars.

7.3 Reinforced Concrete Column

The sample column is a rectangular reinforced concrete column that connects with a circular composite column. The column is 1500 mm x 910 mm. In the connection area, where the rectangular column connects with the circular column the cross section of the rectangular column is increased and is 1500 mm x 1200 mm. The diameter of the circular column is 535 mm. As figure 10 shows, the reinforcement is located too densely in the connection area. The vertical stirrups have 50 mm centre-to-centre when their diameter is 12 mm. According to these values, space between rebars is 38 mm. It is important to take into account the ribs of the rebars which are 5-7 mm. From this we get that the distance between the rebars is 28-24 mm. It is extremely difficult to implement this structure at the construction site. In this case, problem occurs only with stirrups, there is enough space between the vertical reinforcement. Stirrups with 16 mm diameter could be used in order to increase the centre to centre distance between the rebars. The structure was done with a 45 mm concrete cover, that means that the concrete is filled around the structure. However, it is important that the concrete cover connects with the concrete which is inside the column. Otherwise, if the concrete cover is separate from the concrete of the column, the structure is not going to function well.

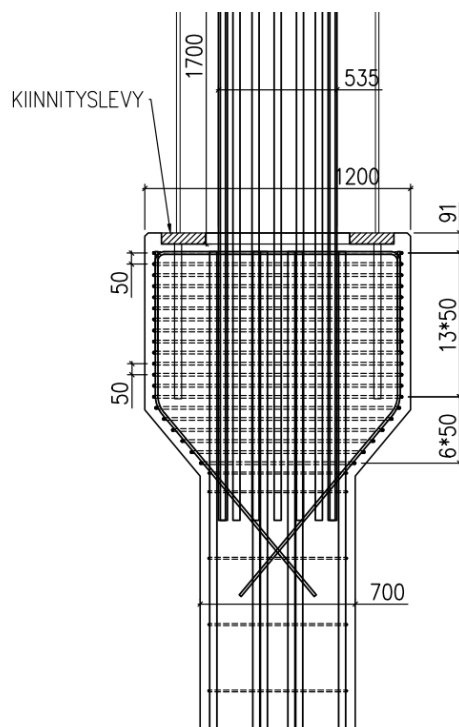


Figure 10. Vertical section of connection area of rectangular column and composite column. (17.)

In the same column, additional reinforcement has been added. However, it has not been noticed that the main reinforcement is cut by additional reinforcement. In figure 11, it is possible to see that the main reinforcement interrupts with the additional reinforcement on the side edges of the column. It is not acceptable to leave reinforcement interrupting another reinforcement without mentioning it in the drawing. Due to the additional reinforcement, it was necessary to cut the main reinforcement and substitute it with overlapping rebars. It required additional work at the construction site, and the bearing capacity of the column could be decreased. (9.)

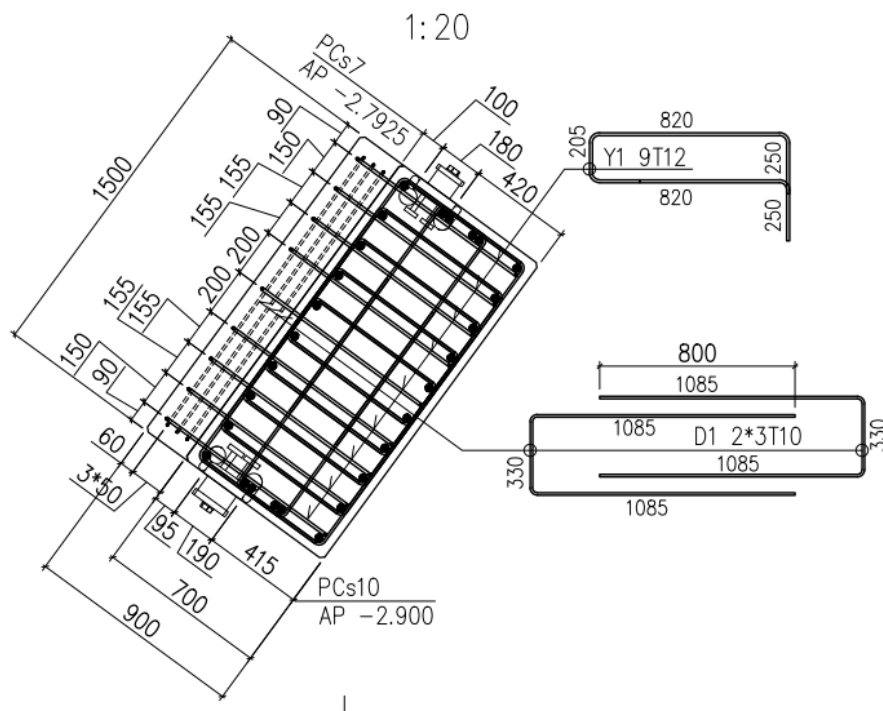


Figure 11. Plan view of the rectangular column with additional reinforcement located on the edges. (18.)

This problem could be solved by moving Peikko PC (additional reinforcement) to another part or to the side where is more space. The problem arose since not enough attention was paid to the additional reinforcement during the designing stage. It is not acceptable to rely on the construction site workers to create a solution and construct a solution.

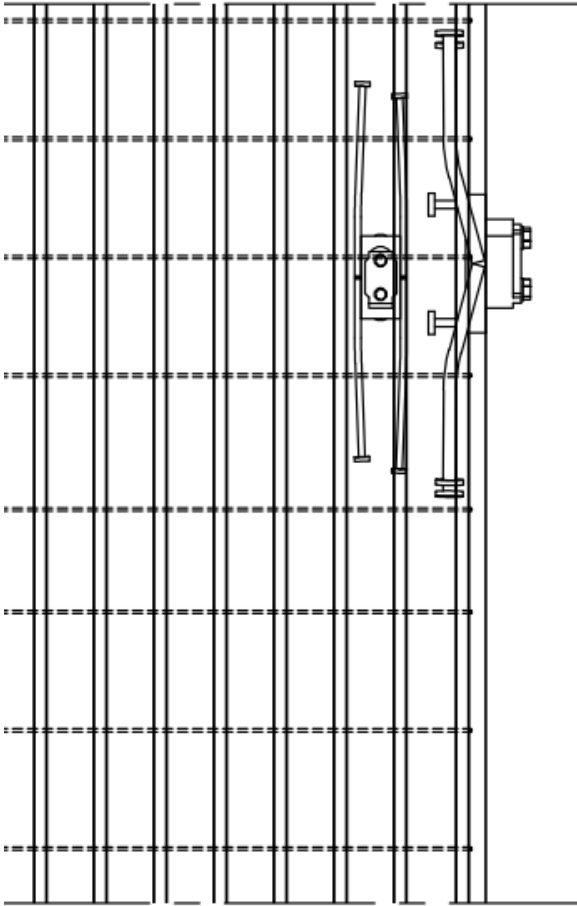


Figure 12. Section of the column. (19.)

In figure 12, can be seen an additional reinforcement that is placed in the same location as the main reinforcement of the column.

7.4 Ribs of the Rebar

In figure 13, it is clearly seen that the rib of the rebar decreases the space from the distance between the rebars.



Figure 13. Installed rebars at construction site.

The rib is from 5 to 7 mm, as mentioned above. That is why it is crucial to take it into account during the design of densely reinforced concrete structures. (8.)

7.5 HVAC Holes & Openings

When planning HVAC holes and openings, it is necessary to take into account that the areas are going to be densely reinforced.



Figure 14. HVAC opening. (20.)

Every hole and opening needs to be considered individually. Depending on the main reinforcement, and the conditions for vibration works, the space in the structure, structural engineer needs to decide whether to set many rebars with smaller diameter or a few rebars with larger diameter. Figure 14 demonstrates as an additional rebars are installed around the openings.

7.6 Sample Column of 400 mm x 400 mm

Reinforcement area of the sample column is 6 % of the cross-section. There are 12 rebars of 32 mm diameter with 100 mm centre-to-centre. In this column, 6 % is a suitable value for reinforcement area since the distance between the rebars is approximately 60 mm.

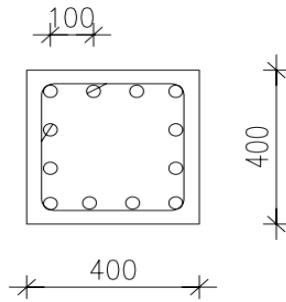


Figure 15. Main reinforcement of the column.

However, the reinforcement overlapping area is problematic. According to Finnish NA, reinforcement overlapping area can be 12 % of the cross-section area. However, with a 12 % reinforcement area it is most probable that the concrete will not fill the space between the rebars. Therefore, the structure will not function correctly. Figure 16 demonstrates a not suitable solution for reinforcement overlapping zone in densely reinforced concrete structures. Rebars are located next to each other, there is not enough space for concrete to be filled in.

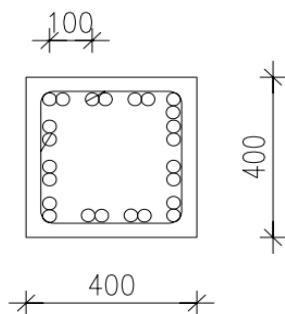


Figure 16. Reinforcement overlapping area.

The correct structural design of this column would be to keep the main reinforcement of the upper column in the same position as the lower one but bend either the upper or the lower reinforcement inwards in the area of overlapping reinforcement as figure 17 shows.

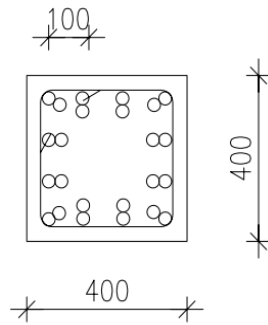


Figure 17. Correct design of reinforcement overlapping.

With this method the length of the required overlapping is longer. However, with this method there will be no problems with concrete and its vibration works. Figure 13 shows the section of the column. In reinforcement overlapping area centre-to-centre distance of stirrups should be $0.6 \times$ maximum stirrups centre-to-centre distance. (11.)

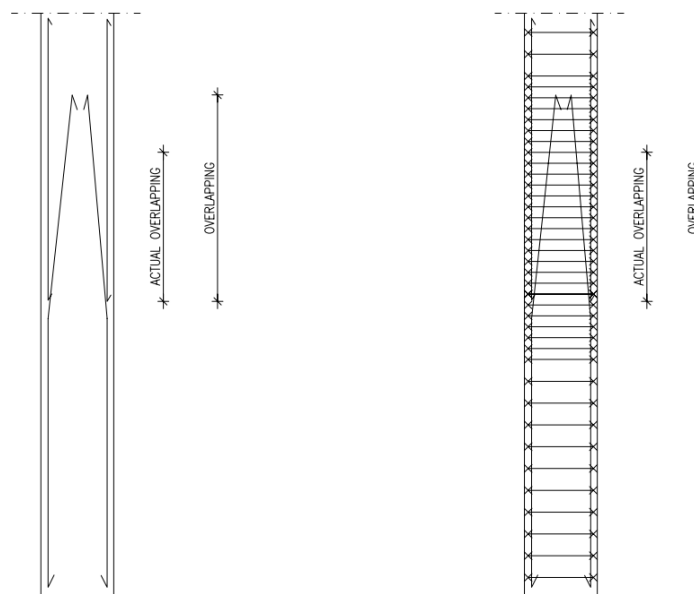


Figure 18. Overlapping area of the main vertical reinforcement, when reinforcement from the lower level is bent inside.

In figure 18, it is shown the total distance of reinforcement overlapping and the actual working overlapping distance. The actual overlapping distance which transfers the forces is shorter than the total overlapping. Therefore, the engineer must calculate actual reinforcement overlapping distance separately.

8 Structural Design Processes

8.1 Planning Stage

In Finland difficult projects are constantly designed. It requires structural design expertise and experience, and cannot be done using general knowledge and common methods. It is crucial to understand that more difficult projects cannot be constructed the same way as an ordinary building. Underestimation of the loads and forces, mistakes and late changes in the preliminary planning stage can cause situations when engineers need to design densely reinforced concrete structures. (9.)

The most important step is to correctly evaluate future loads and forces on the building and estimate the proper values. Loads calculations should be done carefully because they have a great impact on the future process of the project. It is exactly in this stage engineers design the whole building with approximate values. It means that the values of width, heights, and lengths of future structures elements are given. (9.)

For several reasons, engineers sometimes underestimate loads in the building in the preliminary planning stage. Challenging projects usually do not seem difficult, and the planning stage is done the same way as for an average building. However, some special points are not taken into account. (9.)

After engineers have given approximate values for the structure, architects start to work in their field, and the owner starts to sell square meters. At this stage the project is started and any changes should be discussed and explained since any change can affect all of the project processes.

However, detailed design of the structure starts approximately in 1-2 years after the preliminary planning stage. At that point, architects have gone far with work in the project, and the owner has sold most of the space. When engineers start to design the structures in detail, it reveals that some elements of the structure cannot support the loads and they need to be strengthened. The easiest option is to increase the cross-section of the structure. However, it is not that easy because of the architecture of the building and space inside the building. Since every square meter counts this is an economical question. (9.)

In the preliminary planning stage, engineers should pay attention and include a margin for changes or unexpected situations into the design to solve structural design problems more smoothly if anything unexpected appears.

During the preliminary planning stage, the approximate design process should be done carefully, involving experts who have worked in challenging projects and have solved many problems. Companies can create a database for knowledge and experience that can significantly improve the efficiency of projects.

Timeline:

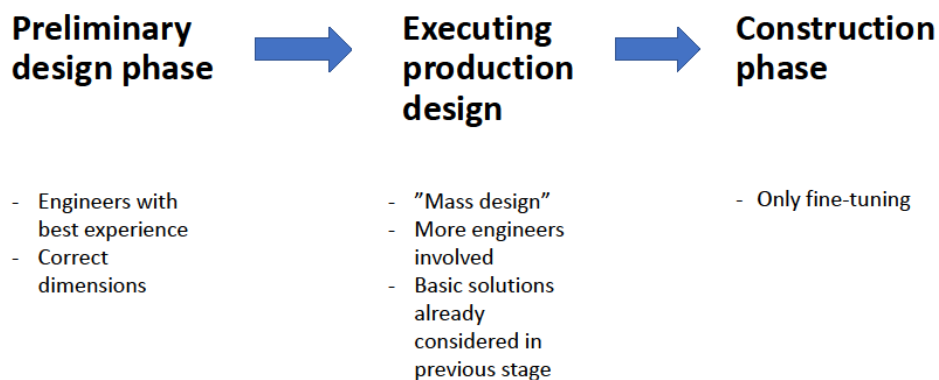


Figure 19. Timeline of structural design phases. (21.)

8.2 Design of Reinforcement

During the design process it is crucial that design engineers cooperate with structural calculation engineers. Sometimes there are misunderstandings happens between design engineers and structural design engineers. (9.)

The design engineer receives details of the structure and loads in the implementation design. If there is not space in the structure for enough reinforcement, and the utilization percentage is close to 100, the design engineer must say that structure is not going to function. It is not acceptable to send a drawing to a construction site and hope that the construction method will be figured out there.

In case structure cannot function properly, other solutions need to be discussed in order to find the most suitable solution for a structure. It can be a substitution of a reinforced concrete structure by a composite or steel structures. Designing structures, the engineer must pay more attention to what he designs. All details of the structure must be taken into account.

8.3 Expertise

Experience is the most valuable asset in the construction of challenging projects. It should be shared as much as possible. Obviously, when designing a difficult project for the first time it is almost impossible to prevent mistakes. However, the most important point is to analyse any mistakes, and learn from them.

Sometimes people do not want to share and analyse mistakes. If an employee makes a mistake, but stays quiet and does not share with others, it simply leads to another employee can easily repeat a mistake. The experience should be discussed as it is the fastest way to educate employees and prevent mistakes in the future. Otherwise, the mistake can be repeated infinitely until everyone learns it. Mistakes in the design process are expensive for a company. Therefore, it is efficient to create a system of analysing mistakes to increase the efficiency of work in companies.

An experience sharing system should collect mistakes, analyse them and share these with employees. Through such a system, employees can educate themselves quickly by analysing examples of various cases, and future mistakes will be prevented.

To implement the preliminary planning stage correctly, an orientation meeting can be organized in the beginning of a project to share well-known solutions to the team. Technical meetings can be held during the project to check periodically that the chosen solutions are suitable.

Engineers who have already been involved in challenging construction should be the first ones in new project to help others to prevent mistakes. A difficult project may not seem as challenging as it is. This can lead to an underestimation of the project that will cause problems later in the designing stage. (9.)

8.4 BIM Modelling

3D modelling is a fantastic tool to design a reinforced concrete structure. In the model it is possible to place reinforcement the way it should be constructed. BIM programs show a real picture of a construction in real life. From the model the designer can see if there is enough space between the reinforcement to be filled by concrete, or if the structure is too densely reinforced. However, to get a clear picture of the situation, the structure should be modelled carefully and all rebars should be located correctly. Modelling the structure, the designer should be able to assess the situation. Sometimes, designers do not have enough time to place reinforcement in the correct position. In such cases, rebars are intersecting in the program, and the 3D model does not show the real picture. Using BIM program properly, the designer sees that there is a lot of space in the structure and concrete will be filled in and implemented properly. If a drawing looks chaotic and rebars intersect each other, it is possible to adjust the location of reinforcement in the drawing. By doing this, the drawing might look fine but it does not mean that the structure is not too densely reinforced. When the drawing is delivered to the construction site, the reinforcement of the structure is set according to the drawing, and the workers notice that the structure is too densely reinforced. In such cases, concrete does not function as well as it should. Vibration works are impossible to implement properly. (9.)

Designers should model structures in a BIM program the same way as they want the structure to be constructed. By correct positioning, the designer will be able to understand whether the structure is going to function properly or whether it is too densely reinforced. BIM is a tool that simplifies construction process. (9.)

8.5 FEM Calculation

FEM programs are widely used in the structural engineering field. Their use saves time in the structural design process, and, therefore, saves money for the company. FEM programs are useful and can calculate the majority of structures. The results are mostly correct and reliable. However, when using the programs, it is possible to make a mistake which can lead to a mistake in the design. When using the FEM program, the most important thing for an engineer is to have an approximate, estimated results in their mind, before the program calculates that. Therefore, the designer can compare

his or her results to those of the program. An approximate result can be calculated quickly by hand and then compared with the calculations of the FEM program. If the results look similar, the engineer can use the detailed numbers from the program. In simple cases, it is easier for engineers to calculate by hand and be 100 % sure of the results. (9.)

Technology is constantly developing, and structural engineering programs are improving. To accelerate the process of technological development, it is crucial to share experience of using FEM programs to improve their use. If a mistake occurs when using a FEM program, it should be analysed and shared with co-workers to prevent similar mistakes in the future.

8.6 Drawings

Drawings should always be clear and understandable. Easy-to-read drawings save time and prevent mistakes at construction sites. An engineer or drawer should understand that at a construction site, workers do not know much about a structure or about how it should be made. In most cases, drawing is the only tool that they can use to figure out information about a structure, and how it should be constructed. Therefore, it is crucial to make a clear drawing where texts and dimension are readable and lines clearly visible.

In the reinforcement drawing of a structure, all pictures for the reinforcement (the plan, sections, details, etc) included in the structure should be in the same drawing. It is not recommendable to place detail views and sections of the structure separately with the plan and other parts of the structure. It is extremely difficult to search for drawings of other parts of the structure at construction site and it can be easily forgotten.

3D modelling programs support the drawing preparation a lot. Everything that is modelled is shown in the drawing. It aids the designer to remember everything. A change of structure in the model automatically changes the drawing. However, BIM programs allow the user to change location, quantity and other properties of reinforcement in the drawing phase. For example, if the rebars are shown by many lines in the drawings, the drawing looks chaotic. It is possible to hide the lines and only leave one of them visible in the middle of the group, or adjust the location of the rebar. This makes the

drawing look clear, and the structure does not seem too densely reinforced in the drawing. However, all properties, such as the amount of rebars, centre-to-centre, and diameter are still the same. Later at construction site, when all reinforcement is installed workers will notice that the structure is too densely reinforced and concrete will not cast evenly. At this point it will be difficult to change anything dramatically to improve the situation. To prevent cases like this, it is necessary to prepare a drawing which shows the real picture of the structure and reinforcement.

9 Structural Design Instruction and Guideline

The design of densely reinforced concrete structures should be done with additional attention. There are points that must be checked in order to design and construct the structure correctly. The structural design instruction can be seen in Appendix 1.

Firstly, the engineer needs to check that concrete has an access to any part of the structure. Horizontal movement of concrete must be as small as possible. Secondly, the engineer must remember about the space for vibration works. Vibration work is one of the most important phases of casting. Concrete gains full strength and properties by correct implementation of vibration works. Therefore, in the structure there should be enough space between the rebars for vibration works. Rebars can be grouped to allow more space between the reinforcement. It is crucial also to consider that the ribs of the rebar take a 5 to 7 mm of space. Vibration work process is explained in detail in chapter 6.3.

It is crucial to provide clear work instruction to construction site. Drawings of the structures, work instructions, views of details and formwork should be clear for implementation.

In case the structure does not carry the loads and the engineer sees that structure is not going to function properly, the engineer must point this out to the project manager and suggest another solution or other materials.

Overlapping area is the most densely reinforced area. According to EN1992-1-1, Finnish NA, reinforcement can cover 12 % of the cross-section area in overlapping areas. (11.) This value is large; thus, engineers need to check that the space between rebars is large enough for concrete to be cast.

The length of anchorage and overlapping reinforcement must follow the regulations. The engineer must check whether there is enough space in the structure. If there is not enough space, overlapping reinforcement should be bent inwards. When rebars are bent inwards, actual overlapping distance is decreased. At some point, the lower level bent rebar gets far away from the upper level rebar, and does not transfer the loads anymore. The engineer must calculate the real functional overlapping distance. According to EN1992-1-1, in overlapping area, maximal distance between overlapped rebars

can be $4 \times$ diameter or 50 mm. (11.) Another option for reinforcement joints is use of couplers. It has a larger diameter than the rebars, however, rebars are not needed to be overlapped and bent inside. Couplers can fully substitute the reinforcement overlapping.

Each structure with holes and openings needs to be considered separately. In some cases, it is better to use some rebars with a higher diameter than many smaller ones to have enough space for vibration works. In some cases, it is more suitable to use many rebars of lower diameter to have space for an equal distribution of aggregates. The main task for an engineer is to take into account the concrete casting process and vibration works.

All additional components must be considered during the design of the reinforcement process. The process should be modelled and seen in the same drawing as the reinforcement. It is important to evaluate working joint area to ensure that there is enough space for reinforcement. If TS joint reinforcement is used, it is necessary to check the width, and to assess whether there is enough space for the reinforcement, as well as check that it does not intersect with other rebars.

A higher concrete class increases the shrinkage of concrete which is not suitable for densely reinforced concrete. In densely reinforced concrete structures, larger shrinkage can cause cracking. Therefore, the structural engineer must use the most suitable concrete class to maintain the bearing capacity and to not allow large shrinkage. (10.)

It is important to consider intersecting structures, effect of loads and connections during the design process. In connections with other structures it is crucial to evaluate the situation. The structure is often densely reinforced in these areas due to the connection of many structures.

The diameter of the rebars used in densely reinforced concrete structures should be as large as possible to get more space for the concrete to be cast. In densely reinforced concrete structures, the maximum size of aggregates can be 0.85 of the distance between rebars of the same direction. (11.)

10 Conclusion

Densely reinforced concrete structures are common in new challenging projects. However, Eurocode 1992-1-1, as well as other structural design materials regulates the maximum value of allowed reinforcement. However, the origin and reasons for the value are not explained. The purpose of this paper was to provide an overall picture of densely reinforced concrete wall and column design. Another aim was to research the origin of the maximum value for reinforcement, and examine problems of its implementation at the construction site. The final aim was to prepare a structural design guide for densely reinforced concrete wall and column design. In order to gather sufficient and valuable information, literary research as well as interviews with experts in the construction field were carried out.

Despite densely reinforced concrete design being a common problem, it became apparent during the research that this issue is not adequately studied and it is mostly experts who possess the ability to talk about this topic. The theoretical basis of the maximum value of reinforcement in a column or wall has not been found. The value is arrived at through experience of application, economic efficiency, as well as laboratory tests. An adequate value is 6 % of the cross-section. This should not be exceeded to ensure that the structure functions correctly. However, even 6 % can be too large a value for a structure. The reinforcement overlapping area, which can be 12 % of the cross section according to EN1992-1-1, is too large. It is crucial to locate the reinforcement correctly so that the distance between the rebars is large enough for the concrete to fill the space completely. Furthermore, enough space is required for the vibration works.

Concrete casting is another significant stage of construction. The design engineer should provide a working guideline to a construction site, including the method for how he or she plans the structure to be cast. The contractor is responsible for correct work implementation, such as casting, vibration work and concrete after care.

The reason why densely reinforced concrete structures exist is alterations of the plans, or an underestimation of the structure during the preliminary planning stage. Therefore, it is crucial to consult as many experts and experienced project managers as possible in the preliminary planning stage to minimize densely reinforced concrete structures.

Sometimes dense reinforcement is not noticed due to haste and mistakes during the design stage.

In summary, preventing future mistakes is far more likely if those within the industry are willing to share and discuss their negative experiences and previous mistakes.

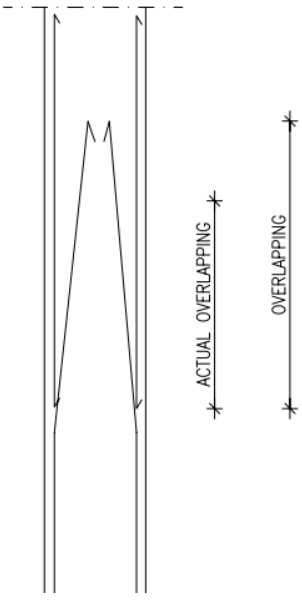
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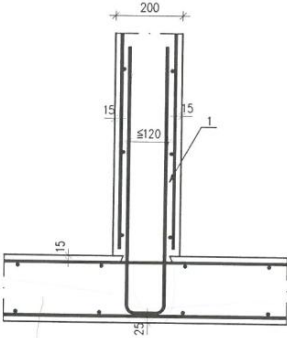
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13. Continues row of reinforcement. Sweco Rakennetekniikka Oy. 2017

14. Main reinforcement of the column. Sweco Rakennetekniikka Oy. 2017
15. Installed reinforcement. Sweco Rakennetekniikka Oy. 2017.
16. Reinforcement overlapping area in the wall. Sweco Rakennetekniikka Oy. 2017.
17. Vertical section of connection area of rectangular column and composite column. Sweco Rakennetekniikka Oy. 2017
18. Plan view of the rectangular column with additional reinforcement located on the edges. Sweco Rakennetekniikka Oy. 2017
19. Section of the column. Sweco Rakennetekniikka Oy. 2017
20. HVAC openings. Sweco Rakennetekniikka Oy. 2017
21. Timeline of structural design phases. Sweco Rakennetekniikka Oy. 2017

Appendix 1 – Structural Design Instruction

Subject to be checked	Description
1. Concrete distribution in the structure	Concrete should be able to access any part of the structure. Horizontal movement of concrete should be as small as possible.
2. Space for vibration works	Vibration is one of the most important stages of casting. Correct implementation of vibration works allows the structure to gain its full properties. Therefore, there should be enough space between the rebars for vibration works. Rebars can be grouped to allow more space between the reinforcements. It is crucial to consider that the ribs in the rebar take a 5mm to 7mm of space. Vibration work process is explained in detail in chapter 6.3.
3. Clear work instructions	Drawings, work instructions, design and views of details and formwork should be clear for implementation at construction site.
4. In case structure cannot be designed correctly, an engineer must say about it.	If the structure does not have a capacity to carry the required loads, an engineer must point this out to the project manager and suggest to look for another solution or other materials.

<p>5. Evaluate overlapping area</p>	<p>According to EN1992-1-1, reinforcement can cover 12 % of the cross-section area in overlapping areas. This value is large; thus, engineers need to check that the space between rebars is large enough for concrete to be cast.</p>
<p>6. Anchorage and overlapping design of reinforcement</p>  <p>Figure 20. Reinforcement overlapping method in densely reinforced concrete column.</p>	<p>The length of anchorage and overlapping reinforcement must follow the regulations. The engineer must check whether there is enough space in the structure.</p> <p>If there is not enough space, overlapping reinforcement should be bent inwards. When rebars are bent inwards, actual overlapping distance is decreased. At some point, the lower level bent rebar gets far away from the upper level rebar, and does not transfer the loads anymore. (Figure 20). The engineer must calculate the real functional overlapping distance. According to EN1992-1-1, in overlapping area, maximal distance between overlapped rebars can be $4 \cdot \text{diameter}$ or 50 mm.</p> <p>Another option for reinforcement joints is use of couplers. It has a larger diameter than the rebars, however, rebars are not needed to be overlapped and bent inside. Couplers can fully substitute the reinforcement overlapping.</p>

	<p>If these components require additional reinforcement, they should be shown too.</p>
<p>9. Working joints</p>  <p>Figure 22. Joint reinforcement in the wall. Modified from Suomen Betoniyhdistys r.y. (1993)/(12.)</p>	<p>It is important to evaluate working joint area to ensure that there is enough space for reinforcement. If TS joint reinforcement is used, it is necessary to check the width, and to assess whether there is enough space for the reinforcement, as well as check that it does not intersect with other rebars. (Figure 22).</p>
<p>10. Shrinkage</p>	<p>A higher concrete class increases the shrinkage of concrete which is not suitable for densely reinforced concrete. In densely reinforced concrete structures, larger shrinkage can cause cracking. Therefore, the structural engineer must use the most suitable concrete class to maintain the bearing capacity and to not allow large shrinkage.</p>
<p>11. Intersecting structures</p>	<p>It is important to consider intersecting structures, effect of loads and connections during the design process.</p>

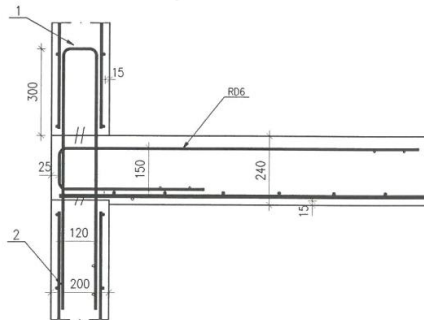


Figure 23. Walls and slab connection. Modified from Suomen Betoniyhdistys r.y. (1993)/(12.)

In connections with other structures it is crucial to evaluate the situation. The structure is often densely reinforced in these areas due to the connection of many structures. Figure 23 shows the connection between a lower level wall, a upper level wall and the slab. Due to the anchorage of these structures, the connection area becomes densely reinforced.

12. Recommendations

The diameter of the rebars used should be as large as possible to get more space for the concrete to be cast.

In densely reinforced concrete structures, the maximum size of aggregates can be 0,85 of the distance between rebars of the same direction.

Concrete strength should be suitable for the structure, but not too high. High concrete class increases shrinkage which is not preferable for densely reinforced structures.

Appendix 2 – Additional Figures & Images



Figure 1. A row of rebars installed for a wall at construction site. Too little space is left for vibration work.



Figure 2. Too densely reinforced concrete structure. (Sweco Rakennetekniikka Oy. 2017)

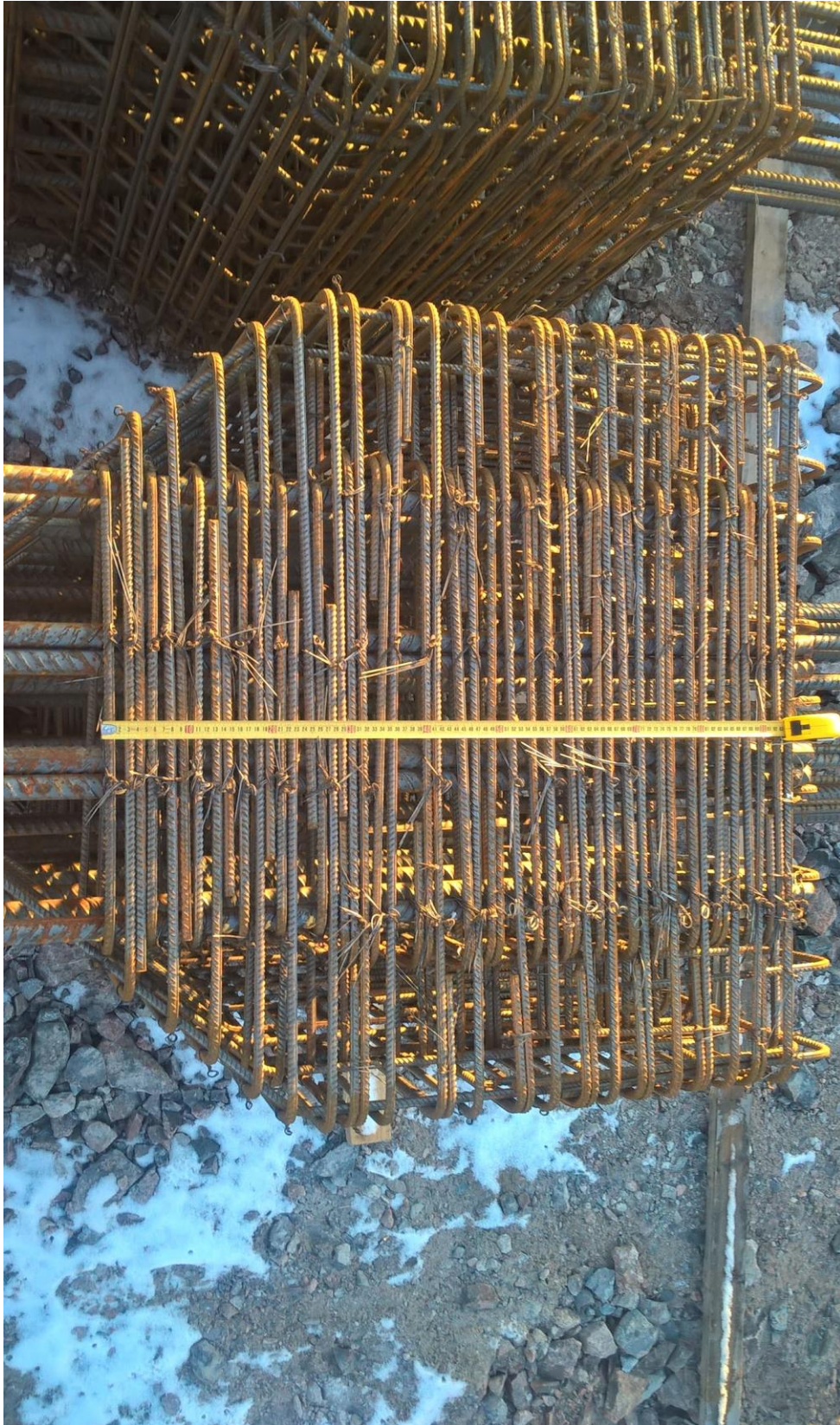


Figure 3. Too densely located stirrups. (Sweco Rakennetekniikka Oy. 2017)

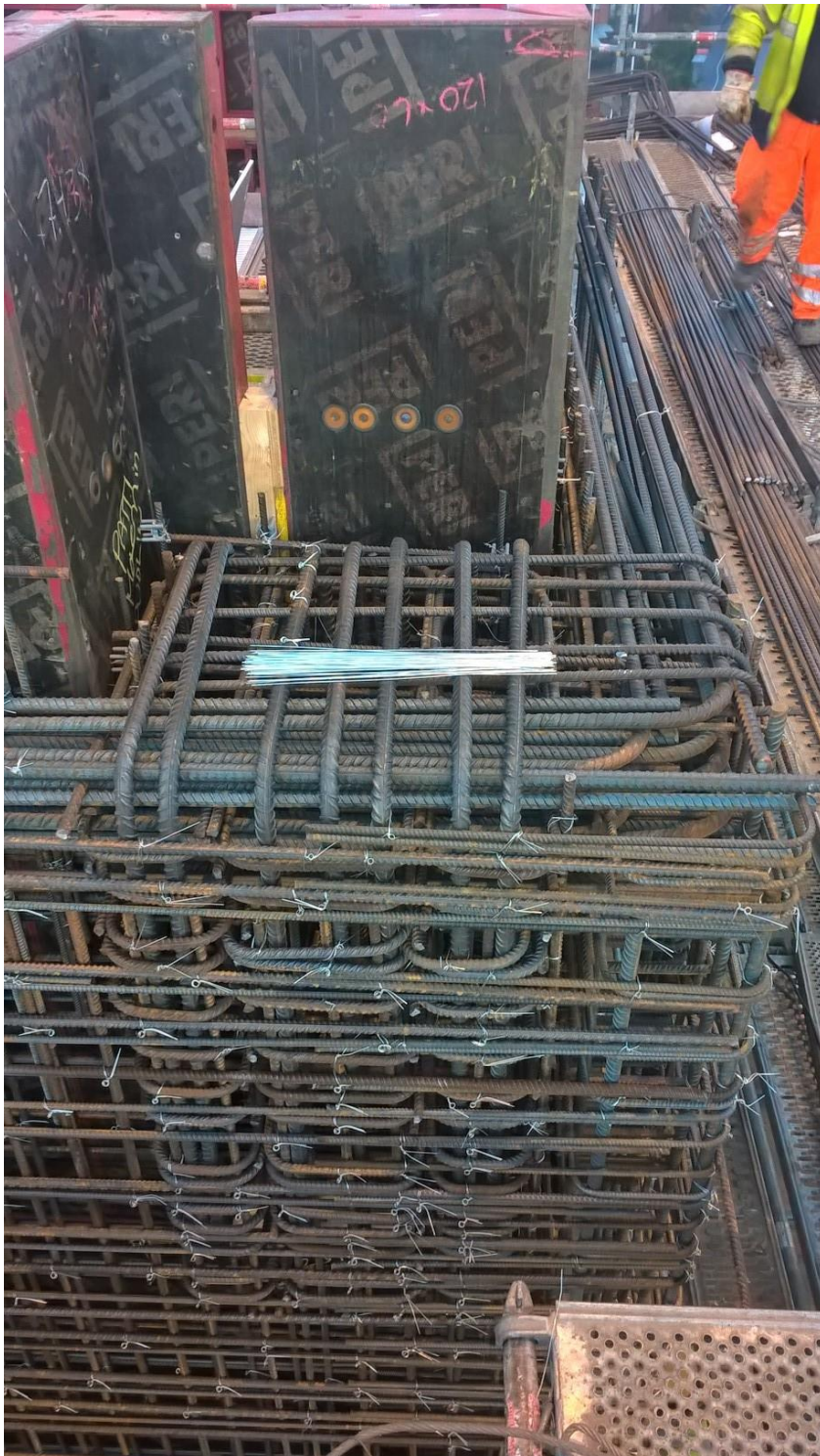


Figure 4. Installed reinforcement at construction site. (Sweco Rakennetekniikka Oy. 2017)



Figure 5. Dense reinforcement installed at construction site. (Sweco Rakennetekniikka Oy. 2017)

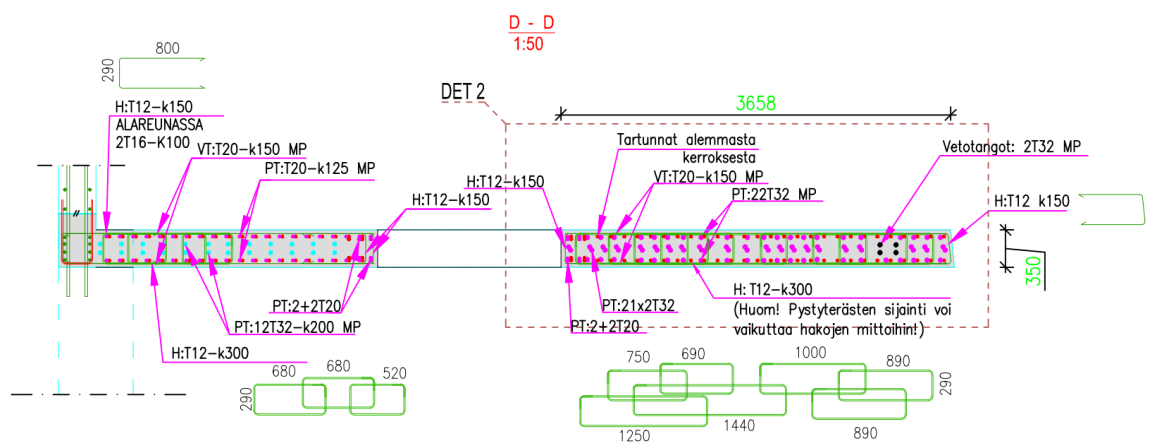


Figure 6. Drawing of densely reinforced concrete wall. (Sweco Rakennetekniikka Oy. 2017)

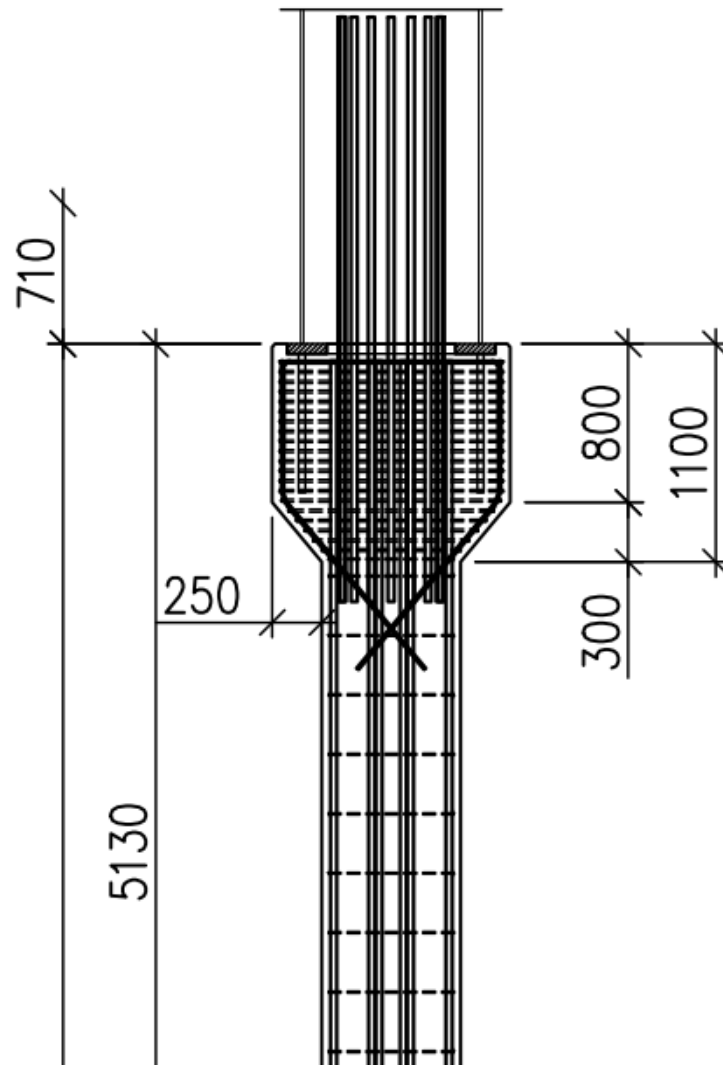


Figure 7. Connection of rectangular column and composite column. (Sweco Rakennetekniikka Oy. 2017)

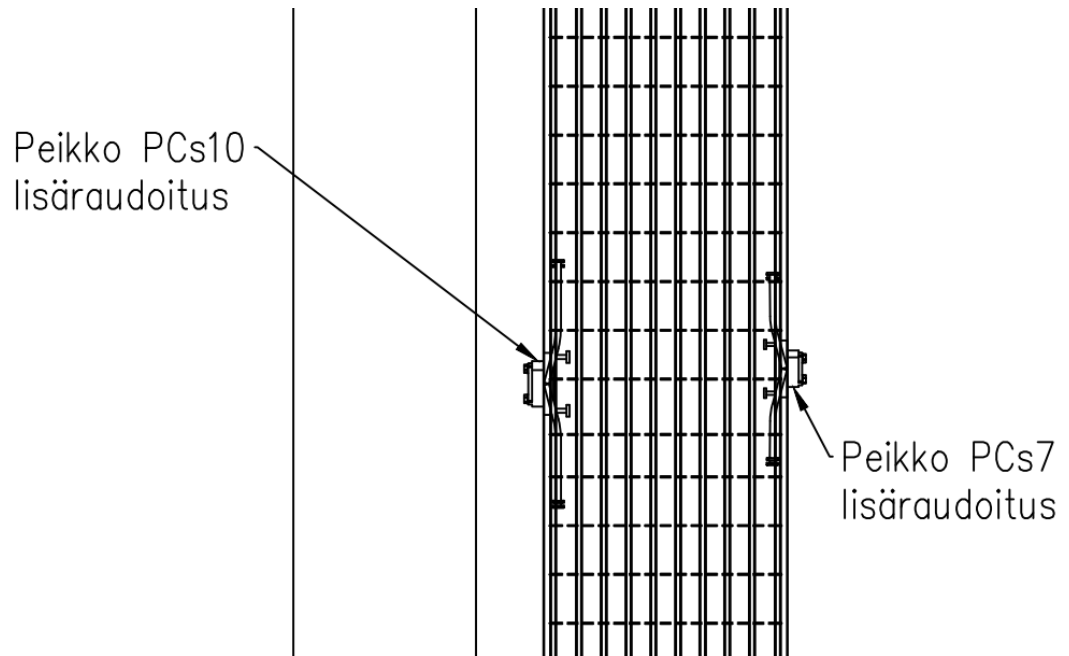


Figure 8. Additional reinforcement which is located in the same location as the main reinforcement. (Sweco Rakennetekniikka Oy. 2017)