OULUN YLIOPISTO

FACULTY OF TECHNOLOGY

COMPARISON AND OPTIMIZATION OF BUILT-UP ROOF AND PREFABRICATED ROOF ELEMENT

Mira Huttunen

DEGREE PROGRAMME OF CIVIL ENGINEERING

Master's thesis 2019

TIIVISTELMÄ OPINNÄYTETYÖSTÄ

Oulun yliopisto Teknillinen tiedekunta

Koulutusohjelma (kandidaatintyö, diplomityö) Rakennus- ja yhdyskuntatekniikan maisteriohjelma	Pääaineopintojen ala (lisensiaatintyö)
Tekijä Huttunen, Mira	Työn ohjaaja yliopistolla Kangaspuoskari, M. TkL

Työn nimi

Paikallarakennetun katon ja esivalmistetun kattoelementin vertailu sekä optimointi

Opintosuunta	Työn laji	Aika	Sivumäärä
Rakennesuunnittelu ja rakentamisteknologia	Diplomityö	Helmikuu 2019	70 + 16 s.

Tiivistelmä

Tämän diplomityön tavoitteena oli saada eristetyille esivalmistetuille kattoelementeille optimoitu ratkaisu eri liitostyypeissä eri jänneväleillä. Työssä vertailtiin perinteistä paikallarakennettua kattorakennetta esivalmistettuihin kattoelementteihin. Kummassakin tapauksessa on käytetty kantavia poimulevyjä, jotka on olleet kummassakin vertailurakenteessa tyypiltään samat. Tarkoituksena oli saada toimivin ja näin ollen vähiten terästä kuluttavin ratkaisu, jonka seurauksena saataisiin suositellut mitat esivalmistetulle kattoelementille annetuilla kuormilla laskelmien ja kustannuksien kautta.

Tässä työssä käytettiin Eurokoodin esittämiä laskelmia ohuen teräslevyn kestävyyden laskemiseksi. Käytössä oli myös ohjelma nimeltä Poimu, joka mitoittaa niin kattoelementtejä kuin poimulevy kattorakenteita. Kustannuksia laskettaessa on käytetty hyödyksi työn tilaajan antamia tietoja aiheesta sekä kyselty urakoitsijoilta heidän kokemuksiaan tämän tyyppisten elementtien asennuksesta.

Tämän työn tuloksena saatiin vertailukelpoista materiaalia yleistyviin kattoelementti -ratkaisuihin ja myös tietoa siitä, miten tässä työssä tutkitut kattorakenteet poikkeavat toisistaan ja kuinka paljon terästä kukin liitostyyppi kuluttaa verrattuna johonkin toiseen liitokseen tai jänneväliin. Tämän diplomityön tärkeimpinä tuloksina voidaan pitää saatuja vertailutaulukoita esivalmistetun kattoelementin ja paikallarakennetun kattorakenteen välillä. Näistä vertailuista saadaan selville parhain ratkaisu annetuille kuormille ja esitetylle rakennukselle. Poimu ohjelmasta saatiin ohuin mahdollinen teräspaksuus erijännevälille sekä myös eri rakenteiden mitoittava tekijä. Tärkeimpänä tuloksena pystyttiin myös asettamaan eristetylle esivalmistetulle kattoelementille markkinahinta.

Tuloksia voidaan käyttää tarkasteltaessa tämän tyyppisiä kattorakenteita. Tuloksia on myös mahdollista hyödyntää tulevissa projekteissa, joissa on käytössä saman tyyppinen poimulevy, näin ollen tulokset eivät ole yleisesti yleistettävissä, mutta toisaalta tulokset antavat hyvää tietoa siitä, kuinka paljon työssä verratut rakenteet poikkeavat toisistaan kestävyyden ja teräksen kulutuksen suhteen.

Muita tietoja

ABSTRACT FOR THESIS

University of Oulu Faculty of Technology

Degree Programme (Bachelor's Thesis, Master's Thesis) Master's Programme in Civil Engineering	Major Subject (Licentiate Thesis)
Author Huttunen, Mira	Thesis Supervisor Kangaspuoskari, M. Lic. Sc. (Tech.)

Title of Thesis

Comparison and optimization of built-up roof and prefabricated roof element

Major Subject Structural Engineering and Construction Tehcnology	Type of Thesis Master's Thesis	Submission Date February 2019	Number of Pages 70 + 16 p.

Abstract

The aim for this thesis was to get optimized solution for prefabricated roof elements with different joint types and span lengths. In this thesis built-up roof structure and prefabricated roof element were compared and these both structures were done by using load-bearing steel sheets. The purpose was to get the most functional solution for prefabricated roof elements that steel consumption is low. This would also give recommended measurements for elements from calculations and costs.

In this thesis basic calculations for thin steel sheets were used from Eurocodes. Program called Poimu were also used. Poimu can calculate different roof structures with steel sheets either it is element or built-up roof structure. When calculating costs, experiences of the company and contractors were used.

Because of this thesis, comparable material for prefabricated roof element solutions were obtained, as well as information on how these roof structures differ from each other and how much steel each joint type consumes comparing to another joint type or span length. The most important result of this thesis can be the tables where built-up roof structure and prefabricated roof element were compared. These comparisons reveal the best solution for the given loads and the measurements that were used in this example building. Poimu program gave the thinnest possible steel thickness for different span lengths with dimensioning factor of the structure. The most important result was the market price which were set for the prefabricated roof element.

The results from this thesis can be used when this kind of roof structures are examined. It is also possible to utilize the results for future projects where load-bearing steel sheets are used. This leads to that results from this thesis are not commonly generalizable but on the other hand, the results provide good information on how much these compared structures differ in terms of durability and the amount of steel.

Additional Information

ALKUSANAT

Diplomityön tarkoituksena oli saada tietoa kehitteillä oleville esivalmistetuille kattoelementeille. Diplomityön aloitin vuoden 2018 huhtikuussa töiden ohessa, myöhemmin työt vähenivät ja keskityin diplomityön tekoon. Diplomityötä tein helmikuuhun 2019 asti.

Oulun yliopistosta työtä ohjasi Matti Kangaspuoskari, jolle haluaisin antaa kiitokset hyvästä ohjauksesta. Kiitokset tahdon myös osoittaa Sweco Rakennetekniikan Teollisuusrakennesuunnittelun osastolle ja erityisesti Tuomo Tourulalle, joka toimi työn ohjaajana yrityksen puolelta ja jonka kautta tämän diplomityön sain tehtäväksi. Tahdon myös kiittää Ruukki Construction Oy:n Jyrki Kestiä ja Pekka Roiviota, haastavasta aiheesta ja hyvästä ohjauksesta työn tilaajan puolelta. Erityiskiitokset tahdon myös osoittaa perheelleni, ystäville sekä sukulaisille, kiitos kannustuksista ja saadusta tuesta. Kiitokset siskoilleni, Emmilotalle ja Annaroosalle.

Oulussa, 27.2.2019

Mira Huttunen

TABLE OF CONTENTS

APPENDICES:

SYMBOLS AND ABBREVIATIONS

A_{eff}	cross sections effective area
A_g	area of cross section
A_s	effective area
A_{sa}	effective area of web stiffener
A_{sb}	effective area of second stiffener of the web
$A_{s,red}$	reduced value of area for effective cross section
b_1	length between first stiffener’s effective area and center of gravity of web and flange
b_2	length between second stiffener’s effective area and center of gravity of web and flange
b_p	length of level width
E	modulus of elasticity
E_d	design value of effect of loads
$E_{d,dst}$	design value of stability weakening effect to the load
$E_{d,stb}$	design value of stability strengthening effect to the load
e_c	length between compressed web and effective cross-section
F	load
F_d	design value of load
F_k	characteristic value of load
f_u	ultimate tensile strength
f_y	yield strength
f_{ya}	average yield strength
f_{yb}	basic yield strength
h_w	height of the web
G	dead load
G_k	characteristic value of dead load
I_s	effective moment of inertia
K	spring stiffness
k	coefficient value for different forming types
k_w	coefficient value including partial rotational support of stiffened flange
l_b	buckling wavelength in compressed flange
$M_{c,Rd}$	bending strength of cross-section

$N_{t,Rd}$	tensile strength of cross-section
$N_{c,Rd}$	tensile strength in cross-section's axial compression
Q	live load
Q_d	design value of live load
Q_k	design value of individual live load
R_d	design value of strength
R_k	characteristic value of strength
$R_{w,Rd}$	web durability of cross-section
r	radius
s_a	the length of the first stiffener of the flange
s_w	oblique length of flange
t	thickness
u	deflection of structure
$V_{b,Rd}$	design value for lateral force
W_{eff}	effective bending resistance
W_{el}	elastic modulus
W_{pl}	plastic modulus
w	bending of the structure

α	coefficient
β_s	effective width factor in shear lag calculation
γ	partial safety factor in ULS or SLS
δ	deflection
$\bar{\lambda}_p$	modified slenderness
$\sigma_{com,Ed}$	compressive stress
$\sigma_{My,Ed}$	normal stress design value caused by $M_{y,Ed}$
$\sigma_{N,Ed}$	normal stress design value caused by N_{Ed}
$\sigma_{tot,Ed}$	design value of normal tension
$\sigma_{cr,s}$	buckling stress
$\tau_{tot,Ed}$	design value of torsional tension
χ_d	reduction factor
ψ	combining factor of live load

AISI	American Iron and Steel Institute
PIR	polyisocyanurate

PUR	polyurethane

In this thesis calculations are based on Eurocodes and Eurocode uses decimal point in calculations. This is the reason why decimal point is used in this thesis in formulas and in text.

1 INTRODUCTION

Money comes always into the question whether building new or renovating old. Nowadays people want to build more cost-effectively, ecofriendly and use light structures and those are one of the reasons for increased use of cold formed steel and thin steel structures (Teräsrakenneyhdistys ry 2014, p. 141). This has led to developing thin steel structures to answer more to these expectations.

Ruukki Construction Oy (further Ruukki) has multiple choices for calculating load-bearing sheets from where structural engineer can choose suitable solution for his/hers constructional project. Usually sheets are overlapped on the supports, so the bending of the sheet is not the decisive factor for its durability. When sheets are overlapping, the design criteria are moment and reaction of abutments. However, overlapping with prefabricated insulated sheets is limited. Prefabricated insulated sheet in this thesis means readymade roof structure which is built in factory and transferred to the construction site and put it into the place when needed. (Kesti 2018a.)

The aim of this master's thesis is to draw up prefabricated insulated roof element's optimal solution for structure and fastener system and to get recommendations for its measurements by calculations and examination of the costs. In this thesis we take a closer look to prefabricated insulated roof element and compare it with the built-up roof structure made with steel sheets.

This comparison is done by using different kinds of calculations, programs and possibly example company's own experiences. Dimensioning includes principle and solutions of connecting points. There are few industrial halls where example company have used prefabricated sheets insulated with polyisocyanurate foam (further PIR-foam). Comparison calculations are made by using different span lengths and load levels.

In this master's thesis we are focusing on what kind of material and technique is used to make sheets and why steel is the right material for doing them. Previous researches about this subject handle only how steel sheet works, its bending, fastenings and so on. There were no previous researches about prefabricated roof elements. In this thesis other roof structure materials, like timber, are outlined off. This thesis is only focusing on roof structures which are done with thin steel sheets. Steel frame or trusses are not dimensioned.

2 BUILT-UP ROOF STRUCTURE

2.1 Manufacturing steel sheets

Iron ore, which is quarried, is dressed and crushed. This iron ore is one of the main raw material in steel manufacturing. The other main raw material is recycled steel. Approximately 40 % of steel manufacturing is made from recycled steel material. Steel can be made from both materials. In dressing impurities are removed from iron ore. After dressing the material is sintered. If ore has strong iron content it can be used without dressing. Iron concentrate, carbonized coal and limestone are raw materials for crude iron. Purpose of using limestone is that it ties waste metal and covers melted material from oxidation. To get temperature high enough in chemical processes, carbonized coal is used. (Teräsrakenneyhdistys ry 2014 p. 13.)

Iron concentrate, carbonized coal and limestone are put into a blast furnace from its top, where materials are mixed in high temperature. To blast furnaces bottom is fed preheated air which creates carbon monoxide when cokes carbon reacts with fed air. Carbon monoxide creates iron from melted material in reduction. Steel which is molten sinks down and is put into a carrier and is moved to the next stage in manufacturing process. Next stage is sulphur removal from the melted steel. After this process steel can be made. Dross is a product coming out from blast furnace process and can be used in various materials after granulating. After this phase crude iron contains too much carbon for steel making the material very short. Extra carbon in crude iron must be removed before steel can be made. Usual amount of carbon in constructional steel is under 0,3 %. Extra carbon is removed from material by burning. This is done with a special converter by air blowing through the crude iron. Manufacturing flowchart is presented in figure 1, where is shown the processes how iron and steel are made, and which manufacturing type leads to certain products. (Teräsrakenneyhdistys ry 2014 pp. 13-15.)

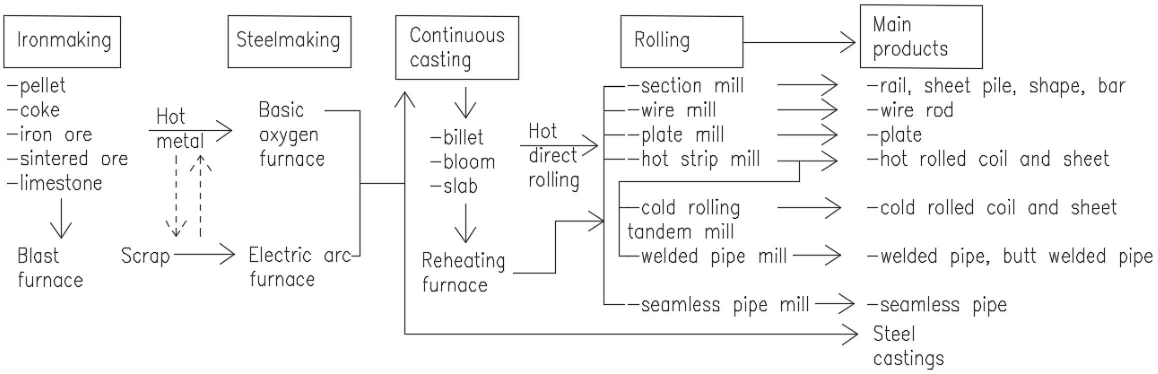


Figure 1. Steel manufacturing process (retell JFE 21st Century Foundation 2003).

The procedure is a little different when steel is made from recycled steel. When using recycled steel material, electric-arc furnace is used. In electric-arc furnace the material is melted and run into a special fire-resistant ladle car to ladle treatment. Needed alloying components are added in ladle treatment besides of temperature levelling. After this there is extra oxygen in melted steel which makes the material porous. When material is melted it is easier to get rid of this extra oxygen by compressing the steel with aluminum or silicon. Stainless steel is made from recycled steel materials and ferrochromium. (Teräsrakenneyhdistys ry 2014, p. 14.)

Cold rolled steel is more expensive than hot rolled, because cold rolled steel needs more work to get to the wanted shape. Cold rolled steel goes through various processes before and this makes cold rolled steel more durable for loads and it is more finished. Measurements of material are more accurate by cold rolling. The surface of hot rolled steel has wrinkles and other remains from hot rolling and its surface can be treated for example with sand blasting to get rid of these unwanted remains and to get smoother finish. (Reliance Foundry, 2017.)

Drawing test piece is loaded, in figure 2 situation A. This load is removed and removing creates a permanent transformation to the test piece. Removing point of the load is after crossing the yield point but before test pieces breaking. This point where load is removed is shown in figure 2 as a point 1, which continues in same angle than before. Same test piece is loaded again. In figure 2 is shown the connection between tension and transformation. This connection starts to transform test piece and continues in same angle as after the load removing acting like the load was never removed. This is how new cold formed steel is created with new physical properties. In situation A after point 1 highest pike steel's necking starts.

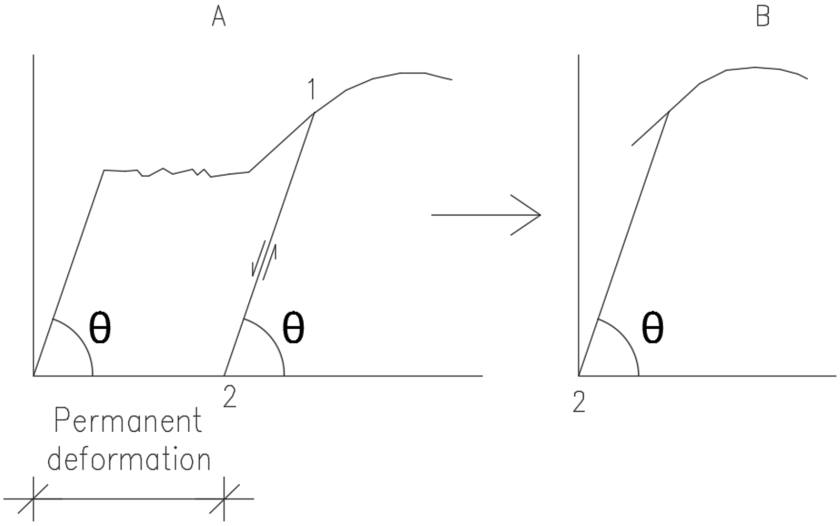


Figure 2. Cold forming steel (retell Teräsrakenneyhdistys ry 2014 p. 16).

Hot rolled steel is thicker than the cold rolled steel, because cold rolled steel goes through various processes. Cold rolled steel is worked from hot rolled steel in room temperature. Hot rolled roll goes through a process where it is transformed into the wanted shape. This process can be done by cold roll forming, trimming press or bending. Most common procedure is cold roll forming. In cold roll forming the steel have the right width and this steel plate goes through a machine where are different kinds of rolls that press the steel into a right shape. Machine starts rolling and working the steel plate from the middle. By starting in the middle, the extra steel material goes to the sides and can be used where the extra material is needed or cut out. For mass production, cold roll forming is cost-effective manufacturing process. Other redeeming features about cold roll forming is short turnaround time, quality and the lack of need of employments. Disadvantages with cold forming are the machines need of space, expensive investments and this working process can cause changes of strength properties of steel. Trimming press manufacturing process for the steel, is done either hydraulic or mechanical pressing. There needs to be more than one pressing when needed difficult structures. One pressing creates one trim. Trimming press is more suitable for short-run production because its turnaround time is slower than in cold roll forming. Usually trimming press is used to get for example C- or U-profiles. Bending is done with a machine made for it. Structured pieces are maximum 3 meters long. As in trimming press, sheets are cut to the right length before bending. (Teräsrakenneyhdistys ry 2014, pp. 24-25.)

In steel quality marking different letters and numbers mean different things. S stands for structural steel and after is told steel yield strengths minimum value which is taken from the thinnest place of the sheet. Yield strength minimum value is given in N/mm^2. Constructional steel sheet is usually made from S350 steel. Constructional steel sheets are purlins, thermoprofiles and load-bearing sheets. Other steel qualities are S220, S250, S280 and S320 and are used in corrugated steel sheets and surface layers of sandwich elements. For thin steel sheet, the minimum value of yield strength is not given. Therefore, qualified value for yield strength needs to be tested with every roll by tension test. (Teräsrakenneyhdistys ry 2014, pp. 22, 24.)

Steel quality can be affected for example by its shape, manufacturing process, microstructures and heat treatment. In AISI, which is American steel grade definer, there are three different steel qualities. These qualities are told based how much carbon the steel contains: high-carbon, medium carbon and low carbon steel. In Eurocodes the grouping is a little-bit different: alloy and non-alloy steel, stainless steel, tool-making steel, non-electric and electric sheets and steel strips. All these various steel grades make various steel constructions possible in different weather conditions. (Total Materia, 2018.)

2.2 Effects of cold working

Cold working has few improvements to the steel sheet. For example, 0,2 % strain strength is used to replace steels yield strength, elasticity and proportional limits have risen, viscosity have decreased and bending with time can increase. Cold forming effects to steels yield point by deleting it. In figure 3 is shown how cold working effects to the steel structure and its development of strength with stress-strain curve where is shown how steels strength affects to its extension (Teräsrakenneyhdistys ry 2014 p. 16).

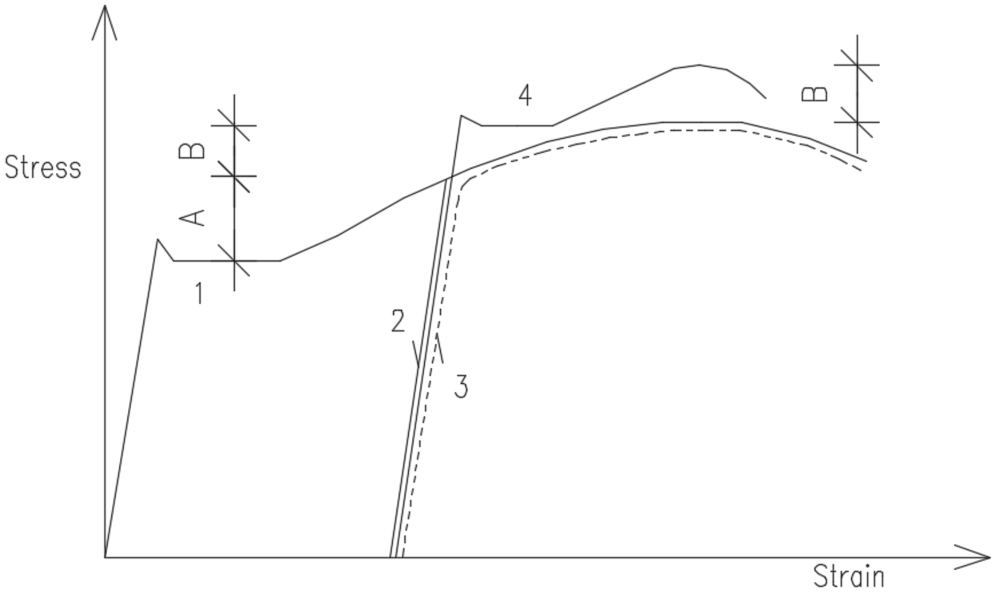


Figure 3. Stress-strain curve of steel (retell Teräsrakenneyhdistys ry 2014 p. 142).

In figure 3 is presented the behavior of steel sheet, where situation 1 shows the behavior of steel sheet when it is worked, situation 2 is when steel sheet is already worked, situation 3 is for steel sheet when it is loaded right after tension removing and situation 4 is when steel sheet is loaded after certain amount of time. In figure 3 is shown the increase of breaking strength, which is presented in the length of B in curve 4. Material's yield strength rises more than ultimate tensile strength, and this can be seen in figure 3. This causes in cold forming that strain hardening relation, between these two relations, decreases. (Teräsrakenneyhdistys ry 2014, p. 141.)

Material properties of steel can be different in the profile's corners than in the plain parts. This is because sheet's corners are more worked and pressed than the straight parts. Profile qualities of steel sheet depends on sheet's thickness, stress-strain strength and bending radius since sheets yield strength. Deformability decreases when sheet's yield strength and strain aging increases yield and tensile strength of the steel. High ability to hardening is caused by sheet's great connection between ultimate tensile strength and yield point. The greater the connection the greater the yield point strength is in worked steel sheet. Big transformations in point of inflection is caused by small connection between inner bending radius and sheet's thickness. The smaller the connection the bigger the yield point strength, when steel sheet is treated. Structure material's strength and deformability are influenced by the cold forming. To the cross section cold forming causes residual stress and geometrical informality. Steels made by cold forming are resistant to fire, moisture, corrosion and wear. For cold formed steel, the fabrication, transportation and installations are easy. (Teräsrakenneyhdistys ry 2014, pp. 141-142, Burnett 2014.)

2.3 Load-bearing sheet

Load-bearing sheets are thin steel structures, which can carry loads. Usually sheets are used as a roofing or load-bearing structure, insulated or not. Sheets can also be used in base or intermediate floor structure. One of the many uses of steel sheets is concrete structures mold frame. When using steel sheet as a casting mold, steel sheet is leaved to the structure to stiffen it. This structure works as a composite structure, steel can bare the tension and concrete the pressure (Väisänen 2007, p. 68). Load-bearing sheets are usually used in roof structures when needed a good load bearing capacity, but the structures thickness becomes an issue.

Another advantage for sheet is that it has a good strength in the level plane. Because sheets have a good strength in the level plane, sheets can also be used stiffen the frame of the construction. There are few different coatings for sheets and these coatings have a different influence on the structure. Usually sheets contain zinc and the normal amount of it is 275 g/m^2. This means 20 µm of zinc in both sides of the sheet which is a good base for paint coating. It is marked after steel quality, like S220 GD +Z275 and this marking means that steel sheet has coating of zinc that is 275 g/m^2. (Teräsrakenneyhdistys ry 2014, p. 24.)

According to standard SFS-EN 1993-1-3 the thickness of load-bearing steel sheet is between 0,35-15 mm and sheets which are used in this thesis the thickness range is 0,6-1,5 mm. For assembling the minimum thickness is 0,7 mm. By using 0,7 mm thickness, sheet can carry the load from assembling and servicing. Span length depends on used structure, loads, capacity of the used profile and limit state of bending. Structures are always calculated by Ruukki's own program called Poimu. Further in this thesis is told the basics behind the calculations of this program. Length of sheet structure is between 500-18300 mm. It is cheaper to use continuous structures and there can be one or multiple span lengths in sheet structure. (Kesti 2018b.)

Load-bearing sheets are the most fabricated steel products by cold-forming. Load-bearing sheet works effectively only when load is coming straight to the structure. When load is coming against vertical to the sheet, load-bearing capacity of the sheet is weak. It cannot hold the load when it is coming against vertical and this kind of load can cause buckling or braking of the sheet. Stiffness is minor in against vertical to sheet's profiling. In dimensioning steel sheet, beam model can be used. This means that when sheet is loaded, loads can be given by unit width and be measured with these values. Steel sheet behaves like a beam when it is loaded, and it can be measured as a beam. (Teräsrakenneyhdistys ry 2014, pp. 141, 143, 147.)

Normal solution for overlapping is half wave side overlapping. By using side overlapping, sheet's load-bearing capacity can be improved if the material thickening is not enough. This can be seen in the results of this thesis. Normal overlapping solution is used when sheets are fastened together. Normal and most commonly used overlapping is where overlapping is on connection points of the sheet. Loadbearing capacity can be doubled by using double sheeting, where two sheets are one upon another. Double sheeting means the material amount is doubled and this usually means double the price. In figure 4 the different types of side overlapping with load-bearing sheets are shown. The first one is normal solution, the second is one wave overlapping and the third is double sheeting. Sheets needs to be fastened in joints on supports. Screws has different place depending if the structure is insulated or not. Usually sheets are also overlapped on supports from the end of the sheet. (Ruukki 2015.)

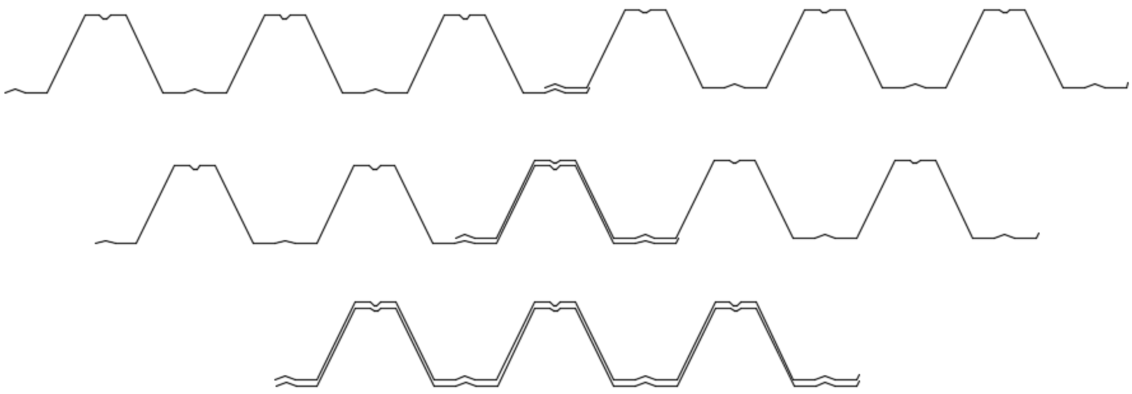


Figure 4. Side overlapping in steel sheets (retell Ruukki 2015, p. 6).

2.4 Introducing the built-up roof structure

Built-up roof structure is done in construction site piece by piece. First there is roof structure, such as steel framework, then steel sheets, after that if needed moisture barrier and on top of this there is insulation and on the top of all this there is chosen roofing. When installing sheets, needs the wider flange to put up, doing like this there is wider support width for insulation (Teräsrakenneyhdistys ry 2014, p. 147). If the sheet is installed wider flange up, it means that the edge of the steel sheet is on support. Narrower flange is used upwards when built-up roof structure is not insulated. In this solution sheet is used as a roofing/water barrier. When using insulated layers, insulation is assembled straight on top of the possible moisture barrier and this means that in fold is no insulation. Fold, where is no insulation, can function as a ventilating slot. Before water barrier can be assembled, there needs to be a hard-mineral wool insulation on top of the load-bearing sheet. The structure and all the layers in built-up roof are shown in figure 5. (Kesti 2018b.)

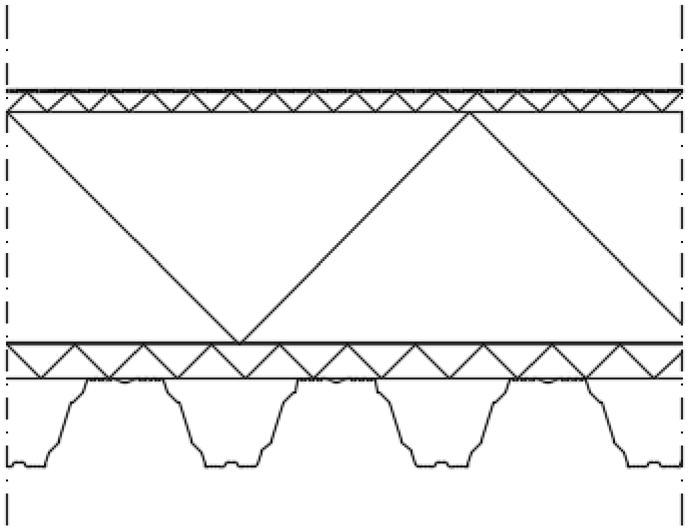


Figure 5. Built-up roof structure (retell Kesti 2018d).

3 PREFABRICATED ROOF ELEMENT

3.1 Introducing the prefabricated roof element

When manufacturing prefabricated roof elements, the wider flange is installed up, like in built-up roof structure. This means that there is more support for insulation, which is good in built-up roof structure. In elements the used PIR insulation gives the needed extra support and therefore this is not relevant when elements are used. (Kesti 2018b.)

When want to be sure that the roof structure is secured from weather conditions and other harmful effects, prefabricated elements can be used. Prefabricated element is faster to assembly, but it can also be faster to build than the usual built-up roof structure. This leads to short construction period and the building, which is under construction, can be in use quicker. Structure of prefabricated roof element which is under closer look in this thesis is presented in figure 6.

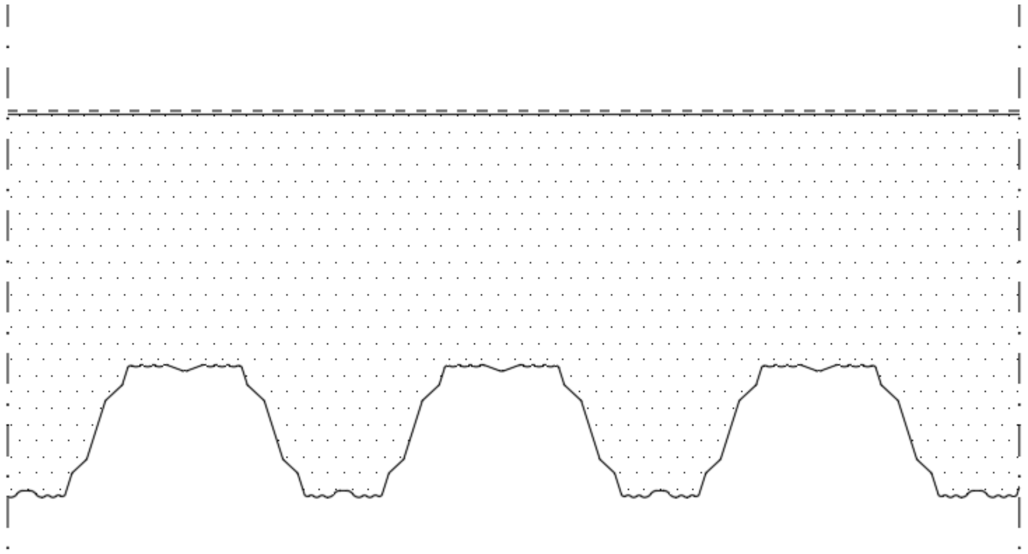


Figure 6. Prefabricated roof element (retell Kesti 2018d).

PIR-foam, polyisocyanurate, is used in prefabricated roof elements in this thesis. PIR-foam is polyurethane insulation foam and it has good qualities for its use. PIR-foam is durable, fire resistant and it does not form mold on the surface. Fire resistance in this foam is better than in PUR-foam, polyurethane. PIR-foam also has a good moisture performance. Difference between PIR-foam and PUR-foam is that PIR-foam has better fire resistance with fire rating D-s1, d0. Both foams can be assembled as a spray. (PU-eristeet, FinnFoam Oy.)

4 DESIGN OF LOAD-BEARING SHEETS

4.1 Measuring steel sheets

When dimensioning steel sheet structure, in ultimate limit state needs to be examined reaction resistance on supports and shear stability, combined effect between bending and reaction abutment in intermediate support and sheet's bending strength between supports. In serviceability limit state deflection and walkability of the sheet. (Teräsrakenneyhdistys ry 2014, p. 147.)

Yield point and ultimate tensile strengths can be used straight form the table 1 or values from product standard or strengths are measured by specific tests. Values in table 1 are given for thin steel sheet with zinc coating. Cold forming increases the steels yield point strength and can be defined from equation 5 or increased value can be noticed some other way in calculations. Rounded corners are taken under consideration by using approximate values. Stiffener lengths needs to be under certain values and stiffeners behave like a string and need to be measure under calculations with deformation. (SFS-EN 1993-1-3, pp. 15-18.)

Table 1. Values for basic yield point stress and ultimate tensile strength of zinc coated steel sheet (SFS-EN 1993-1-3, p. 14).

Steel quality	Basic yield point f_{yb} [N/mm^2]	Ultimate tensile strength f_u [N/mm^2]
S220 GD+Z	220	300
S250 GD+Z	250	330
S280 GD+Z	280	360
S320 GD+Z	320	390
S350 GD+Z	350	420

Steel products dimensioning in Finland is done according to Eurocodes. Eurocodes defines the theory of calculations and the right material for different conditions. SFS-EN 1990 defines the basic calculations and there are different standards for different construction products. Standard SFS-EN 1993-1-3 is used for thin steel sheets. In this thesis these two standards are under closer look. In EN 1990 is told the constructions durability, usability and safety and it has set a regulations and principles how to follow these. Structures need to hold the load which is planned for its whole planned life. Also, structures need to be so strong that it can bare the different effects that goes through within time. All possible damages need to be limited, material need to be suitable for designed structure and it needs to be strong enough.

In limit state analysis ultimate limit and serviceability limit states needs to be examined. Dimensioning situations are normal, temporary and accident/exceptional situation. Serviceability limit state contain situations that are harmful for people or the nature around. Serviceability limit state is for normal use of structure, appearance and user's comfortability. In serviceability limit state calculations contain dislocations, vibrations and damages, and these effects are so clear that they can be seen with bare eye. (SFS-EN 1990, pp. 52-53.)

In ultimate limit state are few stages which needs to be examined if they are coming into a question. These stages are strength (STR), statical equilibrium (EQU), geotechnical (GEO) and fatigue (FAT). Fatigue failure of the structure is calculated when examined the structure in fatigue. In statical equilibrium needs to take care that loads which weakens the structure balance $E_{d,dst}$ are smaller than loads which improves the structure balance $E_{d,stb}$. In strength and in geotechnical calculations needs to take care that effectiveness of loads E_d, is smaller than the design value of durability R_d. Calculating E_d, need to be calculated all loads that are influenced to the structure at the same time. This means different load combinations from which the unfavorable combination is chosen. Load combinations include dead load and either accident or live load. Combination for normal load is shown in formula

$$E_d = \Upsilon_{Sd} E\{\Upsilon_{g,j}, G_{k,j}; \Upsilon_P P; \Upsilon_{q,1} Q_{k,1};\ \Upsilon_{q,i} \psi_{0,i} Q_{k,i}\}, \quad j \geq 1; i > 1 \qquad (1)$$

where
Υ_{Sd} is partial factor for uncertainty,
E is the effect of the loads,
$\Upsilon_{G,j}$ is partial factor of dead load,
$G_{k,j}$ is characteristic value of dead load,
$\Upsilon_{Q,i}$ is partial factor of live load,
Q_k is characteristic value of live load and
ψ_0 is the combination coefficient of live load.

By using load combinations, it is easier to find which load combination has the worst effect to the structure. Worst load combination is used to calculate the strength of the structure towards this combination, if it holds the worst combination it can hold loads that are affecting to the structure. These safety coefficients, that are included in the calculations, makes sure that calculations are on safe side. (SFS-EN 1990, p. 80.)

Load combinations in ultimate limit state are calculated with formulas (2) and (3). Used load combination is the one which gives a bigger value. These formulas are used when finding the worst combination that can possibly happen

$$1{,}35K_{FI}\,G_{k,j,sup} + 1{,}15G_{k,j,inf} \tag{2}$$

$$1{,}15K_{FI}\,G_{k,jsup} + 0{,}9G_{k,j,inf} + 1{,}5K_{FI}Q_{k1} + 1{,}5K_{FI}\,\Sigma\psi_{0,i}Q_{k,i} \tag{3}$$

where K_{FI} is coefficient which is used in reliability of classification,
$G_{k,j,sup}$ is maximum characteristic value for dead load,
$G_{k,j,inf}$ is minimum characteristic value for dead load,
Q_{k1} is design value for decisive live load,
$\psi_{0,i}$ is combination coefficient and its values for different loads are told in table 2 and
$Q_{k,i}$ is design value for live load that is effecting at the same time than the decisive one.

Load combinations in serviceability limit state are calculated with partial factor for action γ_f value 1 if there are no different values recommended in other standards. (SFS-EN 1990, pp. 88-89.)

Loads are classified as accident (A), dead (G) and live load (Q). In serviceability limit state design values needs to fulfil a condition

$$E_d \leq C_d \tag{4}$$

where C_d is defined value of criteria for usability restrictive design value and
E_d is defined value for serviceability criteria for effecting loads.

Maximum value for roof sheeting deflection in serviceability limit state is L/200. Different requirements in other countries are told in National Annexes. (SFS-EN 1990, p. 82.)

Loads are defined by time, how long they are affecting to the structure. Accident load is the shortest, then is live load which lasts little bit longer and then there is dead load which is the longest and structures self-load is calculated as dead load. For example, wind and snow are calculated as a live load that are variable loads. Earthquake can be classified as an accident load. Loads need to be defined also based on its character for dynamic or static, influence place for solid or moving and for its cause to indirect or direct. In table 2 is shown the ψ factors for different kinds of buildings. However, values for ψ can be told in the National Annex. (SFS-EN 1990, pp. 52, 86.)

Table 2. Factor ψ in different buildings (retell SFS-EN 1990 p. 86).

Load	ψ0	ψ1	ψ2
Class A: households, Class B: office premises	0,7	0,5	0,3
Class C: leisure facilities, Class D: shopping space	0,7	0,7	0,6
Class E: storage space	1,0	0,9	0,8
Class F: trafficable space, vehicle weight under 30kN	0,7	0,7	0,6
Class G: trafficable space, vehicle weight minimum 30 kN and maximum 160 kN	0,7	0,5	0,3
Class H: roof	0	0	0
Snow load in buildings			
Finland, Sweden, Island and Norway	0,7	0,5	0,2
Other CEN countries located under 1000 m above the sea	0,7	0,5	0,2
Other CEN countries located under 1000 m above the sea	0,5	0,20	0
Wind load in building	0,6	0,2	0
Temperature inside building	0,6	0,5	0

4.2 Material properties

Used materials needs to be suitable for cold forming and welding, if these are the qualities that are wanted from the needed material. Constructional steel has different steel qualities when qualities are defined with different basic yield point (f_{yb}) and ultimate tensile strengths (f_u). These quality values can be read from tables and use these design values, or they can be defined with product standards or with specified experiments. When steel is cold formed its yield strength can be increased, value for average increased yield strength is calculated with formula

$$f_{ya} = f_{yb} + (f_u - f_{yb})\frac{knt^2}{A_g} \tag{5}$$

where k is coefficient, which value is 7 for cold roll forming and 5 for other forming types,

n is quantity of 90° corners in cross section, where inner bending radius is $r \leq 5t$,

t is steels thickness before cold forming and

A_g is area of cross section.

Increased yield strength f_{ya} needs to meet qualification

$$f_{ya} \leq \frac{(f_u + f_{yb})}{2} \ . \tag{6}$$

Increased yield strength can be considered by using A_{eff} as a same value as A_g and when defining A_{eff} value, f_{yb} is used instead of f_y. If steel sheet is exposed to temperature over 580°C for an hour, increased yield strength, which is caused by cold forming, cannot be used. This is after steel sheet is formed and getting heat treatment afterwards. (SFS EN1993-1-3, pp. 15-16.)

If the structure includes inner angles, structure needs to fulfil conditions

$$r \leq 5t \tag{7}$$

$$r \leq 0{,}10\ b_p. \tag{8}$$

Effect of structures rounded corners can be excluded from calculations if conditions above are satisfied. When calculating stiffness qualities, rounded corners need to be included. (SFS-EN 1993-1-3, p. 18.)

4.3 Profile with intermediate stiffeners

Structure can be stiffened with intermediate or edge stiffeners. Stiffeners can be either folds or slots in the structure. Stiffener behaves like a member which is pressed with a support which behaves like a spring. This member's stiffness depends on bending stiffness of vertical parts next to it. This spring stiffness K is calculated with formula

$$K=u/\delta \tag{9}$$

where u is unit load for the spring and
δ is stiffeners displacement for unit load.

In figure 6 is shown how the spring effects to the structure and how the calculation is formed. (SFS-EN 1993-1-3, p. 26.)

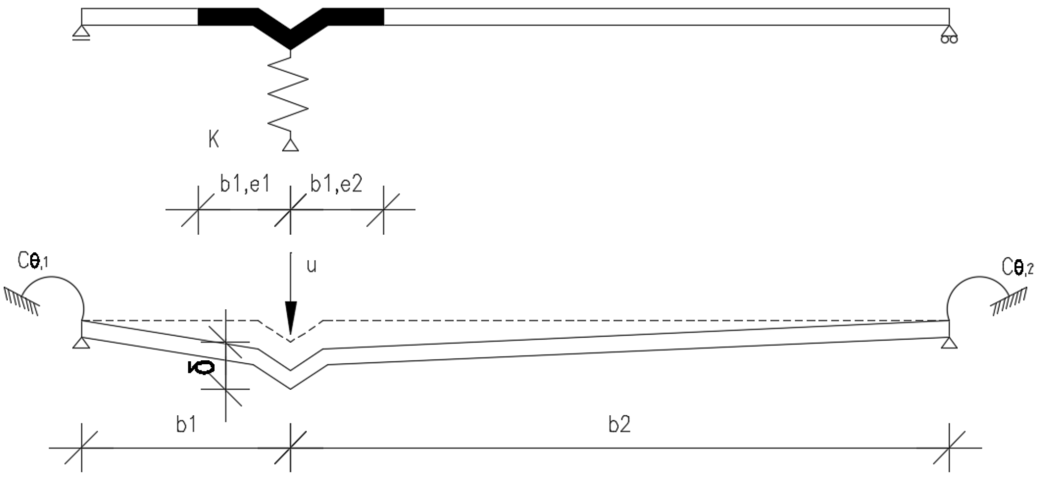


Figure 6. Stiffness of the spring (retell SFS-EN 1993-1-3 p. 26).

When stiffener is in between supports, displacement can be calculated with

$$\delta = \frac{ub_1{}^2b_2{}^2}{3(b_1+b_2)} * \frac{12(1-v^2)}{Et^3} \tag{10}$$

where b_1 is the distance between effective area's center of gravity for first edge stiffener of web and flange,
b_2 is the distance between effective area's center of gravity for second edge stiffener of web and flange,
v is Poisson's ratio,
E is modulus of elasticity and
t is the width of flange (SFS-EN 1993-1-3, p. 27).

Stiffener in structures vertical parts are calculated in three phases with formulas (11-13). In first phase is calculated stiffeners initial value of effective cross section with effective widths. In this calculation is assumed that formula (11) is valid

$$\sigma_{com,Ed} = \frac{f_{yb}}{\Upsilon_{M0}} \tag{11}$$

where $\sigma_{com,Ed}$ is compressive stress in stiffeners effective cross section,
f_{yb} is yield strength and
Υ_{M0} is partial factor.

In phase two is calculated reduction factor of distortion of buckling. Effective area of stiffener is calculated with

$$A_s = t(b_{1,e2}+b_{2,e1}+b_s)\ . \tag{12}$$

In figure 7 is shown what those parts of the formula mean, and which is the area where A_s is affecting.

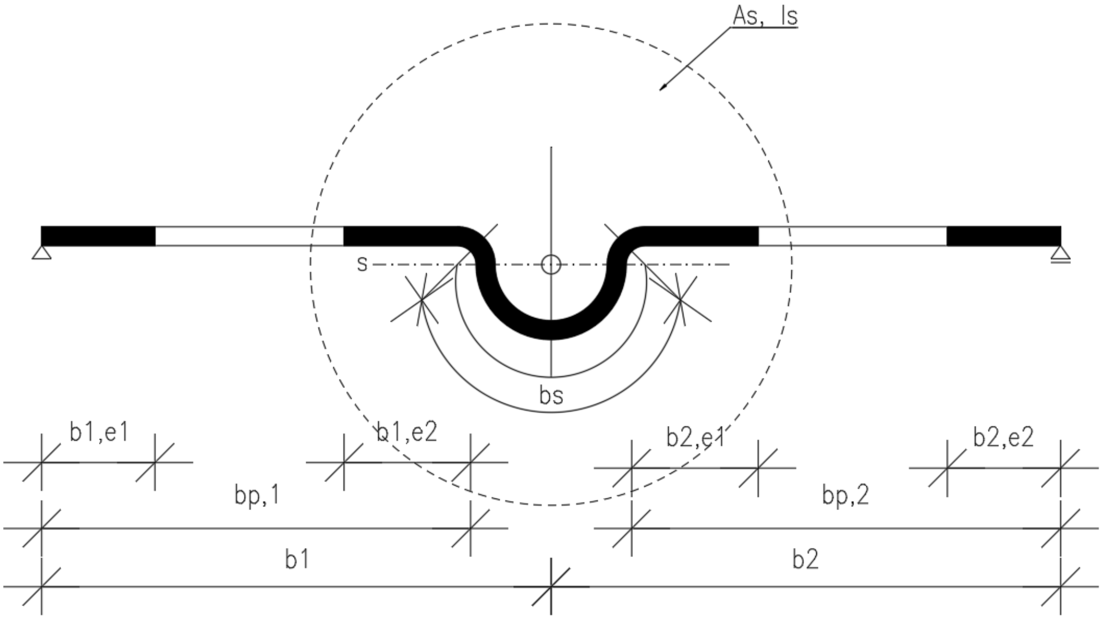


Figure 7. Stiffener dimensions in planar parts (retell SFS-EN 1993-1-3, p. 31).

Buckling stress of stiffener with modulus of elasticity is calculated with

$$\sigma_{cr,s}=\frac{2\sqrt{KEI_s}}{A_s} \tag{13}$$

where I_s is effective moment of inertia of stiffener.

In phase three is calculated stiffener's reduction factor with iteration, if needed corrective value. Stiffeners flexural buckling needs reduction factor for its defining. This reduction factor is χ_d and for defining this reduction factor we need modified slenderness $\bar{\lambda}_p$. Below are terms for reduction factor:

$$\chi_d = 1{,}0 \tag{14}$$

this value can be used when $\bar{\lambda}_p$ is smaller than 0,65,

$$\chi_d = 1{,}47-0{,}723\bar{\lambda}_p \tag{15}$$

this value can be used when $0{,}65 < \bar{\lambda}_p < 1{,}38$,

$$\chi_d = \frac{0{,}66}{\bar{\lambda}p} \tag{16}$$

and this value can be used when $\bar{\lambda}_p$ is bigger than 1,38.

Value for $\bar{\lambda}_p$ can be calculated with formula

$$\bar{\lambda}_p = \sqrt{f_{yb}/\sigma_{cr,s}}. \tag{17}$$

Reduction factor χ_d can be smaller than 1,0. When reduction factor is smaller than 1,0, reduced values needs to be used. Reduced modified slenderness is calculated with formula

$$\bar{\lambda}_{p,red} = \bar{\lambda}_p\sqrt{\chi_d}. \tag{18}$$

Area of effective cross section's reduced value is calculated

$$A_{s,red} = \chi_d A_s \frac{f_{yb}/\gamma_{M0}}{\sigma_{com,Ed}} \tag{19}$$

where $\sigma_{com,Ed}$ is effective cross section of centerline in stiffener with compressive stress.

In this formula above the area of effective cross section's reduced value $A_{s,red}$ needs to be smaller than stiffener's effective area A_s. (SFS-EN 1993-1-3, pp. 31-32.)

4.4 Trapezoidal shaped sheets with stiffeners

$A_{s,red}$ is used when flange is loaded with compression that is even. In figure 8 is shown the pieces that are included in effective cross section's area. These pieces are next to stiffener on its both sides.

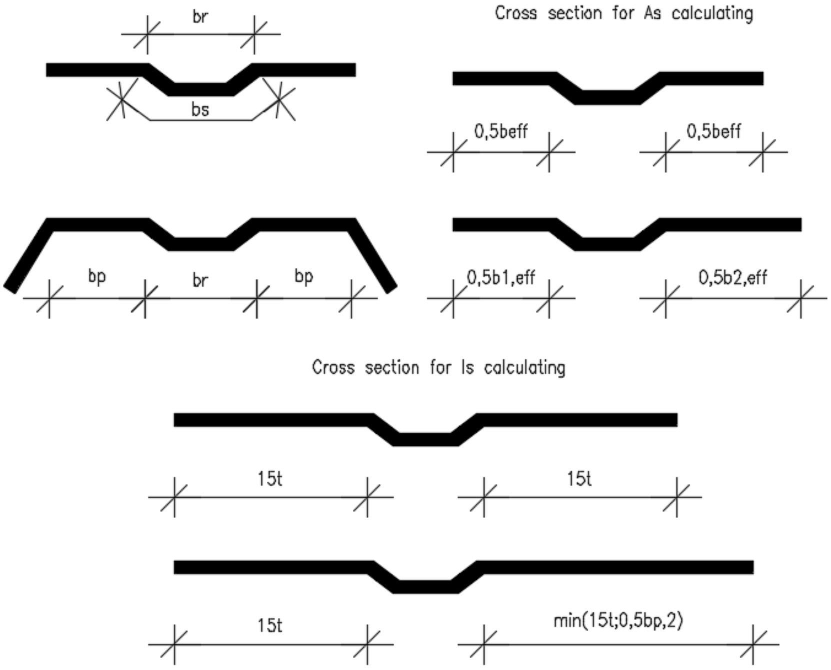


Figure 8. Flange with compressive load (retell SFS-EN 1993-1-3, p. 34).

If there is one stiffener in flange, critical buckling stress $\sigma_{cr,s}$ is calculated with formula

$$\sigma_{cr,s} = \frac{4{,}2\, k_w E}{A_s}\sqrt{\frac{I_s\, t^3}{4b_p^2(2b_p+3b_s)}} \tag{20}$$

where k_w is factor for partial rotational support of stiffened flange which is caused by webs and other parts that are next to flange. Value $k_w = 1$ is used when effective area of axial pressure is calculated. Parameters b_p and b_s are presented in figure 8.

When $l_b/s_w \geq 2$, factor k_w can be calculated with

$$k_w = k_{wo} \tag{21}$$

and when $l_b/s_w < 2$, factor k_w is calculated from formula

$$k_w = k_{wo} - (k_{wo} - 1)\left[\frac{2l_b}{s_w} - \left(\frac{l_b}{s_w}\right)^2\right] \tag{22}$$

where s_w is oblique length of flange and

l_b is compressed flanges buckling wave length.

If flange has one stiffener, values for l_b and k_{wo} can be calculated with

$$l_b = 3{,}07 \sqrt[4]{\frac{I_s b_p^2 (2b_p + 3b_s)}{t^3}} \tag{23}$$

$$k_{wo} = \sqrt{\frac{s_w + 2b_d}{s_w + 0{,}5b_d}} \tag{24}$$

where b_d can be defined with equation

$$b_d = 2b_p + b_s \tag{25}$$

where b_p and b_s are presented in figure 8. (SFS-EN 1993-1-3, p. 36.)

Shear lag -phenomenon

Shear lag-phenomenon does not need to consider, if clause below is fulfilled

$$b_0 < L_e / 50 \tag{26}$$

where b_0 is length either half of the supported edges level or the width of one edge supported plane part and

L_e is length between bending moment's zero points.

If the clause (26) does not fulfil, needs to calculate the effect of shear lag, where the effective widths are used. Effective width is calculated with formula

$$b_{eff} = \beta b_0 \tag{27}$$

where β is factor for effective width and its value can be calculated from table 3.

Table 3. Factor β for calculating effective width (retell SFS-EN 1993-1-5, p. 11).

κ	Value for β	Place under closer look
$\kappa \leq 0{,}02$	β=1,0	
$0{,}02 < \kappa \leq 0{,}7$	$\beta = \beta_1 = \frac{1}{1 + 6{,}4\kappa^2}$	positive moment
	$\beta = \beta_2 = \frac{1}{1 + 6{,}0\left(\kappa - \frac{1}{2500\kappa}\right) + 1{,}6\kappa^2}$	negative moment
> 0,7	$\beta = \beta_1 = \frac{1}{5{,}9\kappa}$	positive moment
	$\beta = \beta_2 = \frac{1}{8{,}6\kappa}$	negative moment
All values for κ	$\beta_0 = \left(\frac{0{,}55 + 0{,}025}{\kappa}\right)\beta_1$	end support
All values for κ	$\beta = \beta_2$	bracket

In table 3 value for κ is calculated from

$$\kappa = \alpha_0 b_0 / L_e \tag{28}$$

where α_0 is defined with formula

$$\alpha_0 = \sqrt{1 + \frac{A_{sl}}{b_0 t}}. \tag{29}$$

where A_{sl} is area of longitudinal stiffeners on the length of b_0.

Shear lag phenomenon in ultimate limit state can be defined with three different calculations. One calculation is combined effect of sheet's buckling and shear lag phenomenon, where A_{eff} is defined with

$$A_{eff} = A_{c,eff}\,\beta_{ult} \tag{30}$$

where $A_{c,eff}$ is effective area of pressed flange and

β_{ult} is effective width factor for shear lag phenomenon in ultimate limit state and it can be calculated with β in table 3, but the value for α_0 is replaced with α_{01}

$$\alpha_{01} = \sqrt{\frac{A_{c,eff}}{b_0 t_f}} \tag{31}$$

where t_f is the thickness of the flange.

In second calculation shear lag phenomenon is considered when ductility is allowed but limited. This can be calculated with

$$A_{eff} = A_{c,eff}\, \beta^{\kappa} \geq A_{c,eff}\, \beta. \tag{32}$$

The third option for calculating shear lag phenomenon is to calculate its effects with elasticity theory. (SFS-EN 1993-1-5, pp. 9, 13.)

4.5 Web with stiffeners

Sheet's webs can also have stiffeners and the maximum amount is two. Webs effective area is calculated differently, depending if there are one or two stiffeners. In figure 9 is told the measurements for stiffeners.

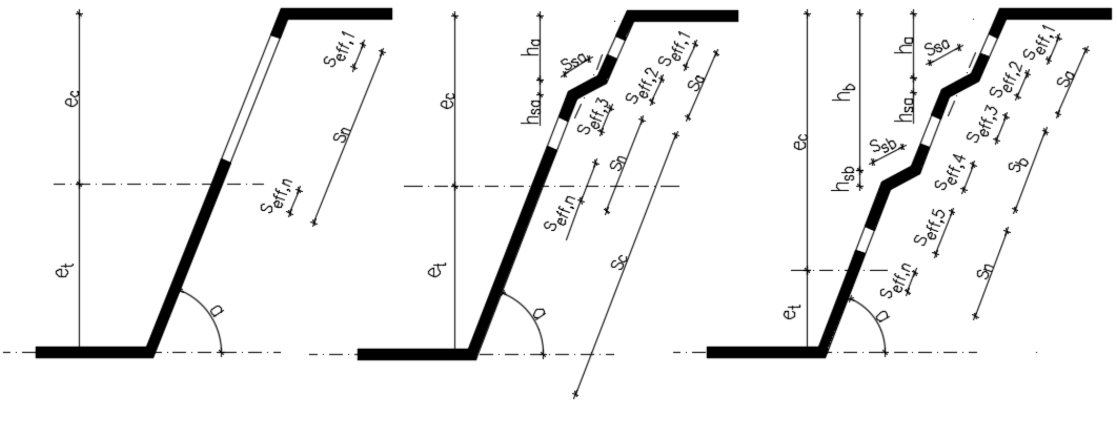


Figure 9. Sheet's webs effective area with supports (retell SFS-EN 1993-1-3, p. 37).

If sheets web has one stiffener it is calculated with formula

$$A_{sa} = t\,(s_{eff,2}+s_{eff,3}+s_{sa}) \tag{33}$$

and when sheet has two stiffeners, the other stiffener is calculated by using formula

$$A_{sb} = t\,(s_{eff,4} + s_{eff,5} + s_{sb}) \tag{34}$$

where all the parameters are shown in figure 9. If sheet's flange and webs are effective, effective length for $s_{eff,0}$ is defined with equation

$$s_{eff,0} = 0{,}76t\,\sqrt{E/(\gamma_{M0}\sigma_{com,Ed})} \tag{35}$$

where $\sigma_{com,Ed} = f_{yb} / \gamma_{M0}$.

There can be sheets which webs are not effective. In this situation all the lengths that are shown in figure 9 needs to be calculated with formulas below

$$s_{eff,1} = s_{eff,0} \tag{36}$$

$$s_{eff,2} = (1+0{,}5h_a / e_c)\ s_{eff,0} \tag{37}$$

$$s_{eff,3} = [1+0{,}5(h_a + h_{as})/ e_c]\ s_{eff,0} \tag{38}$$

$$s_{eff,4} = (1+0{,}5h_b / e_c)\ s_{eff,0} \tag{39}$$

$$s_{eff,5} = [1+0{,}5(h_b + h_{sb})/ e_c]\ s_{eff,0} \tag{40}$$

$$s_{eff,n} = 1{,}5\ s_{eff,0} \tag{41}$$

where e_c is the length between centerlines of compressed web and effective cross section.

Equations before are used if the cross section is not completely effective. When the web is completely effective, and it does not have stiffeners, it fulfills clause

$$s_{eff,1} + s_{eff,n} \geq s_n \tag{42}$$

and lengths for $s_{eff,1}$ and $s_{eff,n}$ are defined with calculations

$$s_{eff,1} = 0{,}4s_n \tag{43}$$

$$s_{eff,n} = 0{,}6s_n. \tag{44}$$

When the web is completely effective, and it has stiffeners and $s_{eff,1}+s_{eff,2} \geq s_a$, lengths for $s_{eff,1}$ and $s_{eff,2}$ are calculated with using formulas

$$s_{eff,1} = \frac{s_a}{2+0,5h_a/e_c} \tag{45}$$

$$s_{eff,2} = s_a \frac{(1+\frac{0,5h_a}{e_c})}{2+0,5h_a/e_c}. \tag{46}$$

When the web is fully effective and has one stiffener and $s_{eff,3} + s_{eff,n} \geq s_n$, lengths for $s_{eff,3}$ and $s_{eff,n}$

$$s_{eff,3} = s_n \frac{[1+0,5(h_a+h_{sa})/e_c]}{2,5+0,5(h_a+h_{sa})/e_c} \tag{47}$$

$$s_{eff,n} = \frac{1,5s_n}{2,5+0,5(h_a+h_{sa})/e_c}. \tag{48}$$

When web is completely effective, and it has two stiffeners and $s_{eff,3} + s_{eff,4} \geq s_b$, lengths for $s_{eff,3}$ and $s_{eff,4}$ are defined with calculations

$$s_{eff,3} = s_b \frac{1+0,5(h_a+h_{sa})/e_c}{2+0,5(h_a+h_{sa}+h_b)/e_c} \tag{49}$$

$$s_{eff,4} = s_b \frac{1+0,5h_b/e_c}{2+0,5(h_a+h_{sa}+h_b)/e_c}. \tag{50}$$

Web is fully effective and $s_{eff,5} + s_{eff,n} \geq s_n$

$$s_{eff,5} = s_n \frac{1+0,5(h_b+h_{sb})/e_c}{2,5+0,5(h_b+h_{sb})/e_c} \tag{51}$$

$$s_{eff,n} = s_n \frac{1,5s_n}{2,5+0,5(h_b+h_{sb})/e_c} \quad . \tag{52}$$

Critical tension $\sigma_{cr,sa}$ is defined with formula (53), when web has two or one stiffeners that is closer to compressed flange

$$\sigma_{cr,sa} = \frac{1,05k_fE\sqrt{I_st^3s_1}}{A_{sa}s_a(s_1-s_2)} \tag{53}$$

where s_1 is calculated with formula (54) when there is only one stiffener in web

$$s_l = 0{,}9(s_a+s_{sa}+s_c) \tag{54}$$

and with formula (55) when s_l is closer to compressed flange with two stiffeners

$$s_l = s_a + s_{sa} + s_b + 0{,}5(s_{sb}+s_c) \tag{55}$$

where s_2 is calculated with formula

$$s_2 = s_l - s_a - 0{,}5s_{sa} \tag{56}$$

where k_f is factor that tells partial. $k_f = 1$ is used when want to be sure and this means that the connection is hinged support. (SFS-EN 1993-1-3, pp. 37-39.)

Sheets that have stiffeners in flange and in web needs to consider these stiffeners co-author. When calculating flexural buckling, modified critical tension $\sigma_{cr,mod}$ needs to be used. Modified critical tension $\sigma_{cr,mod}$ is calculated with

$$\sigma_{cr,mod} = \frac{\sigma_{cr,s}}{\sqrt[4]{1+[\beta_s \frac{\sigma_{cr,s}}{\sigma_{cr,sa}}]^4}} \tag{57}$$

where β_s is for profile, that is bended and is calculated with formula (58). If the profile is compressed with axial force, the value for β_s is 1 (SFS EN-1993-1-3, p. 40)

$$\beta_s = 1-(h_a + 0{,}5h_{ha})/e_c. \tag{58}$$

Calculations in ultimate limit state (ULS)

Stiffness of the sheet and durability can be influenced by local and distortional buckling and these need to consider with effective cross-section. Design value for uniform tension of cross-section's tensile strength, $N_{t,Rd}$ is calculated with formula

$$N_{t,Rd} = \frac{f_{ya}A_g}{\gamma_{M0}} \tag{59}$$

where f_{ya} is average yield strength and
A_g is gross area of cross-section.

Value for uniform tension of cross-section's tensile strength $N_{t,Rd}$ needs to be smaller than tensile strength with connections $F_{n,Rd}$. If $A_{eff} < A_g$, cross-sections that are loaded with axial compression are defined with calculation

$$N_{c,Rd} = \frac{f_{yb} A_{eff}}{\gamma_{M0}} \tag{60}$$

and if effective area of cross-section $A_{eff} = A_g$, axial compression of cross-section is calculated with

$$N_{c,Rd} = \frac{A_g [f_{yb} + (f_{ya} - f_{yb}) 4 \left(1 - \frac{\bar{\lambda}_e}{\bar{\lambda}_{e0}}\right)]}{\gamma_{M0}}. \tag{61}$$

Value for $N_{c,Rd}$ cannot be more than clause

$$N_{c,Rd} \leq \frac{A_g f_{ya}}{\gamma_{M0}} \tag{62}$$

where A_{eff} is cross-section's effective area, when calculating the value f_{yb} is used,
f_{yb} is yield strength of steel,
without stiffeners $\bar{\lambda}_e = \bar{\lambda}_p$ and $\bar{\lambda}_p$ is calculated with formula (65) and $\bar{\lambda}_{e0} = 0{,}673$,
with stiffeners $\bar{\lambda}_e = \bar{\lambda}_d$ and $\bar{\lambda}_d$ is calculated with formula (17) and $\bar{\lambda}_{e0} = 0{,}65$.
(SFS-EN 1993-1-3, pp. 41-42.)

If the cross section of sheet does not have stiffeners and the structure is uniformly loaded, compressed effective area is calculated with formula

$$A_{c,eff} = \rho A_c \tag{63}$$

where ρ is reduction factor that includes buckling of sheet.

When sheet structure is supported on both sides, reduction factor ρ is 1 when $\bar{\lambda}_p \leq 0{,}5+\sqrt{0{,}085-0{,}055\psi}$ and when $\bar{\lambda}_p > 0{,}5+\sqrt{0{,}085-0{,}055\psi}$ ρ is calculated with formula

$$\rho = \frac{\bar{\lambda}_p - 0{,}055(3+\psi)}{\bar{\lambda}_p^2} \leq 1 \tag{64}$$

where $\bar{\lambda}_p$ is calculated with formula

$$\bar{\lambda}_p = \sqrt{\frac{f_y}{\sigma_{cr}}} = \frac{\bar{b}/t}{28{,}4\varepsilon\sqrt{k_\sigma}} \tag{65}$$

where ψ is stress ratio and its value is 1,0 when sheet structure has supports on both sides,

$\bar{b}$ value depends on calculation situation, in this thesis $\bar{b}$ can mean b_w as a flange length or b which means the length of structure with two supports of planar part,

k_σ is buckling coefficient between stress ratio ψ and boundary condition,

t is thickness of the sheet,

σ_{cr} buckling stress of the sheet and

$$\varepsilon = \sqrt{\frac{235}{f_y\,[\frac{N}{mm2}]}}.$$ (SFS-EN 1993-1-5, p. 16.)

If the value of effective bending resistance W_{eff} is $W_{eff} < W_{el}$, $M_{c,Rd}$ is value for bending strength of cross-section and it is defined with calculation

$$M_{c,Rd} = \frac{f_{yb} W_{eff}}{\gamma_{M0}}. \tag{66}$$

When the value of effective bending resistance W_{eff} is same than W_{el}, $M_{c,Rd}$ is calculated from

$$M_{c,Rd} = \frac{f_{yb}[W_{el} + (W_{pl} - W_{el})4\left(1 - \frac{\bar{\lambda}_{emax}}{\bar{\lambda}_{e0}}\right)]}{\gamma_{M0}} \tag{67}$$

where $\bar{\lambda}_{emax}$ is maximum value for ratio $\bar{\lambda}_e/\bar{\lambda}_{e0}$,

$\bar{\lambda}_e = \bar{\lambda}_p$ and $\bar{\lambda}_{e0} = 0{,}5 + \sqrt{0{,}25 - 0{,}055(3 + \psi)}$ for supports in both sides and

$\bar{\lambda}_e = \bar{\lambda}_p$ and $\bar{\lambda}_{e0} = 0{,}673$ for structures with outstand.

Value for $M_{c,Rd}$ from calculation (67) cannot be more than maximum value for $M_{c,Rd}$ which is calculated from (SFS EN-1993-1-3, p. 43.)

$$M_{c,Rd} = \frac{f_{yb} W_{pl}}{\gamma_{M0}}. \tag{68}$$

Design value for lateral force $V_{b,Rd}$ is calculated

$$V_{b,Rd} = \frac{\frac{h_w}{\sin\theta} t f_{bv}}{\gamma_{M0}} \tag{69}$$

where h_w is height of the web and
θ is angle between web and flange.

Different values for buckling length of shear, f_{by}, with modified slenderness are presented in table 4.

Table 4. Strength of buckling length f_{bv} (retell SFS-EN 1993-1-3, p. 45).

Modified slenderness	$\bar{\lambda}_w \leq 0{,}83$	$0{,}83 < \bar{\lambda}_w < 1{,}4$	$\bar{\lambda}_w \geq 1{,}4$
Web without stiffeners	$0{,}58 f_{yb}$	$0{,}48 f_{yb} / \bar{\lambda}_w$	$0{,}67 f_{yb} / \bar{\lambda}^2_w$
Web with stiffeners	$0{,}58 f_{yb}$	$0{,}48 f_{yb} / \bar{\lambda}_w$	$0{,}48 f_{yb} / \bar{\lambda}_w$

Modified slenderness, when structure does not have stiffeners, is calculated with formula

$$\bar{\lambda}_w = 0{,}346 \frac{s_w}{t} \sqrt{\frac{f_{yb}}{E}} \tag{70}$$

where s_w is length of web's oblique part from corner to corner in corners centerline.

When structure have stiffeners, modified slenderness is calculated with

$$\bar{\lambda}_w = 0{,}346\frac{s_d}{t}\sqrt{\frac{5{,}34 f_{yb}}{k_\tau E}} \tag{71}$$

where $\bar{\lambda}_w \geq 0{,}346\frac{s_p}{t}\sqrt{\frac{f_{yb}}{E}}$,

$k_\tau = 5{,}34 + \frac{2{,}10}{t}\left(\frac{\Sigma I_s}{s_d}\right)$,

s_d, s_p and s_w are presented in figure 10. (SFS-EN 1993-1-3, p. 45.)

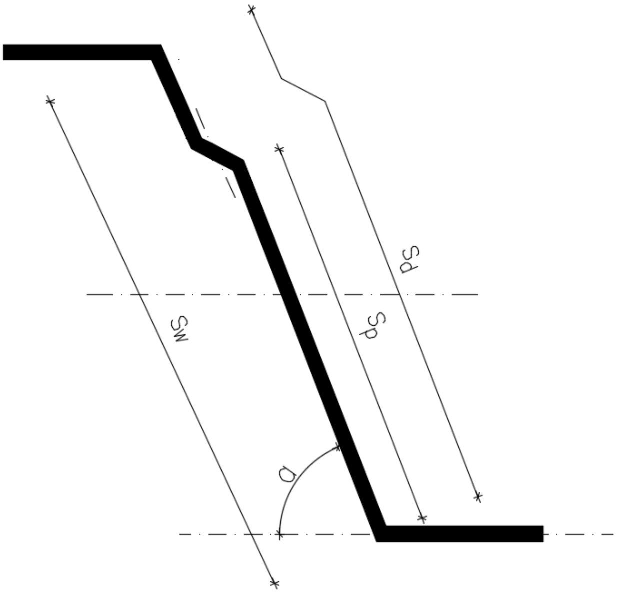


Figure 10. Web with one stiffener (retell SFS-EN 1993-1-3, p. 46).

Torsional moment is considered when loads are eccentric towards the cross-section. When structure is affected by torsional effects, it needs to fill up regulations below

$$\sigma_{tot,Ed} \leq \frac{f_{ya}}{\gamma_{M0}} \tag{72}$$

$$\tau_{tot,Ed} \leq \frac{f_{ya}/\sqrt{3}}{\gamma_{M0}} \tag{73}$$

$$\sqrt{{\sigma_{tot,Ed}}^2 + 3{\tau_{tot,Ed}}^2} \leq 1{,}1\frac{f_{ya}}{\gamma_{M0}} \tag{74}$$

where $\sigma_{tot,Ed}$ is design value for normal tension which is calculated with cross-section that is effective and

$\tau_{tot,Ed}$ is design value for torsional tension which is calculated with gross cross-section. (SFS EN-1993-1-3, p. 46.)

Values for $\sigma_{tot,Ed}$ and $\tau_{tot,Ed}$ are calculated with formulas

$$\sigma_{tot,Ed} = \sigma_{N,Ed} + \sigma_{My,Ed} + \sigma_{Mz,Ed} + \sigma_{w,Ed} \tag{75}$$

$$\tau_{tot,Ed} = \tau_{Vy,Ed} + \tau_{Vz,Ed} + \tau_{t,Ed} + \tau_{w,Ed} \tag{76}$$

where $\sigma_{N,Ed}$ is design value for normal stress which is caused by N_{Ed} axial,

$\sigma_{My,Ed}$ is design value for normal stress which $M_{y,Ed}$ bending moment is causing,

$\sigma_{Mz,Ed}$ is design value for normal stress which $M_{z,Ed}$ bending moment is causing,

$\sigma_{w,Ed}$ is design value for normal stress which is caused by obstructed torsion,

$\tau_{Vy,Ed}$ is design value for shearing stress which $V_{y,Ed}$ cross shear force is causing,

$\tau_{Vz,Ed}$ is design value for shearing stress which $V_{z,Ed}$ cross shear force is causing,

$\tau_{t,Ed}$ is design value for shearing stress which is caused by free regular torsion and

$\tau_{w,Ed}$ is design value for shearing stress which obstructed torsion is causing (SFS EN-1993-1-3, p. 46).

If structure is loaded with reaction of abutments or some other local cross force through flanges, for the structure to hold it needs to fill up regulation

$$F_{Ed} \leq R_{w,Rd}. \tag{77}$$

Cross-section’s web durability is calculated with formula

$$R_{w,Rd} = \alpha t^2 \sqrt{f_{yb} E}\left(1 - 0{,}1\sqrt{\frac{r}{t}}\right)[0{,}5 + \sqrt{\frac{0{,}02 l_a}{t}}](2{,}4 + \left(\frac{\phi}{90}\right)^2)/\gamma_{M1} \tag{78}$$

where α is coefficient, which is set by classes: for sheets in class 1 $\alpha = 0{,}075$ and in class 2 $\alpha = 0{,}15$ and

l_a is effective force length.

Formula (78) can be used when conditions of clauses below are kept

$$\frac{r}{t} \leq 10 \tag{79}$$

$$\frac{h_w}{t} \leq 200\sin\phi \tag{80}$$

$$45° \leq \phi \leq 90° \tag{81}$$

where r is radius for internal corners,

h_w is length of web in center lines and

ϕ is angle between web and flange. (SFS EN-1993-1-3, pp. 50-51.)

Clause (82) is used, when cross section is loaded with combined bending moments $M_{y,Ed}$ $M_{z,Ed}$ and axial tension N_{Ed}

$$\frac{N_{Ed}}{N_{t,Rd}} + \frac{M_{y,Ed}}{M_{cy,Rd,ten}} + \frac{M_{z,Ed}}{M_{cz,Rd,ten}} \leq 1 \tag{82}$$

where $N_{t,Rd}$ is design value for equipartition tension for cross section's tensile strength,

$M_{cy,Rd,ten}$ is design value for bending strength with biggest tensile strength when bending moment is only effecting axis y-y and

$M_{cz,Rd,ten}$ is design value for bending strength with biggest tensile strength when bending moment is only effecting axis z-z.

When $M_{cy,Rd,com} \leq M_{cy,Rd,ten}$ or $M_{cz,Rd,com} \leq M_{cz,Rd,ten}$, needs clause to be valid (SFS-EN 1993-1-3, p. 53)

$$\frac{M_{y,Ed}}{M_{cy,Rd,com}} + \frac{M_{z,Ed}}{M_{cz,Rd,com}} - \frac{N_{Ed}}{N_{t,Rd}} \leq 1. \tag{83}$$

Clause below is used, when cross section is loaded with combined bending moments $M_{y,Ed}$ and $M_{z,Ed}$ and axial compressive force N_{Ed}

$$\frac{N_{Ed}}{N_{c,Rd}} + \frac{M_{y,Ed}+\Delta M_{y,Ed}}{M_{cy,Rd,com}} + \frac{M_{z,Ed}+\Delta M_{z,Ed}}{M_{cz,Rd,com}} \leq 1. \tag{84}$$

Additional moments, which are caused from movement of center of gravity, are defined with formulas

$$\Delta M_{y,Ed} = N_{Ed}\, e_{Ny} \tag{85}$$

$$\Delta M_{z,Ed} = N_{Ed}\, e_{Nz} \tag{86}$$

where e_{Ny} and e_{Nz} are lengths of displacements for center of gravity in y- and z-axis.

When cross section is loaded with combined transversal force F_{Ed} and bending moment M_{Ed}, clauses need to be valid (SFS EN-1993-1-3, pp. 54-55)

$$\frac{M_{Ed}}{M_{c,Rd}} \leq 1 \tag{87}$$

$$\frac{F_{Ed}}{R_{w,Rd}} \leq 1 \tag{88}$$

$$\frac{M_{Ed}}{M_{c,Rd}} + \frac{F_{Ed}}{R_{w,Rd}} \leq 1{,}25. \tag{89}$$

Calculations in serviceability limit state (SLS)

In serviceability state needs to examine the deflection from the load to the span structure. Deflection needs to be smaller than the deflection of the span, which is in this thesis L/200. If ULS is calculated by using theory of plasticity, in SLS moments and forces can appear as rearranged if so these need to take under closer look. Limits of deflections, vertical or horizontal, are usually set before each construction project. (SFS EN-1993-1-3, p. 60, SFS-EN 1993-1-1, p. 81.)

5 COMPARISON AND OPTIMIZING

In this thesis is compared prefabricated roof element and common built-up roof structure done piece by piece with steel sheets.

5.1 Structural comparison

Structural comparison is done between prefabricated roof element and built-up roof structure. The structure of prefabricated roof element and built-up roof structure are shown in figure 11. Both structures have three main layers which are trapezoidal steel sheet, insulation and roof material. In built-up roof there are also these layers, but it needs a moisture barrier between insulation layers. Biggest difference between these two roof structures is their thickness. Prefabricated roof element has almost the same qualities than built-up roof structure, but it needs less material for it. First layer in both cases is trapezoidal steel sheet. Other difference between prefabricated roof element and built-up roof is the insulation layer. Prefabricated roof elements have thermal insulation also on its folds unlike built-up roof where the thermal insulation plates are used. Thickness is different which leads to the different weight of these roof structures. Dead load of built-up roof structure without steel sheet is 37 kg/m2 and dead load of prefabricated roof element without steel sheet is 20 kg/m2 with Finnish regulations. With Swedish regulations dead load of built-up roof structure is 30 kg/m2 and for prefabricated elements 17 kg/m2 both dead load values are told without steel sheet. (Kesti 2018d.)

In this thesis the calculations are done with Finnish and Swedish regulations. Difference between these two regulations is in U-value, which effects to the structure making it thicker in Finland than in Sweden. U-value in roof structure needs to meet the requirements which are 0,09 W/m^{2}K in Finland and 0,12 W/m^{2}K in Sweden. The sectional drawing of a roof structure A in the figure 11 is built in situ and B is prefabricated element. Due to the different insulation material, prefabricated elements can reach the needed U-value with thinner structure. (Kesti 2018d.)

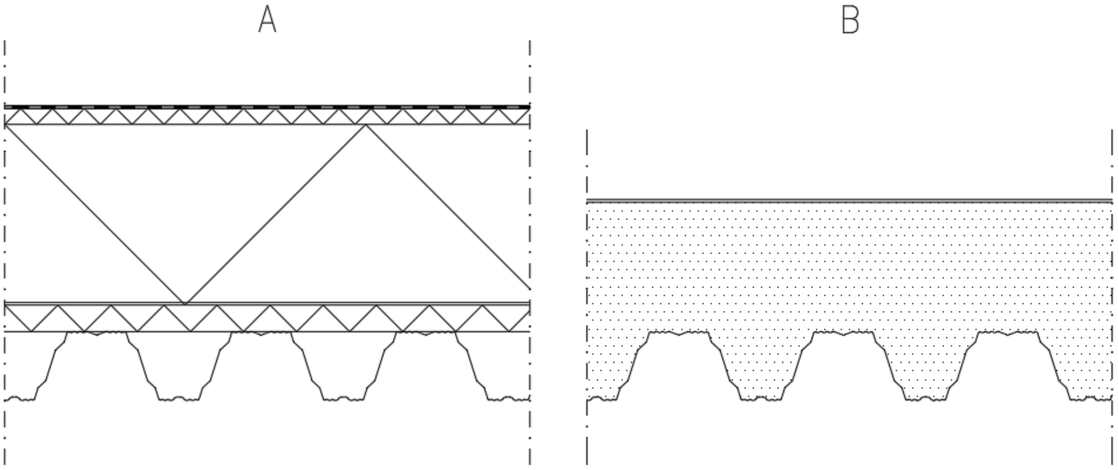


Figure 11. Roof structures in comparison (retell Kesti 2018d).

Characteristic values for live load in Finland for snow is 2,5 kN/m^2 and in Sweden 2,0kN/m^2. This live load for snow is calculated from ground. (Kesti 2018d.)

Sheet under review has stiffeners in webs and in flanges. Used load-bearing sheet is T130M-75L-930, which means that it is 130 mm high, narrower web’s width is 75mm and the sheet’s effective width is 930 mm. In figure 12 is presented these measurements. Load-bearing sheet T130M-75L-930 thickness can be 0,7, 0,8, 0,9, 1,0, 1,2 or 1,5 millimeters and length anything between 800-18300 millimeters. (Ruukki 2015, p. 15.)

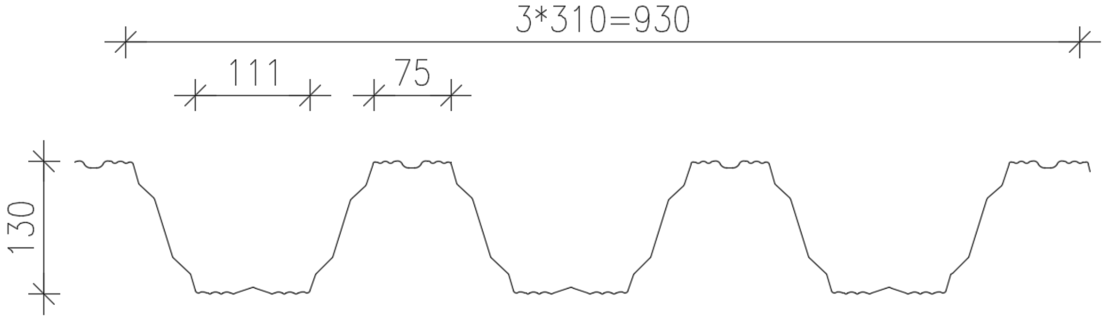


Figure 12. T130M-75L-930 load-bearing sheet profile (retell Ruukki 2015, p. 15).

Used program to compare these two roof structures is called Poimu which is one of the calculation programs of Ruukki. In Poimu program sheets can be designed in different situations and constructions. The design theory of Poimu program is based on Eurocodes. Constructional project’s information, loads, span lengths, supports and connecting screws and so on are set to the program. Loads to the program are given in three phases: live load, dead load, live load for snow and live load for wind. Loads can be given for suction and for pressure. In the program pressure factor of wind load can be calculated if it is not given beforehand. Program suggests the right sheet for given loads and other regulations for the specific constructional project. It shows the utilization rate of every span length and what is the critical part of the steel sheet. Critical part of the sheet can be in the span area, on the supports or it can be the deflection of the sheet. The program suggests the right sheet for the loads that have been set to the structure. Program can give such a sheet that needs a special ordering, special profiles. As a result, Poimu program gives suitable sheet for given loads from Ruukki's own product options. (Ruukki 2018.)

The structures that are under closer look in this thesis are presented in figure 13. Calculations are based on these structures. In figure is only presented the structures for span length that is 6000 meters, but the structure types are the same with different span lengths, only the measurements are different. In this thesis there are four different structures. First one is where the sheets are connected on the supports, single span. In single span structure a sheet length equals to the one span. Second one is where the sheets are connected on every second support, double span. In double span structure sheet length is the length of two span lengths. Third one is for Gerber joints and in built-up roof structure there is also the fourth joint type which is continuous. When dimensioning prefabricated roof elements in Poimu program, continuous structure needs to be ruled out due to poor overlapping of elements.

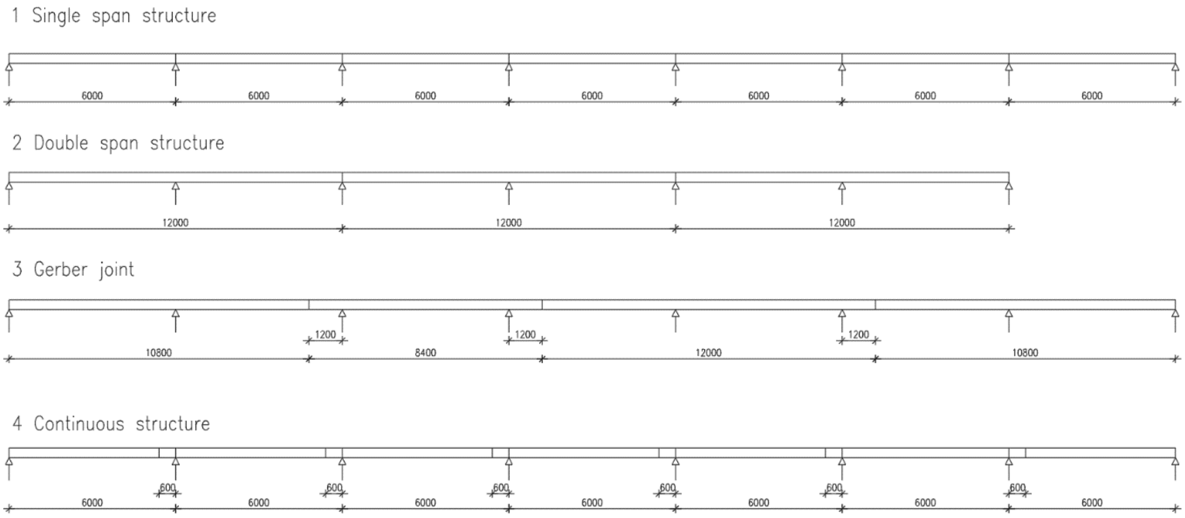


Figure 13. Different structures with span length 6000 meters.

Different joint types for prefabricated roof elements are separated in figure 14. All the elements are fastened to the supporting structure form above by drilling a hole. In Gerber joint type the elements are fastened together underneath and as can be seen in the figure 14.

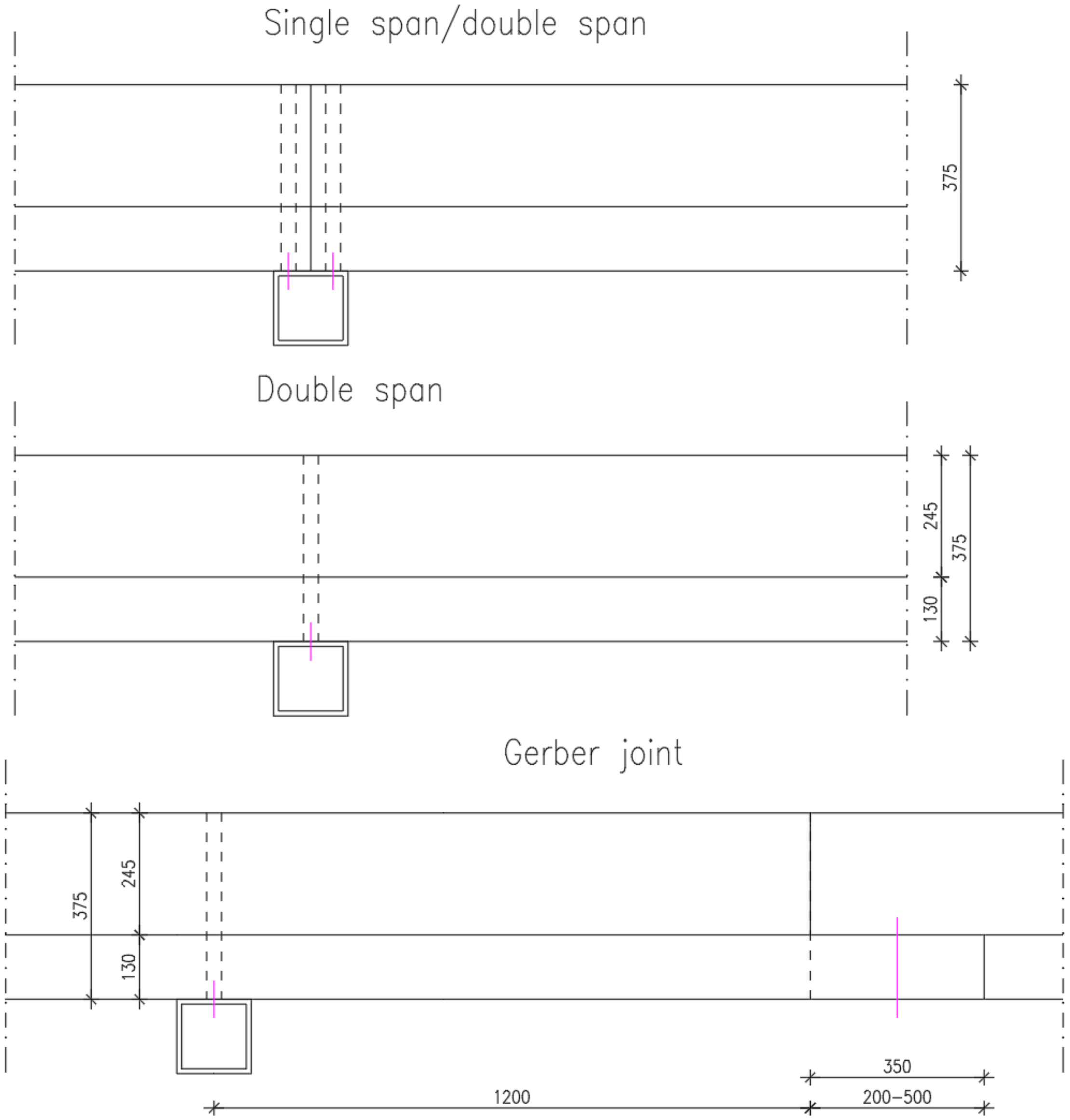


Figure 14. Typical joint types with prefabricated roof elements.

Typical joints for built-up roof structure are presented in figure 15. When built-up roof structure is used, there are four different joint type solutions.

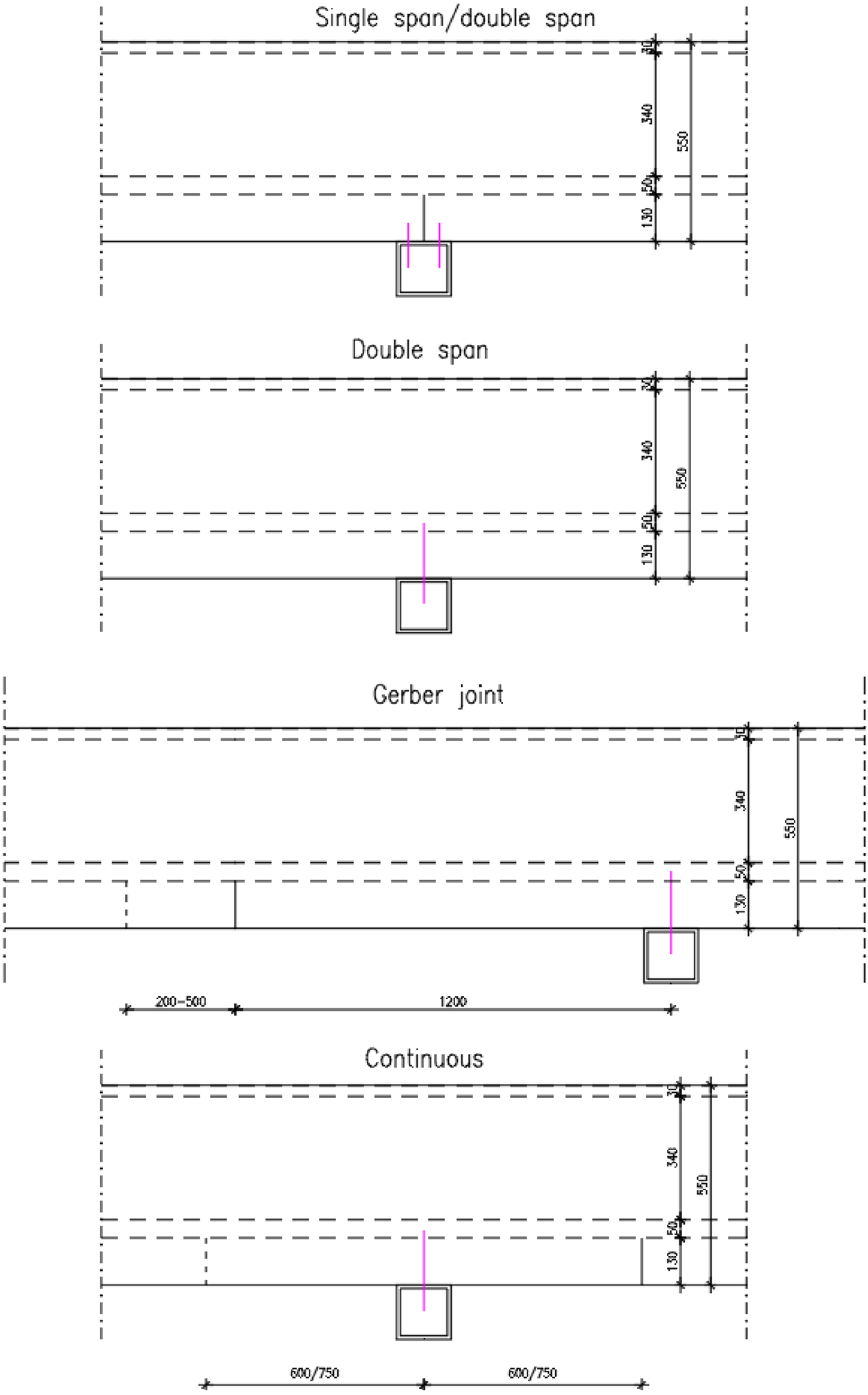


Figure 15. Typical joint types with built-up roof structure.

Gerber joint structure in butt joints is presented in figure 16. Gerber joint means that span joints are on zero points of the bending moment (Kesti 2018b). Element on the left of the figure is placed first and the end that is fastened to the other elements is without insulation about 200-500 millimeters, depending on the forces, loads and other things that are affecting to the structure. Fastener in this joint type is in between the chosen length of the overlapping on abutment joint. In Gerber joint the structure needs an extra examination. This is because in this joint the connection point of the sheets is not on supports.

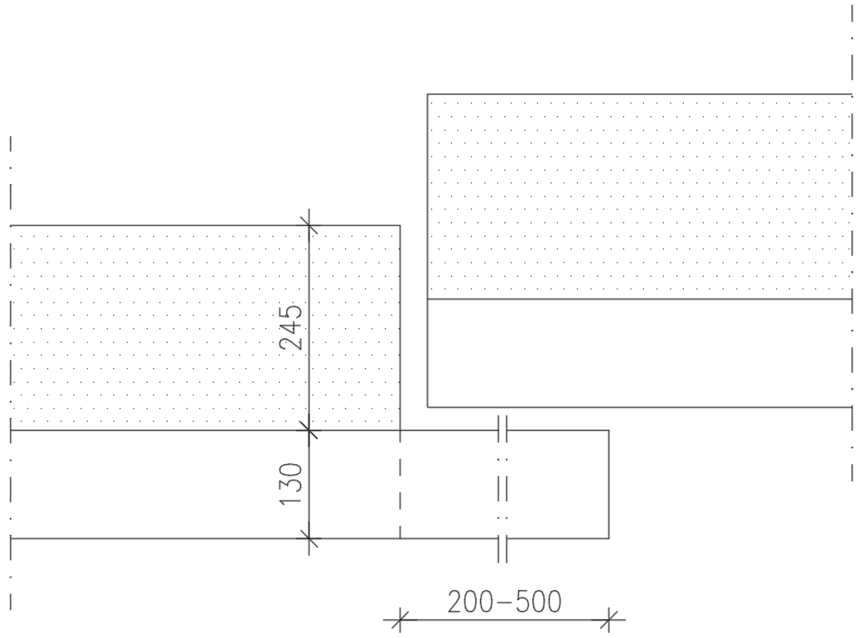


Figure 16. Gerber joint structure in prefabricated roof elements.

Overlapping with prefabricated roof elements is limited. Elements cannot be overlapped as normal roof structure made from steel sheets or at least it is not as easy. One solution for longitudinal overlapping for elements is shown in figure 17. Holes for truss fastening are also shown in figure 17.

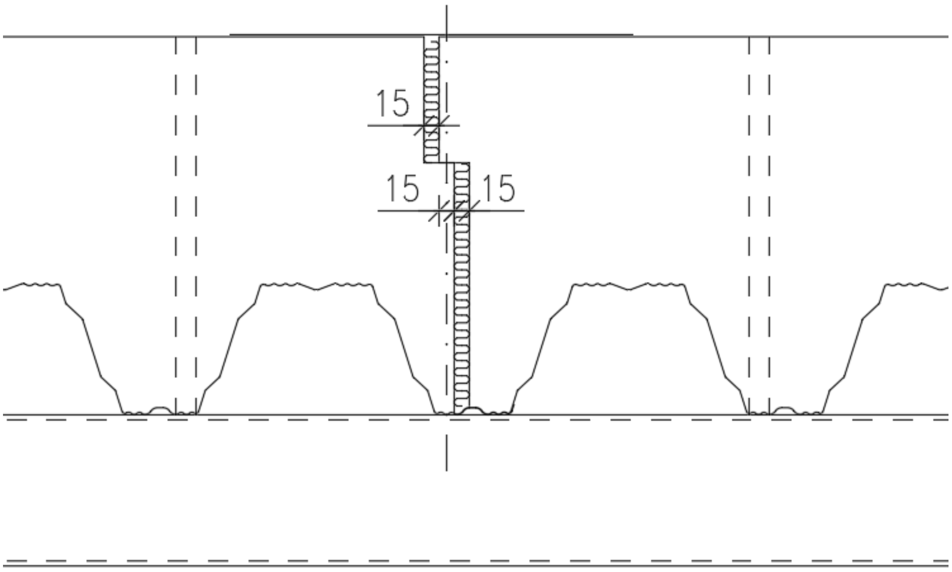


Figure 17. Longitudinal overlapping with key joint in prefabricated elements (retell Kesti 2018c).

The key joint solution with dimensions and installation order is shown in figure 18. Insulations in the gap are shown in figure 17 and the one below can be connected to the element that is installed first. It is easier to fasten the elements together from underneath and to the trusses from above the elements.

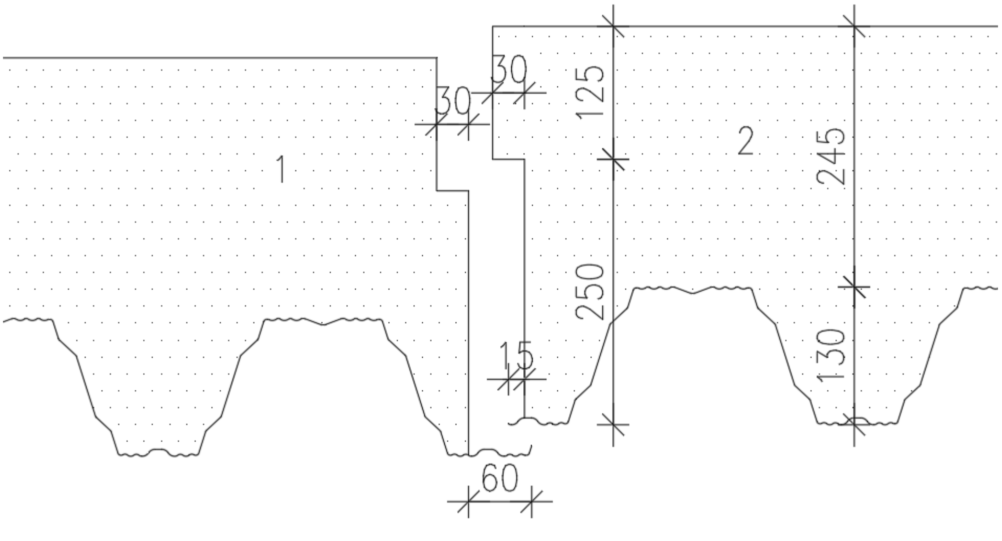


Figure 18. Dimensions in longitudinal overlapping with key joint in prefabricated elements (retell Kesti 2018c).

Overlapping solution presented in figure 17 and 18 is done by placing the left element first because its steel sheet goes further and because the small insulation layer is easier to assembly between these elements. Also, the other element is easier to get into right place when the element on the left side of the figure above is placed first. When fastening elements to the trusses, hole needs to be drilled through the insulation material. After the steel sheet is fastened to the trusses, holes need to be filled and secured properly.

In situation presented in figures 17 and 18 the elements need to be fastened together from underneath because there is no room for connecting these elements together from above. The second option for longitudinal overlapping with prefabricated elements is presented in figure 19. In solution presented in figure 19 element on left is assembled first then the right one as in key joint overlapping. After the elements are put one over the another they are fastened together from the gap between elements and the gap is blocked properly.

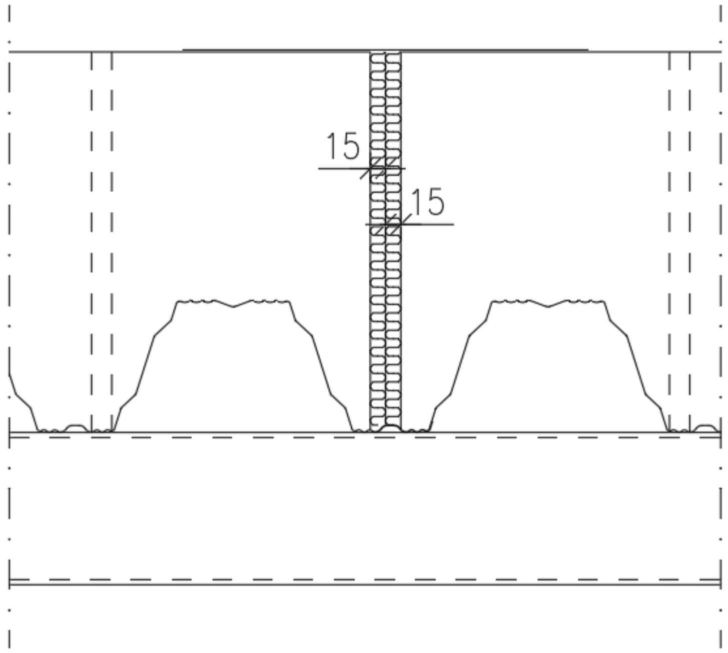


Figure 19. Longitudinal overlapping with straight joint in prefabricated elements.

The dimensions of longitudinal overlapping with straight joint are presented in figure 20.

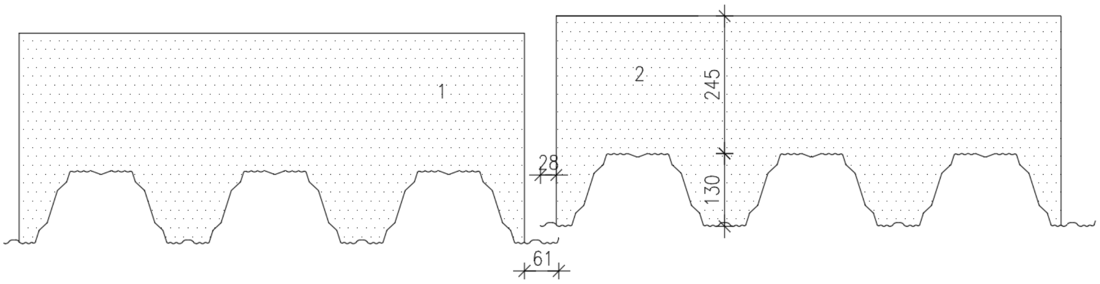


Figure 20. Dimensions in longitudinal overlapping with straight joint in prefabricated elements.

One solution for built roof structures with prefabricated elements is to do elements that are three sheets wide. Doing like this there is not that many joints that needs to be connected on construction site and the joints that are done beforehand in the factory can be assumed being airtight. Three-sheet wide roof element is presented in figure 21. (Kesti 2018c.)

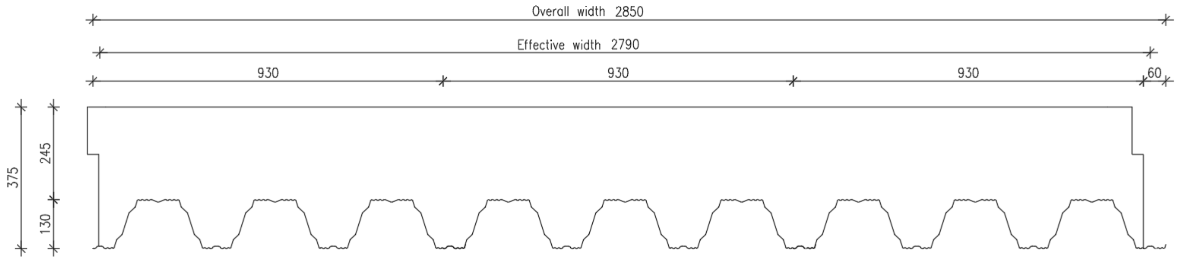


Figure 21. Three-sheet wide prefabricated roof element (retell Kesti 2018c).

There are many different factors that are affecting to the amount of screws when steel sheets are fastened together or to the steel structure. These factors are for example loads, snow and wind, and if the sheet is used to stiffen the structure it causes different types of forces to the structure and these need to take under consideration among other loads and forces. Another thing that is affecting to the number of fasteners is the shape of the roof structure. The shape of the roof structure can cause suction with wind load and these factors are different with different roof shapes. If these joints are used, the screws need to be calculated separately since of the many factors that are affecting to the structure and its amount of screws in the joints. (SFS-EN 1993-1-3, pp. 60-62, 66.)

In the fire situations when trapezoidal steel sheet is exposed to the heat long enough, it loses its load bearing capacity and starts to act like a rope (Teräsrakenneyhdistys ry, 2011). This sets special regulations for overlapping and fastenings of steel sheets, especially when joints are not on support. Gerber joint structure is one of these structures which joints are not on support. With Gerber joints the seam can be locally protected from fire with fire-retardant paints. For steel sheet structure with Gerber joints the fire sets different kind of forces comparing to the structure which joints are on support. In worst case scenario the lower steel sheet can start to dangerously hang in the end and fire can expand to the structures above when Gerber joints are used.

Forces that are affecting to the Gerber joint structure are forces that come straight to the connection point and forces that are affecting in planar line towards the structure. Because these elements are different structure, the connection point of these elements are more vulnerable to different effects. In figure 22 is presented these forces and possible affects to the structure with over reacting. On the right of the figure 22 is presented the possible uplift and its affect a little bit over the normal situation.

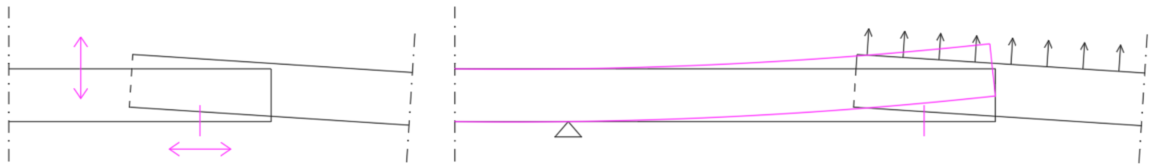


Figure 22. Forces affecting to the Gerber joint structure.

5.2 Constructability

Prefabricated roof elements are manufactured in the factory. On top of the steel sheet insulation is extruded and on top of that the chosen roof material is installed. In this solution the chosen roof material also works as a water insulation. There is only three layers in prefabricated roof elements unlike in built-up roof. Built-up roof is built piece by piece on site. Usually when roof structure is going to be built all the materials are already on site. This quickens the construction of the roof. There can be a possibility that some roof materials delivery is late, which effects to the construction work negatively.

When elements are ready, they are delivered to the construction site. Delivery has some regulations set by logistics, because there can only be elements that are under certain length. In this thesis maximum length for prefabricated elements is 15 meters (Kesti 2018b.)

Assembling of prefabricated roof elements do not take much time comparing to the time of assembling built-up roof layers. Prefabricated elements are set to their right places and then fastened to the main structure and to each other. When build roof structure on site from different products/layers, every layer needs to be installed separately. In this thesis the built-up roof structure has 5 to 6 different layers:

- trapezoidal steel sheet,
- insulation (50 mm),
- moisture barrier,
- insulation layer with two different layers (thicknesses 340 mm and 30 mm) and
- wanted roof material (Paroc 2019).

Thicknesses above are from structures that are used in Finland according to Finnish regulations. Thicknesses in Sweden are first insulation layer which is on top of the trapezoidal steel sheet is the same than in Finland, but the thicker layer is 230 mm and 30mm. (Kesti 2018d.)

Construction site can be effective when prefabricated elements are used. This is because elements can speed up the construction work. While piece by piece built-up roof takes more time on site, because every layer needs to put separately and then fasten. Steel sheets need to be fastened first before any other layers are put on top of it. Prefabricated elements are placed straight on the trusses and roof structure is almost finished, depending how finished prefabricated roof elements are. Built-up roof structure the steel sheets are fastened to each other from flanges (Ruukki 2015, p. 7).

On the other hand, piece by piece built-up roof structure can be also effectively built, but this requires that all the construction layers for the roof are on site on time, so the installation can be done without waiting of material deliveries. Despite of this, the installation of built-up roof takes more time than when prefabricated roof elements are used.

Prefabricated roof elements can be exposed to different weather conditions in delivery and if they are stored on site. Built-up roof's layers are also exposed to different conditions in same places that the elements, but layers are more vulnerable when they are built. Different weather conditions are affecting until the roof structure is completely built. This means that all the different layers are assembled and fastened. If wanted to be sure that different weather conditions are not affecting to the structures or different layers, protective canvas can be used. Protective canvas can be put over the whole building, but it needs supporting structure and assembling this can take some more time from construction project, but after it is done the whole building is protected from weather. (Rakennusteollisuus 2018.)

Different weather conditions can destroy construction materials. For example, rain or snow, which can make the material wet and the moisture can get into the structure and it is harder to get out from the material or at least it takes time. Unless, more durable or suitable materials are used that can bare the moisture from outdoor air which are caused by different weather conditions.

5.3 Differences in calculations

When calculating prefabricated elements, Poimu program has taken differences in capacity into account. For example, the used insulation material. Comparison in Poimu program were done between element and built-up roof structures with same loads. Examined structure, joints and the effecting loads were the same in both cases. This leads to differences in results especially in utilization rates on supports. From these results can be seen that in built-up roof structures utilization rates on supports are little bit higher than in prefabricated elements, approximately 1,37 percent higher. According to the research report made by Tampere University of technology the ratio between elements and built-up roof is above 1,0 and the ratio depends on steel sheet's thickness and support width. (Vilppu, 2017.)

Design with Eurocodes makes experimental examinations possible. With experimental examinations, Poimu program has set the values for both built-up roofs and prefabricated roof elements. In experimental dimensioning the results are more accurate which leads to more accurate results for designing. (SFS-EN 1993-1-3, p. 72.)

5.4 Optimizing

Optimization of the studied structures in Finnish conditions is based on the example building dimensions shown in figure 23. Dimensions 20*42 meters and 20*52,5 meters are used when dimensioning single span, Gerber and continuous structures. Dimensions 20*36 meters and 20*45 meters are used when dimensioning double span structures. Same dimensions in Sweden are 20*42 meters and 20*50,4 meters for single span, Gerber and continuous structures and for double span structures 20*36 meters and 20*43,2 meters. In Finland span lengths are 6 meters and 7,5 meters and in Sweden 6 meters and 7,2 meters.

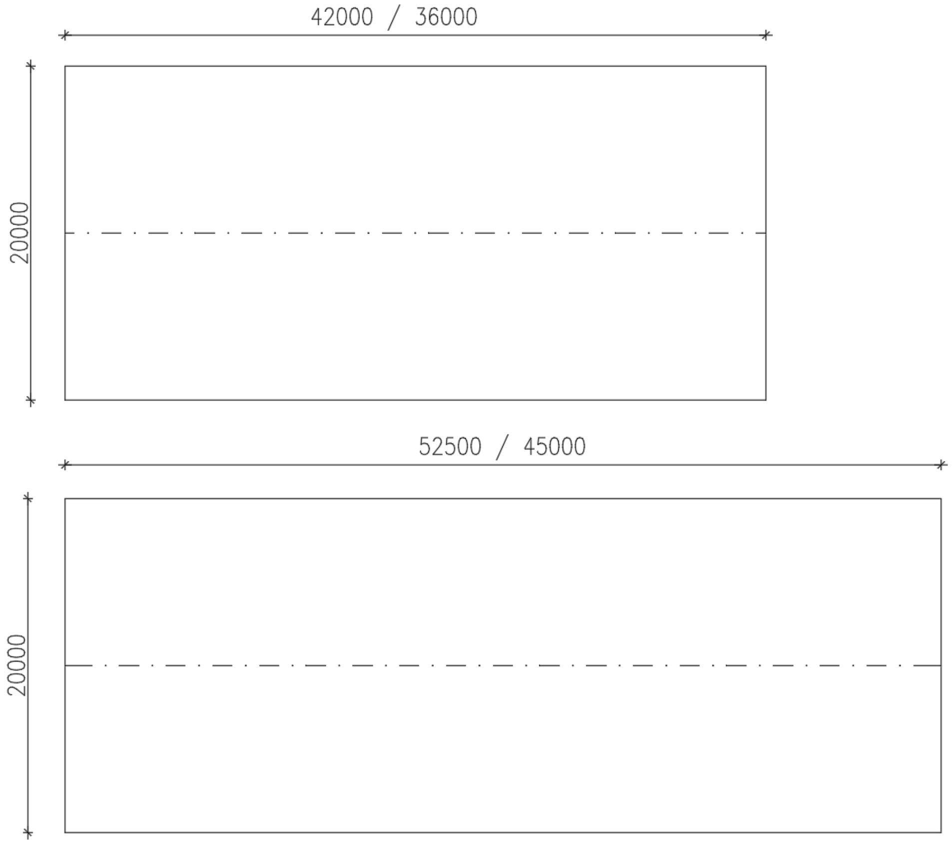


Figure 23. Dimensions of buildings.

Dimensions and loads are put into the program called Poimu and it gives results which are compared to each other. There are four different structure situations that are under closer look. The structure types are described in figure 13. The dimensioning results are separated with Finnish and Swedish regulations and different span lengths. In the results are shown how much steel every structure situation and joint type needs by kilos per square meters with the highest utilization rate.

Steel consumption comparing

Steel consumptions for prefabricated roof elements with different structure situations for joints are shown in figure 24. With red font is separated the structure situations that do not hold the given load. In this case the 5 % breach is acceptable when deflection is the critical factor. In figures are shown the maximum utilization rates of the joint types. Joint types are presented in figure 22. Three possible statical structure types for prefabricated roof elements are single span, double span and Gerber joint structure. One notable thing is in joint type 2, where is only used double span three times (3*6000/7500mm) in both span lengths, which makes the structure one span length smaller than in the other joint types. In this figure can be seen that the steel consumption in joint type 2 is the lowest in span length of 6000 millimeters and in span length 7500 millimeters the lowest steel consumption is in double span since other joint type options does not carry the given load. With both span lengths the joint type two have the lowest steel consumption, since the other joint types did not hold the given load in span length 7500 mm. Explanation for high utilization rate in prefabricated elements can be that overlapping is not an option, so the thickness of the sheet is in high importance.

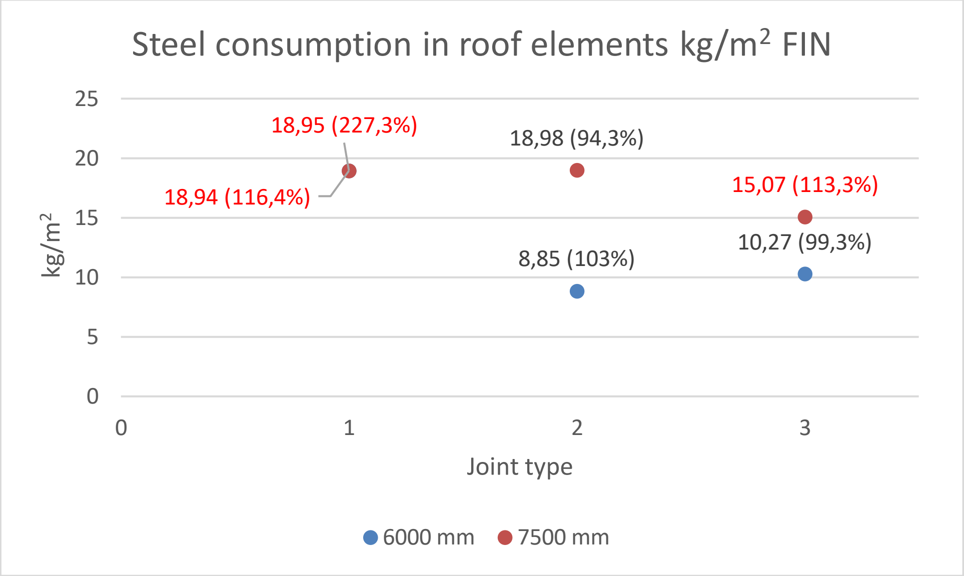


Figure 24. Steel consumption in roof elements with Finnish regulations.

Steel consumption in built-up roof structures with different structure situations are presented in figure 25. In some of these solutions one wave side overlapping is used. Difference between element and built-up roof solution is that in built-up roof structure there are four different structure solutions for joints when elements only have three. One structure solution for built-up roof is continuous structure where sheets are overlapped on supports both sides or only on other side at least the length of 0,1 times span length. Continuous joint type is presented in figure 25 as a joint type 4. From figure 25 can be seen that Gerber joint type steel consumption is the lowest with span length 6000 millimeters but in span length 7500 millimeters the continuous structure uses less steel.

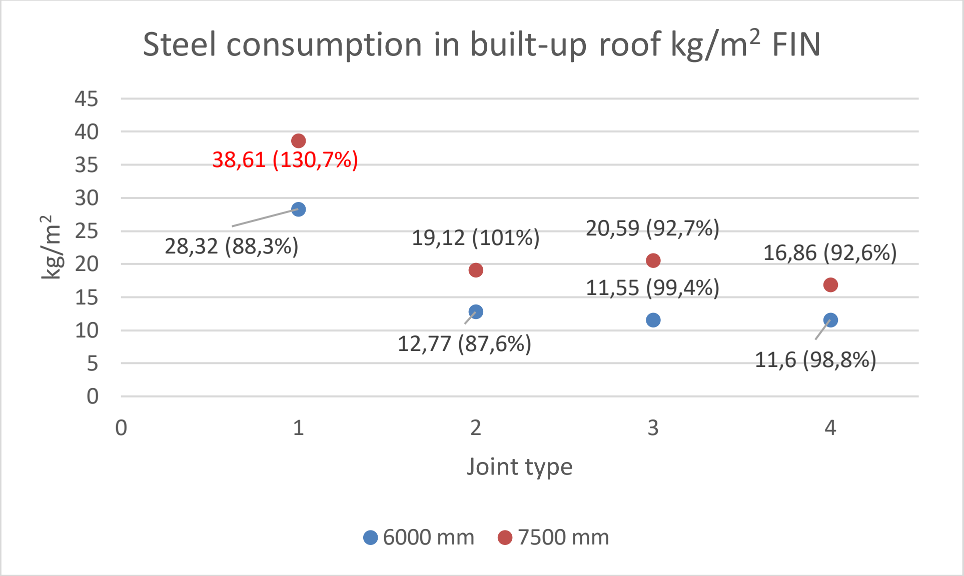


Figure 25. Steel consumption in built-up roof with Finnish regulations.

With Finnish regulations double span joint type needs less steel material in prefabricated elements and with built-up roof structure Gerber joint type needs less steel material. Almost the same steel consumption in built-up roof structure is when continuous structure is used. When span length is 7,5 meters, continuous joint type needs less steel material in built-up roof structure and in elements this span length did not hold the given load. Steel consumption in built-up roof structure is high when using single span joint type, because of the side overlapping. In appendix 1 is shown which spans were overlapped on their sides.

Steel consumptions for prefabricated roof elements and built-up roof structures with Swedish regulations are presented in figures 26 and 27. Difference between Finnish and Swedish calculations is that in Sweden 7200 mm span length is used. All the joint types and utilization rates for different joint types on different span lengths are shown in appendix 2.

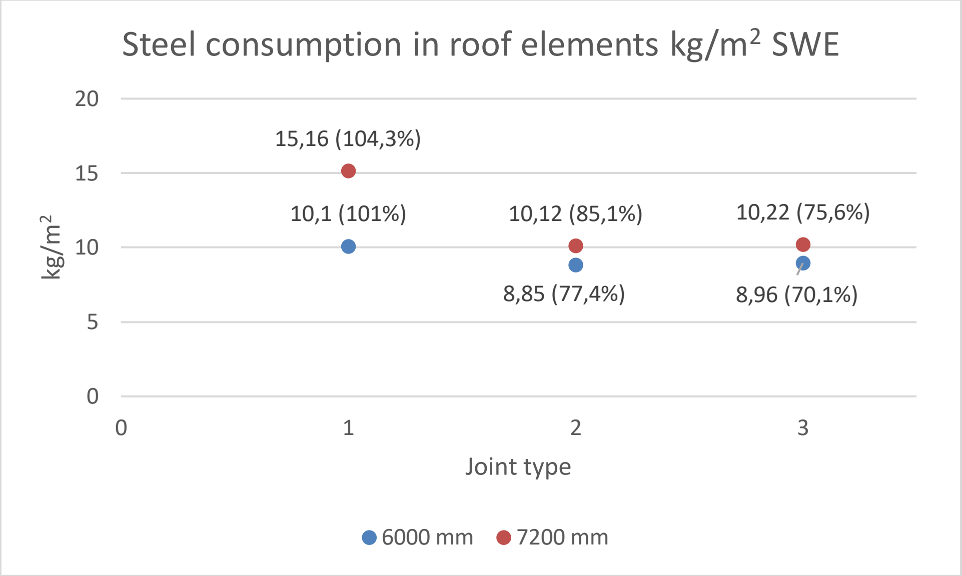


Figure 26. Steel consumption in roof elements with Swedish regulations.

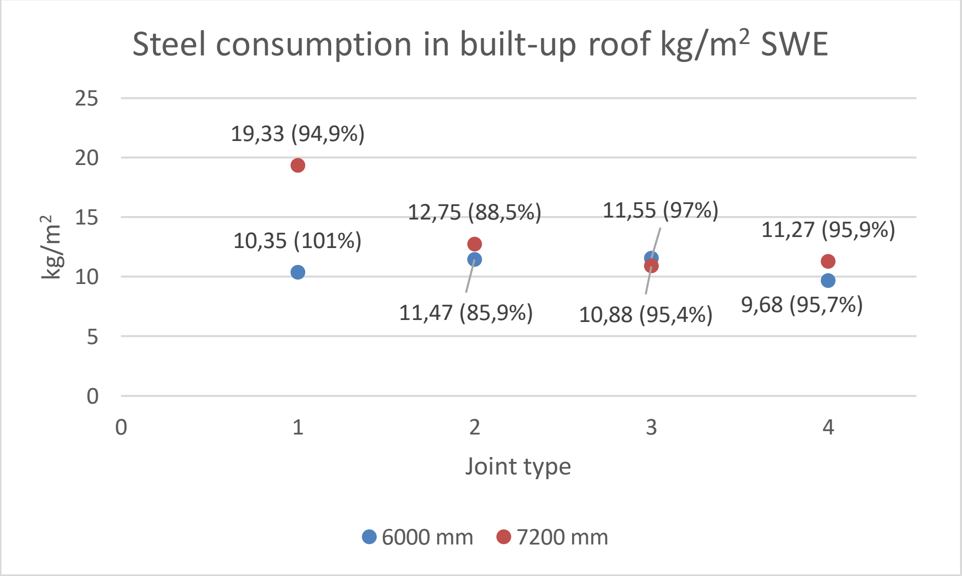


Figure 27. Steel consumption in built-up roof with Swedish regulations.

With Swedish regulations in double span structure steel consumption was the lowest in elements. In built-up roof structure the lowest steel consumption was in continuous structure with span length 6000 mm and 7200 mm.

Results in figures 24, 25, 26 and 27 are collected from calculations of Poimu program. For every joint type steel consumption is optimized and in figures above is shown the minimum values that holds the given load with Finnish or Swedish regulations.

Optimization is done with using different steel thicknesses in different span lengths. Thicknesses for different span lengths with different joint types are told in appendix 1 and 2. Less steel material in built-up roof structure needs in Gerber joint structure. Almost the same amount steel consumption is when continuous structure is used. The crucial factors of measurements are also shown in appendixes 1 and 2. In some cases the structure did not hold the given load even though every solution for structure strengthening were used. These solutions in Poimu program are for example the material thickening and side overlapping.

In figures 28 and 29 the differences in steel consumption between elements and built-up roof with Finnish regulations are shown and in figures 30 and 31 with Swedish regulations. In these figures can be seen that prefabricated steel elements use less steel than built-up roof structures. Prefabricated roof element does not have solution for continuous structure which is presented in the figures with steel consumption NA kg/m^2. The first joint type is for single span structure, the second one is for double span, the third one is for Gerber joint and the fourth is for continuous joint type.

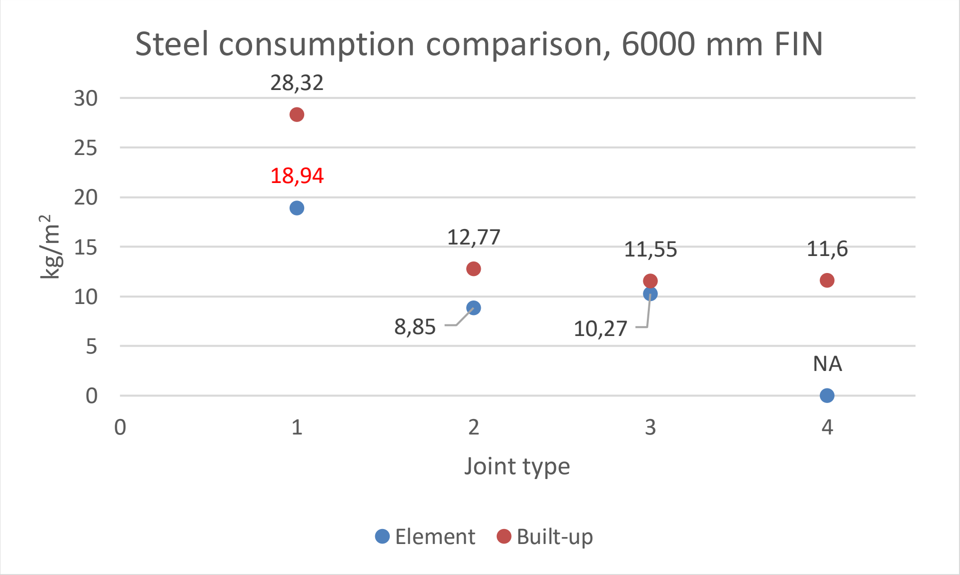


Figure 28. Comparing steel consumption between elements and built-up roof structures with span length 6000 millimeters and Finnish regulations.

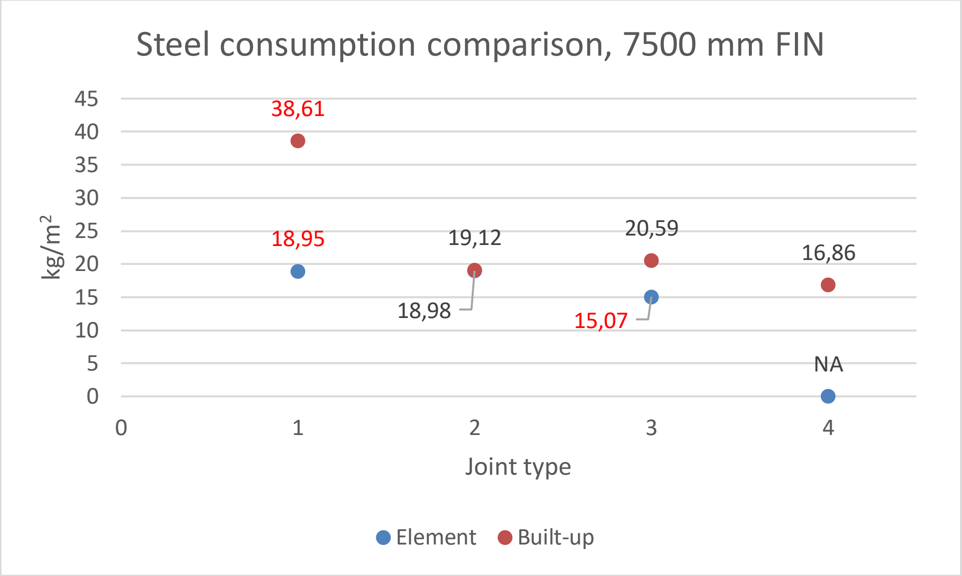


Figure 29. Comparing steel consumption between elements and built-up roof structures with span length 7500 millimeters and Finnish regulations.

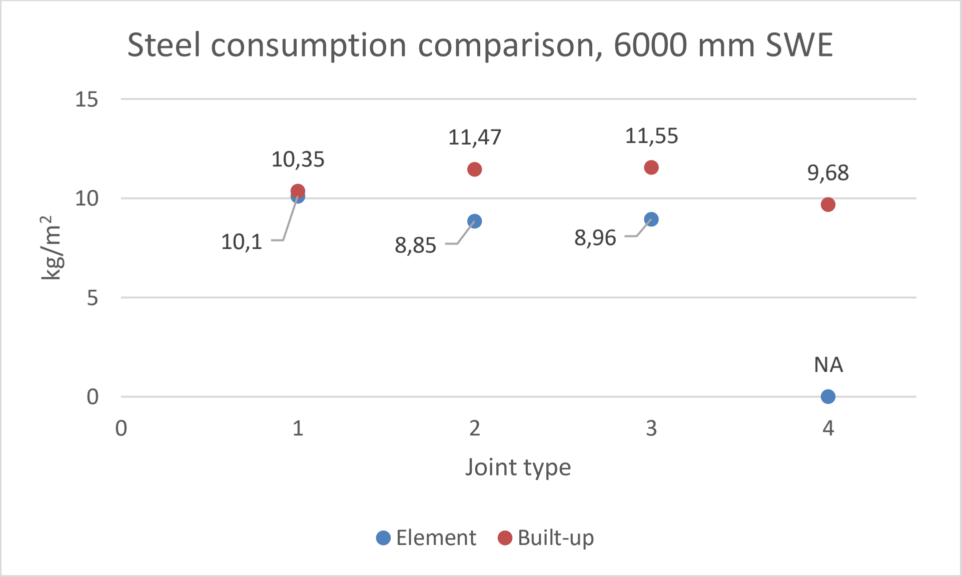


Figure 30. Comparing steel consumption between elements and built-up roof structures with span length 6000 millimeters and Swedish regulations.

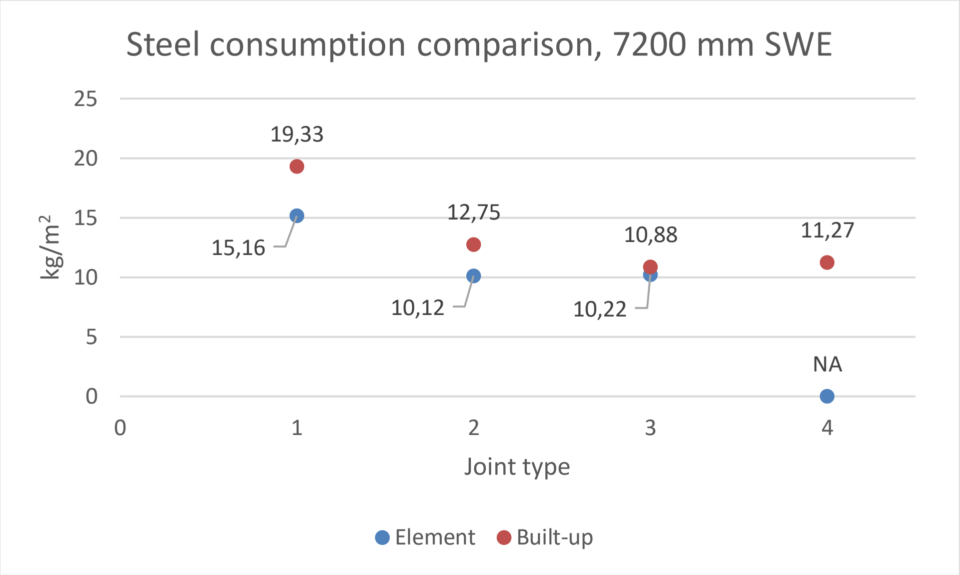


Figure 31. Comparing steel consumption between elements and built-up roof structures with span length 7200 millimeters and Swedish regulations.

In tables 5 and 6 is presented how much material the joint type needs when the utilization rate in every case is 100 %. In Poimu program thicknesses of the steel sheets are set beforehand, which leads to the utilization rates that are presented in figures above. In some cases, the utilization rate is way under or way over 100 %. Numbers in tables 5 and 6 are efficiency numbers for the strength which are calculated when steel consumptions are multiplied with maximum utilization rates for different joint types. In tables the efficiency numbers are given kg/m^2.

Table 5. Plot ratio kg/m^2 for different joint types and span lengths with Finnish regulations.

	Prefabricated roof element (utilization rate 100%)		Built-up roof (utilization rate 100%)	
	6000 mm	7500 mm	6000 mm	7500 mm
1	22,05	43,02	25,00	50,46
2	9,12	17,89	11,19	19,31
3	10,20	17,06	11,48	19,09
4	0	0	11,46	15,61

Table 6. Plot ratio kg/m^2 for different joint types and span lengths with Swedish regulations.

	Prefabricated roof element (utilization rate 100%)		Built-up roof (utilization rate 100%)	
	6000 mm	7200 mm	6000 mm	7200 mm
1	10,20	15,81	10,45	18,34
2	6,85	8,61	9,85	11,28
3	6,28	7,73	11,20	10,38
4	0	0	9,26	10,80

5.5 Cost comparison

Built-up roof structure costs approximately 85 €/m^2. Price includes materials, trapezoidal steel sheet, insulation etc. with every layer assembling and fastening. Cost information is calculated for bigger construction project with u-value of 0,09 W/mK. Price for steel sheet assembling is 7 €/m^2 and for assembling insulation and roofing material the price is 12€/m^2. Insulation and roofing material costs approximately 45 €/m^2. In built-up roof structure steel sheet with thickness 1,2 millimeters is used and this steel sheet costs 21€/m^2. The thicker the steel material the more it costs. (Kesti 2018e.)

Building's roof built with prefabricated elements needs to cost less or about the same than built-up roof, if it is reasonable to use elements. If using prefabricated roof elements costs approximately the same amount than built-up roof structure it is very useful to use elements, because time for assembling is quicker. Cost comparison is only done with Finnish roof structures and materials. For prefabricated roof element, which is done from wood, the price is approximately 120 €/m^2 (Vuolli 2019). Price includes assembling, fastening and seam welding.

Interviews with different contractors showed that the assembly of prefabricated elements is approximately 8-12 €/m^2. With this information we can set the market price for prefabricated element by comparing it to the price of built-up roof structure. If the assembly of prefabricated elements is 12 €/m^2, the price for element itself can be 73 €/m^2 and this price needs to include all the materials that prefabricated elements include. This 73 €/m^2 can be the highest price for the element, since the built-up roof costs 85 €/m^2. This gives a range for prefabricated element's price 70-73 €/m^2 without assembling.

One factor that can affect to the price of elements is time. This can be one factor that customer is willing to pay more when using elements, since savings in construction time due to assembling time of prefabricated roof elements.

5.6 Conclusions

Main conclusion of this thesis was that steel consumption with prefabricated roof elements is smaller than when built-up roof structure is used. This can be explained with the used insulation layer in prefabricated roof elements.

Other conclusion from the results of this thesis was that single span structures did not hold the given load except when dimensioning was done with using Swedish regulations. Measurement factor for single span structure was the deflection of the sheet, which exceeded by 10-130 %.

As a conclusion for prefabricated roof elements the working solution is double span structure, and this is with both span lengths with Finnish regulations. Steel consumption for span length 6 meters was 8,85 kg/m^2 and for span length 7,5 meters 18,98 kg/m^2. For built-up roof structure for span length 6 meters the most working solution was with Gerber joint with steel consumption 11,55 kg/m^2 and with span length 7,5 meters continuous structure with steel consumption 16,86 kg/m^2. These joints were taken since they hold up the given load and the steel consumption in these structures were the lowest.

With Swedish regulations for prefabricated roof elements the working solution was double span with span length 6 and 7,2 meters. Steel consumption with span length 6 meters was 8,85 kg/m^2 and with span length 7,2 meters 10,12 kg/m^2. For built-up roof the structure was continuous structure with span length 6 meters and with span length 7,2 meters the working structure was when Gerber joints were used. Steel consumption with span length 6 meters was 9,68 kg/m^2 and with span length 7,2 meters 10,88 kg/m^2.

Steel consumptions with different span lengths and different joint types are collected to the figure 32 and 33. Diagrams in figures 32 and 33 present assumed value for steel consumption when utilization rate is 100 %. Relative difference between capacity with different span lengths and joint types is easier to see when utilization rate 100 % is used.

Steel consumptions with Finnish regulations are told in figure 32 and with Swedish regulations in figure 33.

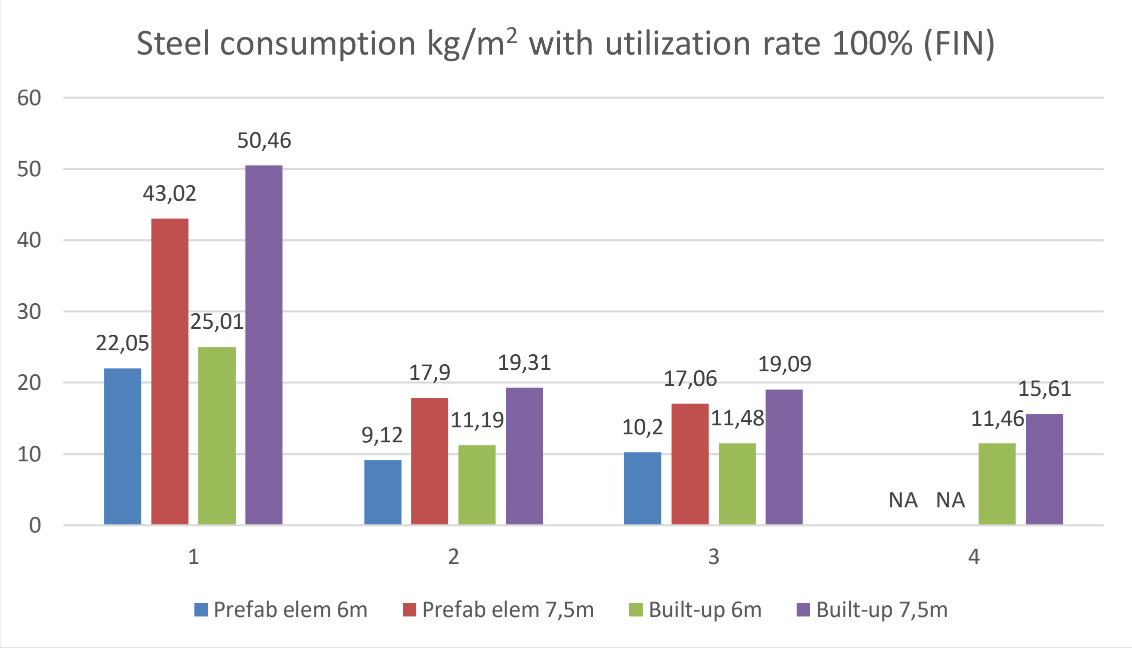


Figure 32. Steel consumptions with utilization rate 100% with Finnish regulations.

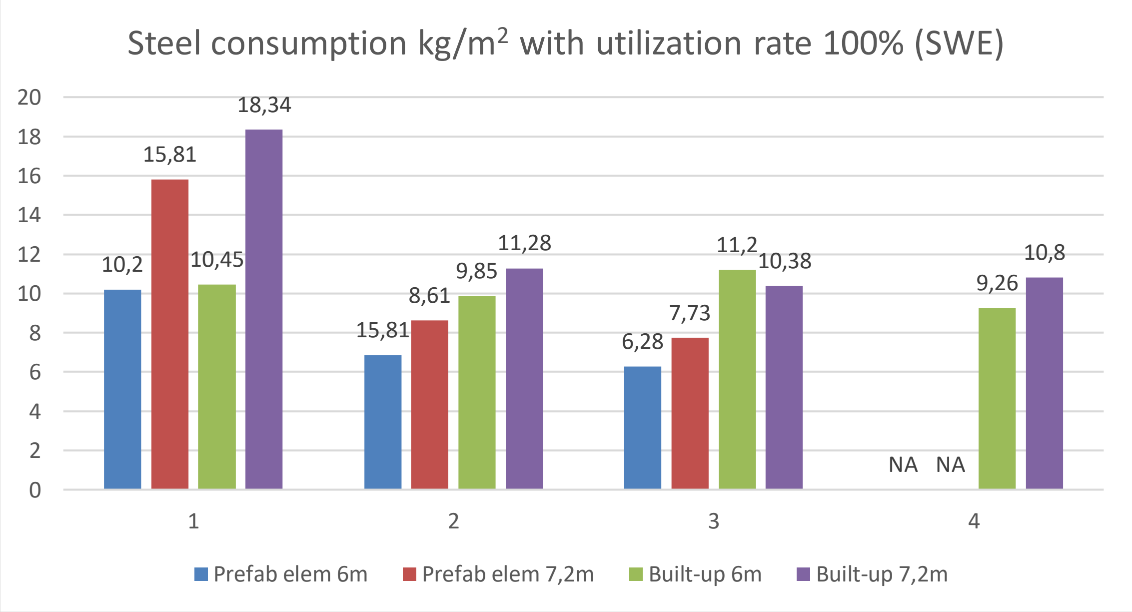


Figure 33. Paragraph with steel consumptions in utilization rate 100% with Swedish regulations.

According to these results that are collected from Poimu program with Finnish regulations, double span joint type is recommended when prefabricated elements are used. In built-up roof structure recommended joint type is continuous joint structure, which has comparable results to Gerber joint and double span structures. When Swedish regulations were used for prefabricated roof elements the recommended joint type is double span joint type, but in Gerber joint structures the steel consumption was almost the same than in double span joint type. For built-up roof structures the recommended joint types are Gerber joint and continuous structure. Other good notice is that when prefabricated roof element and built-up roof structures were compared, prefabricated roof elements consume less steel material than built-up roof structures.

6 SUMMARY

The subject for this thesis was comparison and optimization of built-up roof and prefabricated roof element. The aim for this thesis was to get optimized structure for prefabricated roof elements with different span lengths and joint types.

First part of this thesis deals with how steel is manufactured and how steel sheets are made. In this part is also presented the compared structures, built-up roof and prefabricated roof element. In second part is told more of the basics with calculations for load-bearing sheets. Behind these calculations is the basic calculations for steel sheets that are used in Eurocodes. After these two parts is the research part where is done the comparison between these two structures. Comparison is made with structural and assembling differences, steel consumptions and costs. In research part is also introduced the compared roof structures with span lengths, loads and measurements of the used building. For comparison, the special calculation program was used. Comparison results are collected from program and put into a chart. Every span length and joint type were presented in these charts with steel consumption and highest utilization rate. From comparison charts it is easier to find the working solution for different joint types in different span lengths. These two roof structures were compared with costs and with the prices and knowledge from example company and from different constructions, market price for prefabricated roof element was able to set.

Follow-up researches can be for example the fire situation in Gerber joint structures due to that joints in this structure are not on supports. In this thesis the fire situations were told shortly. Further research can also be done by comparing fire situations between built-up roof structure and prefabricated roof elements. One follow-up research can be recycling of prefabricated roof element. This research could get more information how well the different layers in element and the element itself are reusable.

Prefabricated roof elements are comparable solution next to built-up roof solutions. This thesis showed that prefabricated roof elements, that were used in this thesis, are a really good solution as a roof of a building.

7 REFERENCES

Burnett, C., 2014. Cold-Formed Steel Shakes Up Building Construction, [internet article verkkojulkaisu]. Available: https://www.thermofisher.com/blog/metals/cold-formed-steel-shakes-up-building-construction/ [referred 23.5.2018].

FinnFoam Oy, Unknown date. Tehokas ja turvallinen [verkkodokumentti] Salo: FinnFoam Oy. Available: https://www.finnfoam.fi/files/4515/0849/8159/FF-PIR_esite_2017_WEB_RES.pdf [referred 31.5.2018].

JFE 21st Century Foundation. 2003. Chapter 2, Smelting, Refining and continuous casting. 2A Manufacturing process for iron and steel. Japan.

Kesti, J., 2018a. Technology director, Ruukki Construction Oy. E-mail message 6.4.2018. Receiver: M. Huttunen. Diplomityö.

Kesti J., 2018b. Technology director, Ruukki Construction Oy. E-mail message 24.4.2018. Receiver: M. Huttunen. Aineistoa.

Kesti J., 2018c. Technology director, Ruukki Construction Oy. E-mail message 27.4.2018. Receiver: M. Huttunen. Dippatyöaineistoa.

Kesti J., 2018d. Technology director, Ruukki Construction Oy. E-mail message 27.6.2018. Receiver: M. Huttunen. Kattospeksejä.

Kesti, J., 2019e. Technology director, Ruukki Construction Oy. E-mail message 14.1.2019. Receiver: M. Huttunen. Kustannuslaskelmat.

KS-Profile, Unknown date. Benefits of roll-forming [verkkodokumentti]. Available: https://www.ksprofile.com/benefits-roll-forming [referred 1.6.2018].

Paroc Group, 2019. Loivan katon eristys ja lisäeristys. Uudiskohteen eristysratkaisut. Profiilipelti [verkkodokumentti]. Available: https://www.paroc.fi/kayttokohteet/rakennusten-eristaminen/katon-ja-ylapohjan-eristys-ja-lisaeristys/loivan-katon-eristys-ja-lisaeristys [referred 6.2.2019].

PU eristeet, Unknown date. PU eristeet. [verkkodokumentti]. Available: http://www.pueristeet.fi/pu-eristeet/ [referred 4.6.2018].

Rakennusteollisuus, Unknown date. Rakennustelineet ja sääsuojat. [verkkodokumentti]. Available: https://www.rakennusteollisuus.fi/Toimialat/Talonrakennusteollisuus/Rakennustelineet-ja-saasuojat/ [referred 20.12.2018].

Reliance foundry, 2017. Hot Rolled vs Cold Rolled Steel. Learn the benefits of each type of steel, and which to pick for your project [verkkodokumentti] North America: Reliance foundry. Available: http://www.reliance-foundry.com/blog/hot-vs-cold-rolled-steel [referred 1.6.2018].

Ruukki, 2015. Load-bearing profiled sheet. Installation instructions [verkkodokumentti] Load-bearing sheet documents. Installation instructions. Available: https://www.ruukki.com/gbr/b2b/support/document-library/load-bearing-sheet-documents [referred 8.8.2018].

Ruukki, Unknown date. Mitoitusesimerkki – Poimu. [verkkodokumentti] Available: https://software.ruukki.com/PublishedService?file=page&pageID=9&itemcode=1-3-3-1 [referred 1.12.2018].

SFS-EN 1990, 2006. Eurokoodi. Rakenteiden suunnitteluperusteet. Suomen standardoimisliitto SFS: 1 + 184 s.

SFS-EN 1993-1-3, 2006. Eurokoodi. Teräsrakenteiden suunnittelu. Osa 1-3: Yleiset säännöt. Lisäsäännöt kylmämuovatuille sauvoille ja levyille. Suomen standardoimisliitto SFS: 1 + 127 s.

SFS-EN 1993-1-5, 2006. Eurokoodi. Teräsrakenteiden suunnittelu. Osa 1-5: Levyrakenteet. Suomen standardoimisliitto SFS: 1 + 57 s.

Teräsrakenneyhdistys ry, 2011. Teräsnormikortti N:o 19/2011. Teräksestä valmistetun kantavan muotolevyn kestävyys tulipalossa. Helsinki: Teräsrakenneyhdistys Ry. 34 p.

Teräsrakenneyhdistys ry, 2014. Teräsrakenteiden suunnittelu ja mitoitus Eurocode 3 -oppikirja. Helsinki: Teräsrakenneyhdistys Ry. 183 p. ISBN 978-952-9683-54-3.

Total Materia, 2018. Teräslaadut [verkkodokumentti]. Total Materia: Maailman kattavin materiaalitietokanta. Available: https://www.totalmateria.com/page.aspx?ID=SteelGrades&LN=FI [referred 24.7.2018].

Vilppu, J., 2017. Internal support FEM-calculations. Seinäjoki/Tampere: Tampere university of Technology / Laboratory of Civil Engineering. Publishing limited, 44 + 228 p.

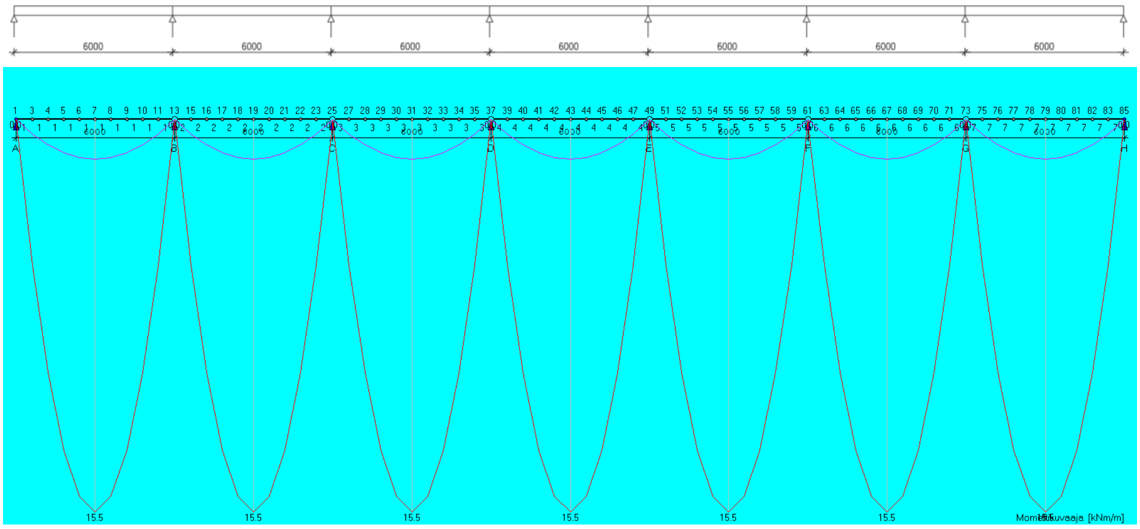
Vuolli, V., 2019. Osastopäällikkö, Sweco Rakennetekniikka Oy. E-mail message 22.1.2019. Receiver: M. Huttunen. Puuelementtikatto – budjettihinta.

Väisänen, P., 2007. Teräs. Perustietoa arkkitehtiopiskelijalle. Vammala: TKK Arkkitehtiosasto Rakennusoppi, 47 s. ISBN 978-951-22-8651-5.

Appendix 1. Results from Poimu program with Finnish regulations. (1)

Prefabricated element: 6000 mm

Single span structure

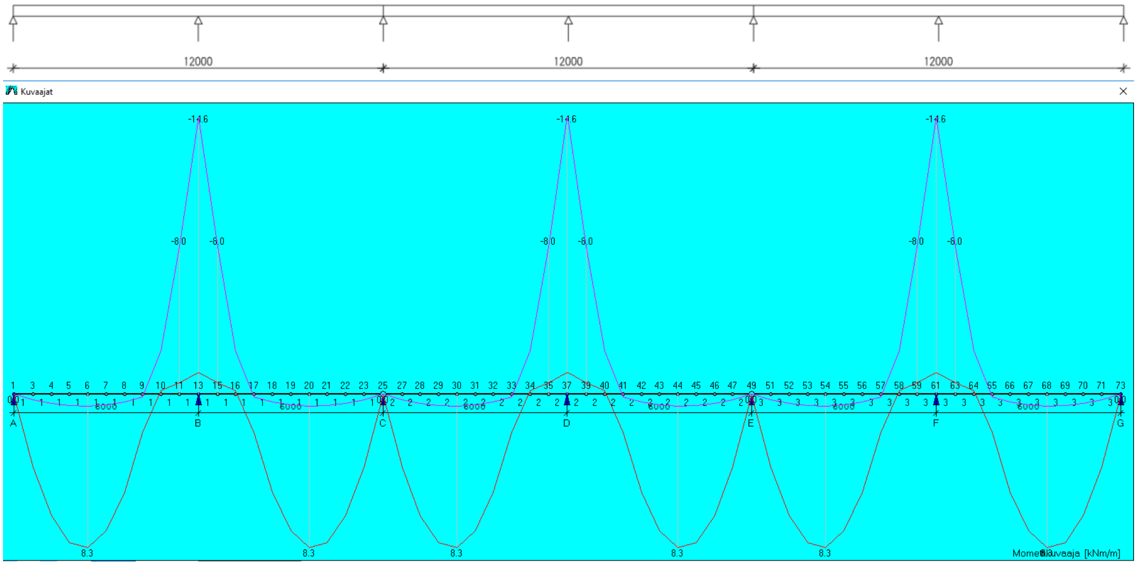


Thickness	1,5/350	1,5/350	1,5/350	1,5/350	1,5/350	1,5/350	1,5/350
Length (mm)	6090	5980	5980	5980	5980	5980	6090
Utilization rate between supports (%)	39,1	39,1	39,1	39,1	39,1	39,1	39,1
Utilization rate on supports (%)	32,1	32,1	32,1	32,1	32,1	32,1	32,1
Utilization rate of deflection (%)	116,4	116,4	116,4	116,4	116,4	116,4	116,4

➔ Utilization rate of deflection is too much

Steel consumption 18,94 kg /m^2

Double span structure

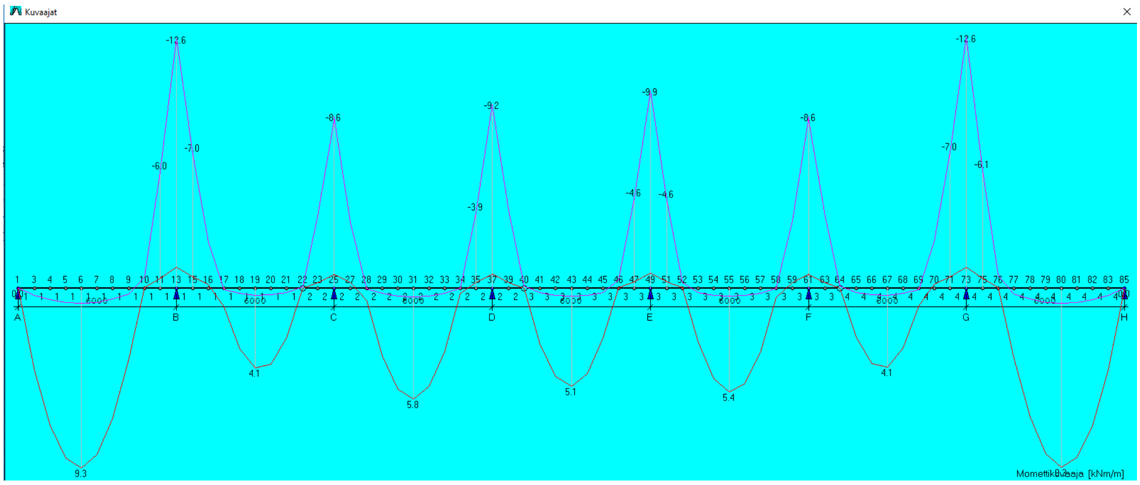


Thickness	0,7/350	0,7/350	0,7/350
Length (mm)	12090	11980	12090
Utilization rate between supports (%)	80,2	80,2	80,2
Utilization rate on supports (%)	98,9	98,9	98,9
Utilization rate of deflection (%)	103,0	103,0	103,0

➔ Utilization rate of deflection is under given terms

Steel consumption 8,85 kg /m^2

Gerber joint



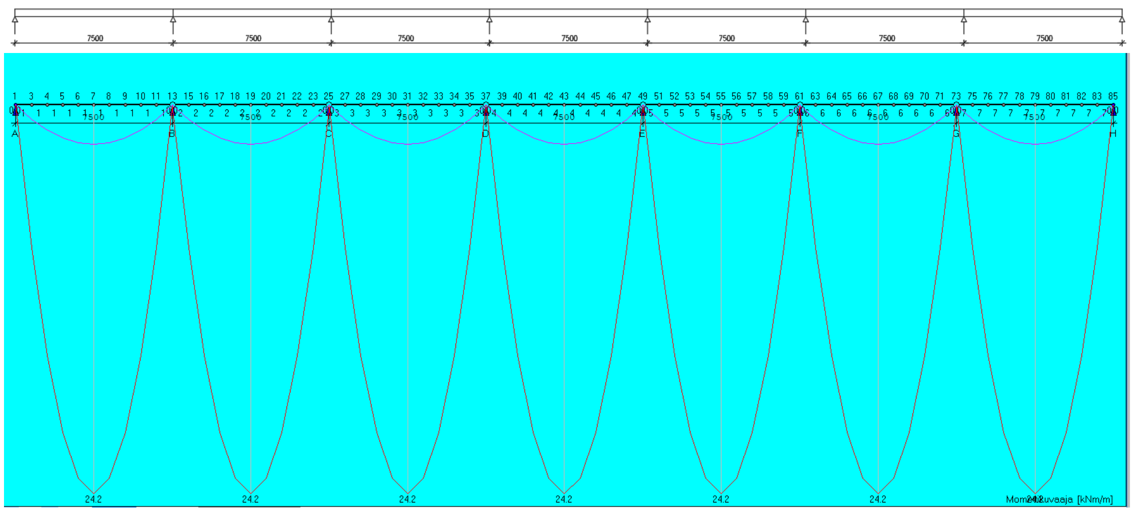
Thickness	0,9/350	0,7/350	0,7/350	0,9/350
Length (mm)	10975	8850	12150	10975
Utilization rate between supports (%)	57,2	55,3	51,9	57
Utilization rate on supports (%)	60,3	64,1	68,5	60,6
Utilization rate of deflection (%)	99,3	65,1	58,1	98,8

➔ OK

Steel consumption 10,27 kg /m^2

Prefabricated element: 7500 mm

Single span

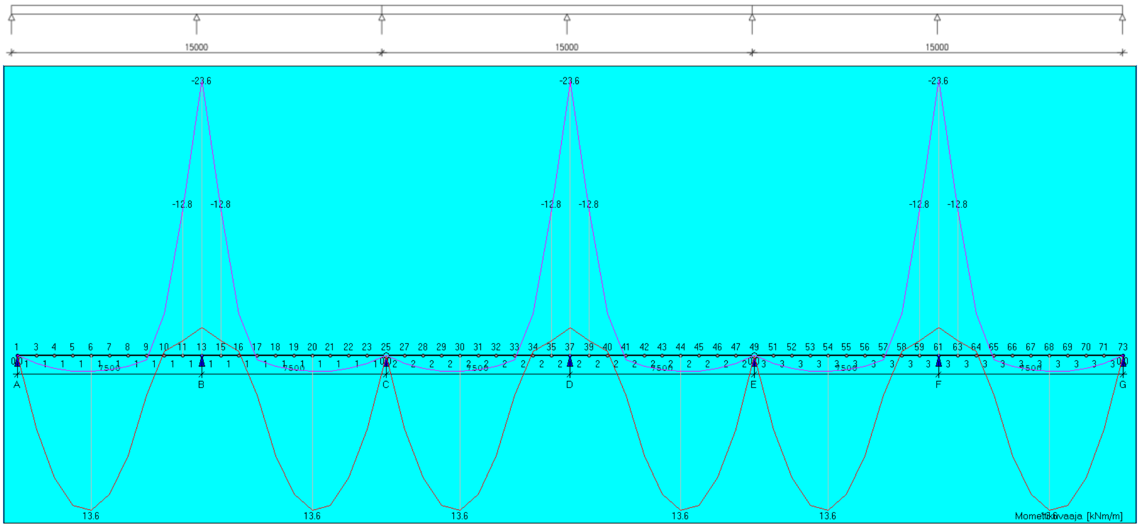


Thickness	1,5/350	1,5/350	1,5/350	1,5/350	1,5/350	1,5/350	1,5/350
Length (mm)	7590	7480	7480	7480	7480	7480	7590
Utilization rate between supports (%)	61,1	61,1	61,1	61,1	61,1	61,1	61,1
Utilization rate on supports (%)	40,1	40,1	40,1	40,1	40,1	40,1	40,1
Utilization rate of deflection (%)	227,3	227,3	227,3	227,3	227,3	227,3	227,3

➔ Utilization rate of deflection is too much

Steel consumption 18,95 kg /m^2

Double span

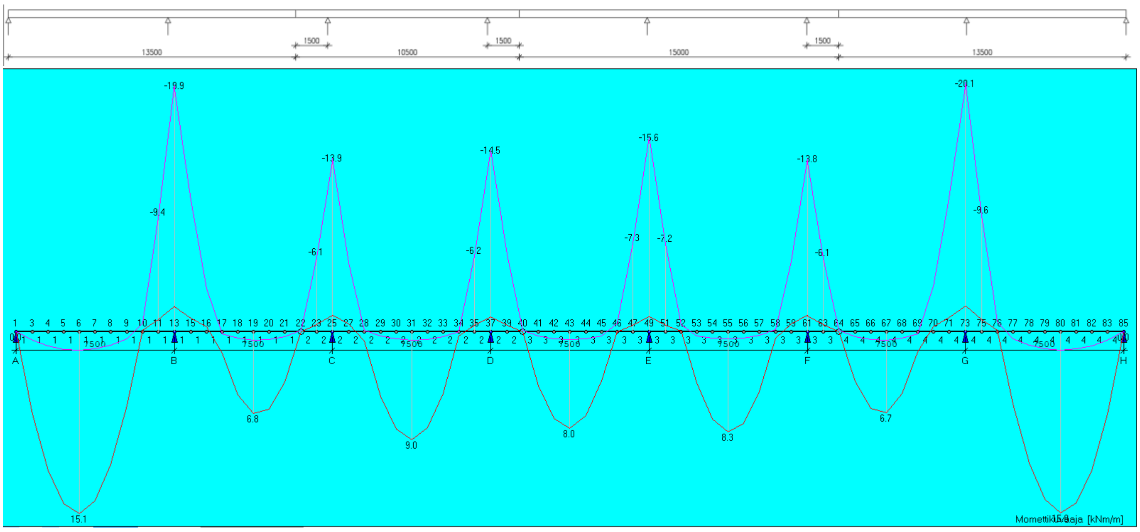


Thickness	1,5/350	1,5/350	1,5/350
Length (mm)	15090	14980	15090
Utilization rate between supports (%)	34,2	34,2	34,2
Utilization rate on supports (%)	55,3	55,3	55,3
Utilization rate of deflection (%)	94,3	94,3	94,3

➔ OK

Steel consumption 18,98 kg /m^2

Gerber joint



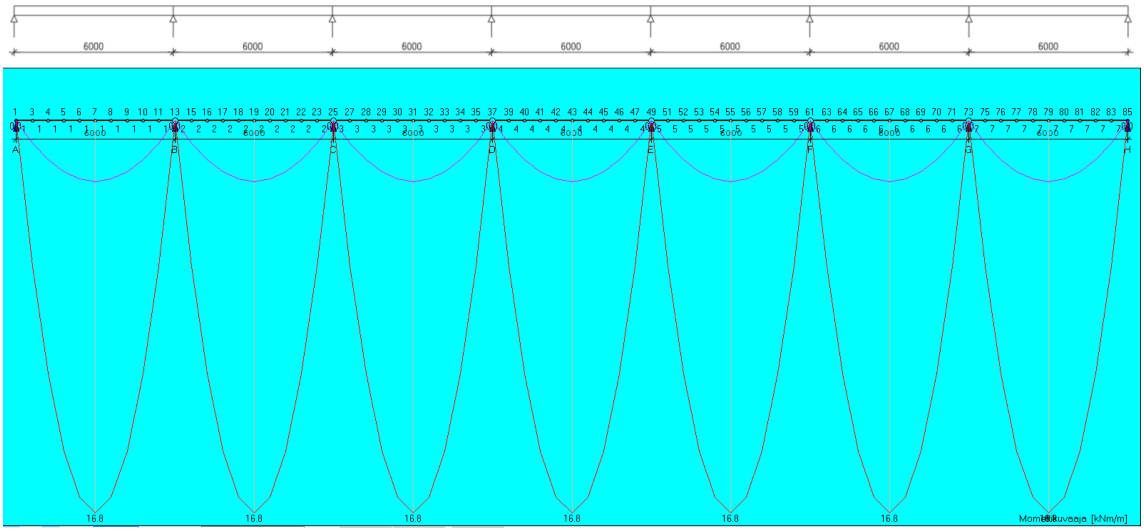
Thickness	1,5/350	0,9/350	0,8/350	1,5/350
Length (mm)	13675	10650	15150	13675
Utilization rate between supports (%)	38,0	54,9	62,4	37,8
Utilization rate on supports (%)	47,2	68,7	85,9	47,6
Utilization rate of deflection (%)	113,3	100,1	97,8	112,3

➔ Utilization rate is too much in side spans

Steel consumption 15,07 kg /m^2

Built-up roof structure 6000 mm

Single span

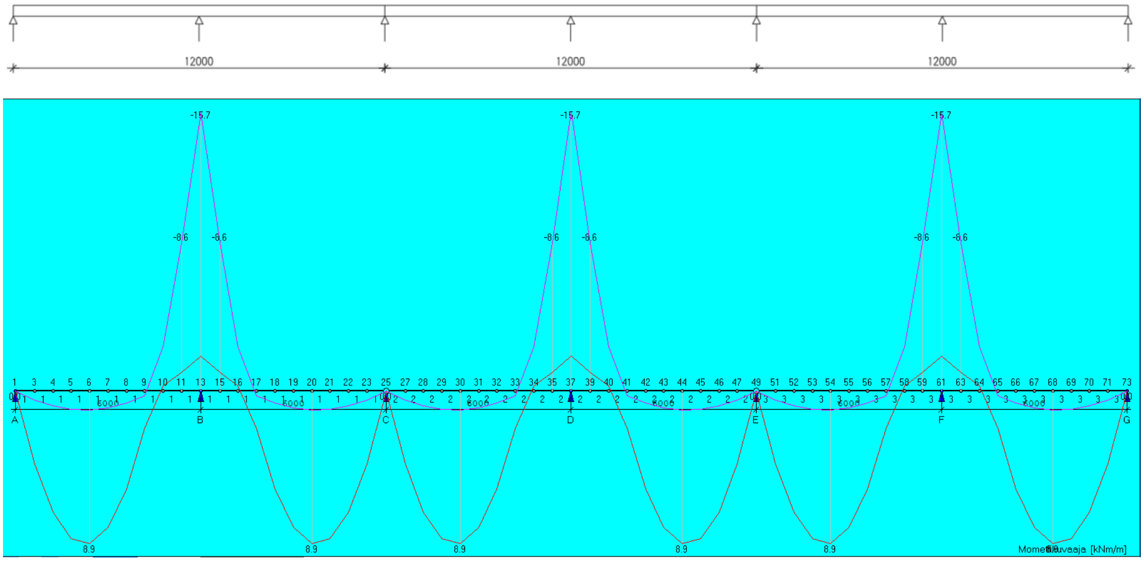


Thickness	1,5/350	1,5/350	1,5/350	1,5/350	1,5/350	1,5/350	1,5/35
Overlapping	one side	one side	one side	one side	one side	one side	one sid
Length (mm)	6175	6150	6150	6150	6150	6150	6175
Utilization rate between supports (%)	29,1	29,1	29,1	29,1	29,1	29,1	29,1
Utilization rate on supports (%)	28,9	28,9	28,9	28,9	28,9	28,9	28,9
Utilization rate of deflection (%)	88,3	88,3	88,3	88,3	88,3	88,3	88,3

➔ OK

Steel consumption 28,32 kg /m^2

Double span

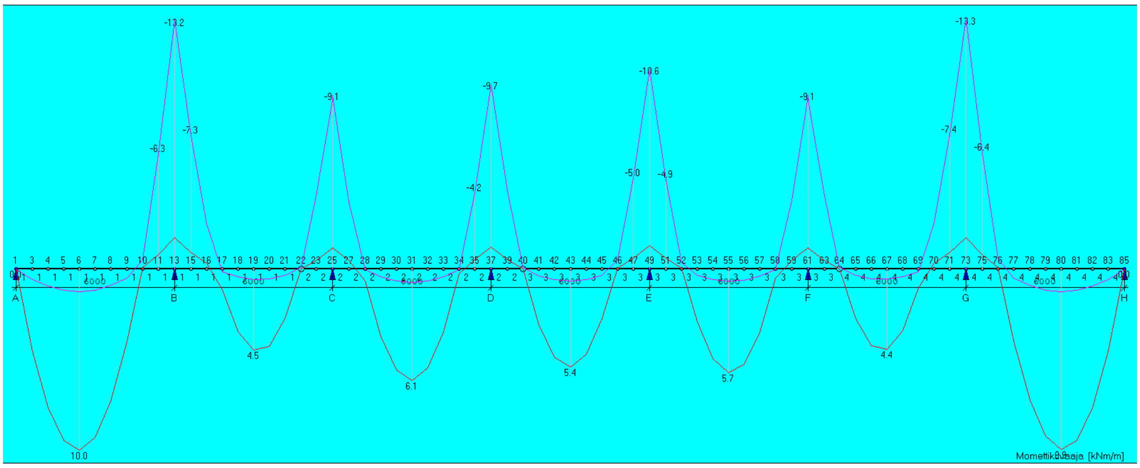


Thickness	1,0/350	1,0/350	1,0/350
Overlapping	-	-	-
Length (mm)	12175	12150	12175
Utilization rate between supports (%)	45,5	45,5	45,5
Utilization rate on supports (%)	87,6	87,6	87,6
Utilization rate of deflection (%)	79,2	79,2	79,2

- ➔ OK

Steel consumption 12,77 kg /m^2

Gerber joint

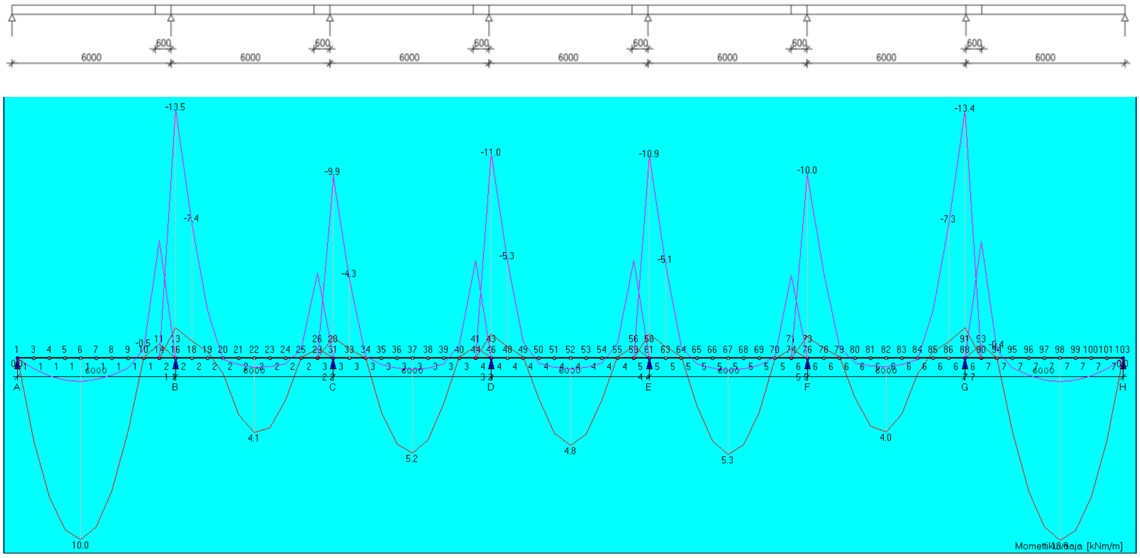


Thickness	1,0/350	0,8/350	0,8/350	1,0/350
Overlapping	-	-	-	-
Length (mm)	10975	8550	12150	10975
Utilization rate between supports (%)	50,8	45,8	42,7	50,7
Utilization rate on supports (%)	75,7	96,2	99,4	76,0
Utilization rate of deflection (%)	95,7	62,3	55,0	95,2

- ➔ Utilization rate is too much in side spans

Steel consumption 11,55 kg /m^2

Continuous structure



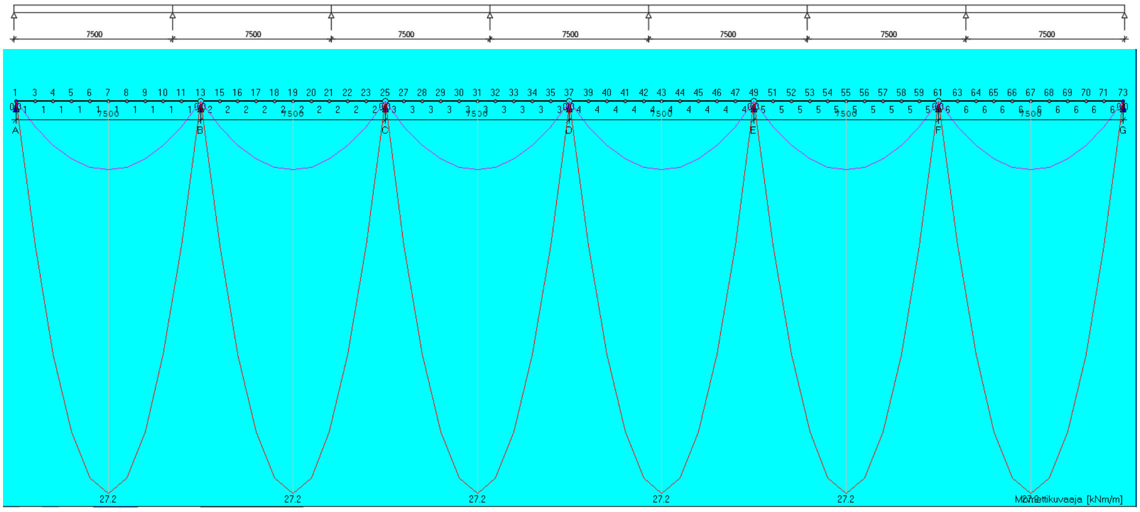
Thickness	1,0/350	0,8/350	0,7/350	0,8/350	0,8/350	0,8/350	1,0/35
Overlapping	-	-	-	-	-	-	-
Length (mm)	6125	6650	6650	6650	6650	7250	6125
Utilization rate between supports (%)	50,9	54,0	50,2	38,9	39,6	53,8	51,0
Utilization rate on supports (%)	34,3	98,8	92,9	80,6	80,0	98,3	34,2
Utilization rate of deflection (%)	97,0	27,2	54,0	39,9	48,8	25,3	97,5

➔ OK

Steel consumption 11,60 kg /m^2

Built-up roof structure 7500 mm

Single span

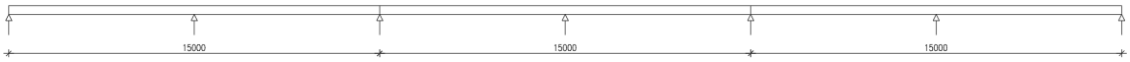


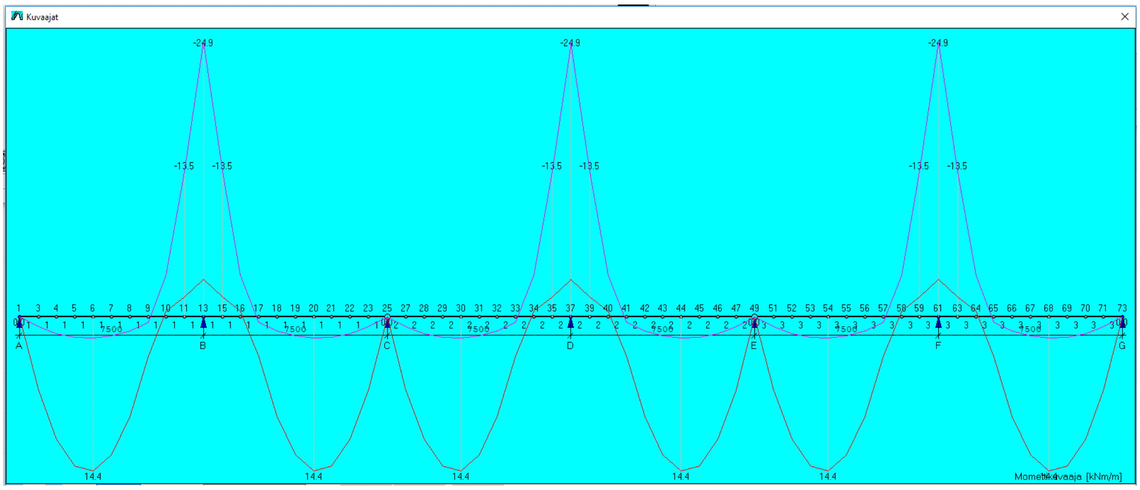
Thickness	1,0/350	0,8/350	0,7/350	0,8/350	0,8/350	0,8/350	1,0/35
Overlapping	double	double	double	double	double	double	doubl
Length (mm)	7675	7650	7650	7650	7650	7650	7675
Utilization rate between supports (%)	34,2	34,2	34,2	34,2	34,2	34,2	34,2
Utilization rate on supports (%)	18,6	18,6	18,6	18,6	18,6	18,6	18,6
Utilization rate of deflection (%)	130,7	130,7	130,7	130,7	130,7	130,7	130,7

➔ Utilization rate of deflection is too much

Steel consumption 38,61 kg /m^2

Double span



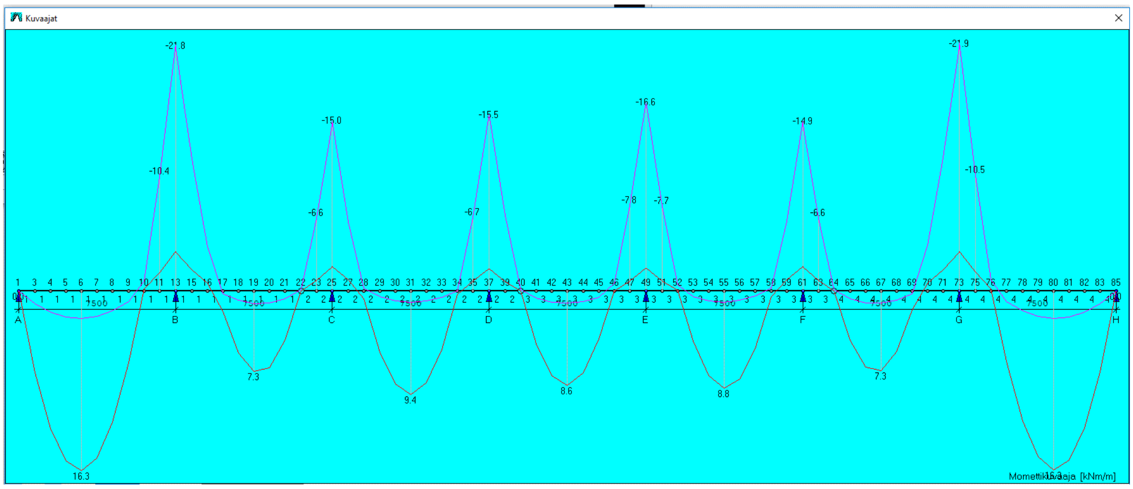


Thickness	1,5/350	1,5/350	1,5/350
Overlapping	-	-	-
Length (mm)	15175	15150	15175
Utilization rate between supports (%)	36,2	36,2	36,2
Utilization rate on supports (%)	66,0	66,0	66,0
Utilization rate of deflection (%)	101,0	101,0	101,0

➔ OK

Steel consumption 19,12 kg /m^2

Gerber joint

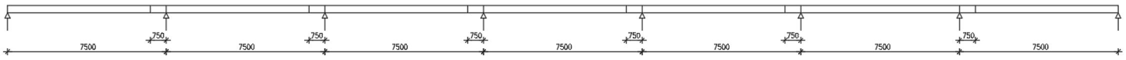


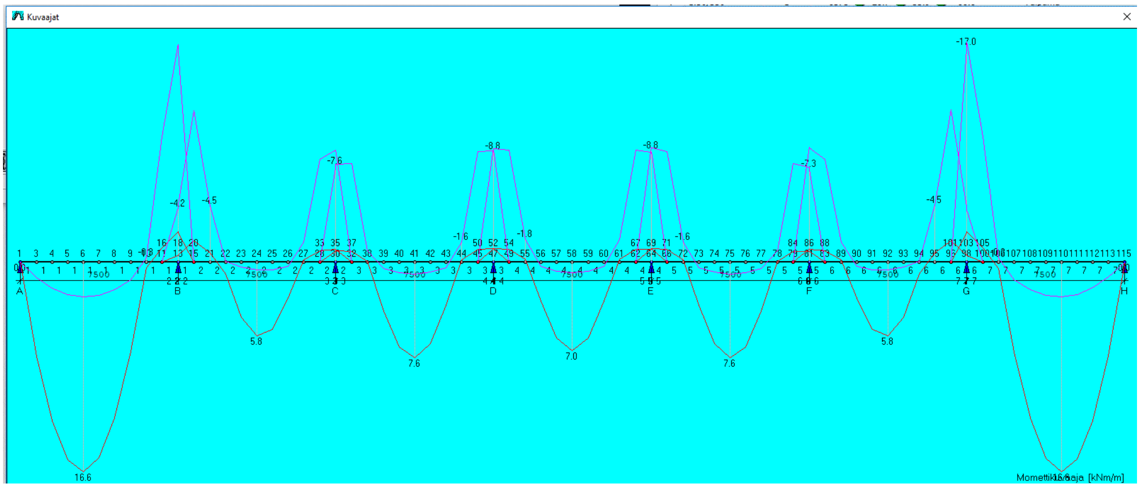
Thickness	1,5/350	1,0/350	1,0/350	1,5/350
Overlapping	one side	-	-	one side
Length (mm)	13675	10650	15150	13675
Utilization rate between supports (%)	28,2	47,9	45,1	28,1
Utilization rate on supports (%)	43,6	86,6	91,2	43,9
Utilization rate of deflection (%)	85,2	92,7	83,1	84,6

➔ OK

Steel consumption 20,59 kg /m^2

Continuous structure





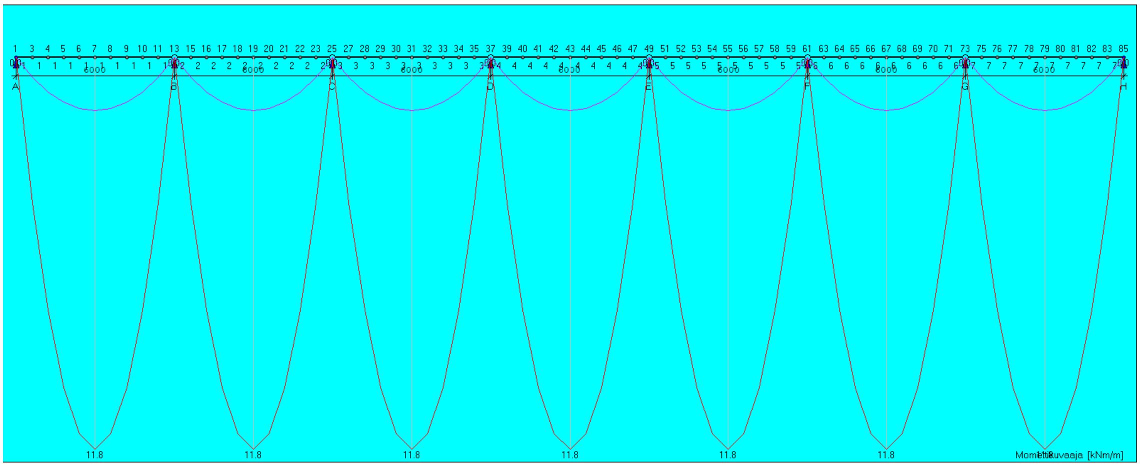
Thickness	1,5/350	0,8/350	0,7/350	0,7/350	0,7/350	0,8/350	1,5/35
Overlapping	one side	-	-	-	-	-	one sid
Length (mm)	8375	9050	9050	9050	9050	9050	8375
Utilization rate between supports (%)	28,7	43,7	72,9	67,3	72,9	43,6	28,7
Utilization rate on supports (%)	33,7	88,4	91,7	92,5	92,6	88,5	34,0
Utilization rate of deflection (%)	88,9	41,6	91,0	75,9	91,0	41,7	88,8

➔ OK

Steel consumption 16,86 kg /m^2

Prefabricated element: 6000 mm

Single span

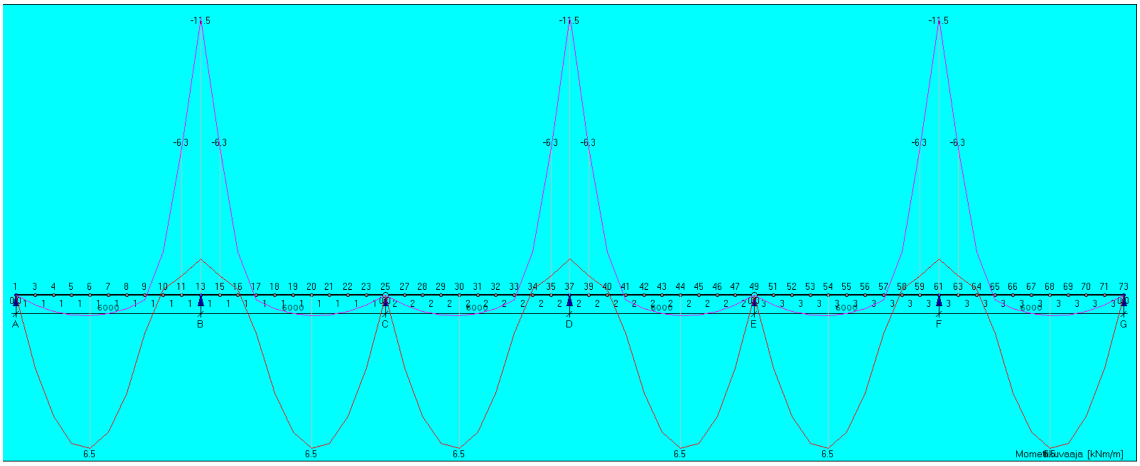


Thickness	0,8/350	0,8/350	0,8/350	0,8/350	0,8/350	0,8/350	0,8/350
Length (mm)	6090	5980	5980	5980	5980	5980	6090
Utilization rate between supports (%)	88,4	88,4	88,4	88,4	88,4	88,4	88,4
Utilization rate on supports (%)	69,9	69,9	69,9	69,9	69,9	69,9	69,9
Utilization rate of deflection (%)	101,0	101,0	101,0	101,0	101,0	101,0	101,0

➔ OK

Steel consumption 10,10 kg /m^2

Double span

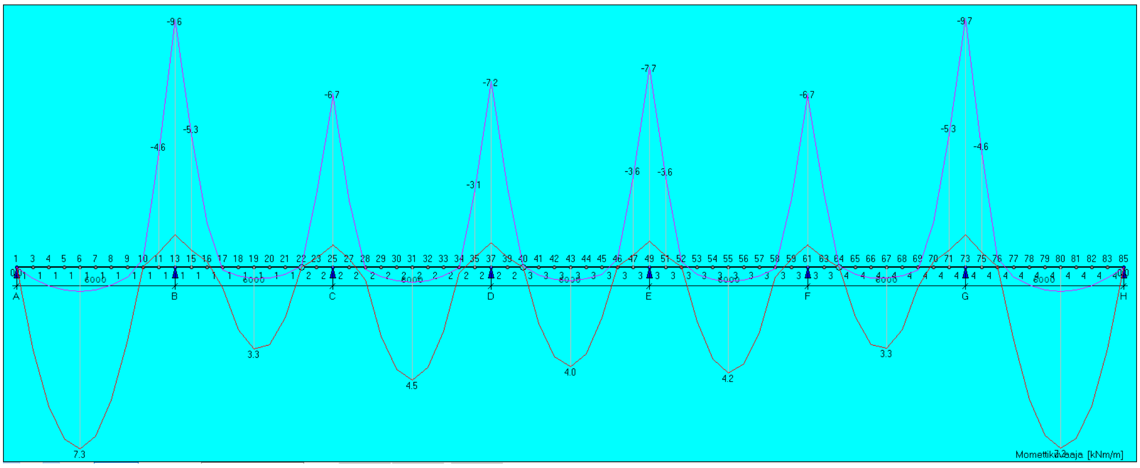


Thickness	0,7/350	0,7/350	0,7/350
Length (mm)	12090	11980	12090
Utilization rate between supports (%)	62,8	62,8	62,8
Utilization rate on supports (%)	77,4	77,4	77,4
Utilization rate of deflection (%)	46,2	46,2	46,2

➔ OK

Steel consumption 8,85 kg /m^2

Gerber joint



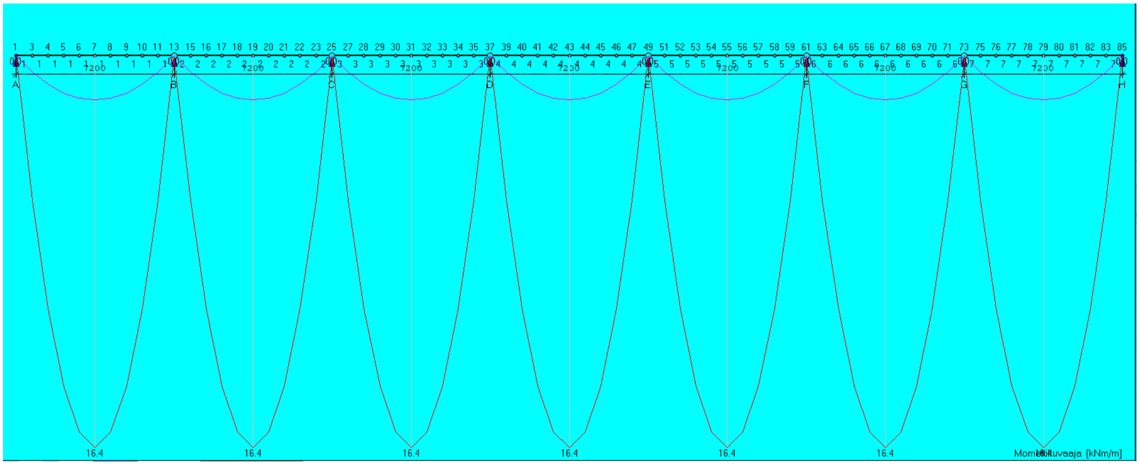
Thickness	0,7/350	0,7/350	0,7/350	0,7/350
Length (mm)	10975	8850	12150	10975
Utilization rate between supports (%)	70,1	43,4	40,7	69,9
Utilization rate on supports (%)	65,6	50,2	53,6	65,9
Utilization rate of deflection (%)	55,9	29,4	26,2	55,6

➔ OK

Steel consumption 8,96 kg /m^2

Prefabricated element: 7200 mm

Single span

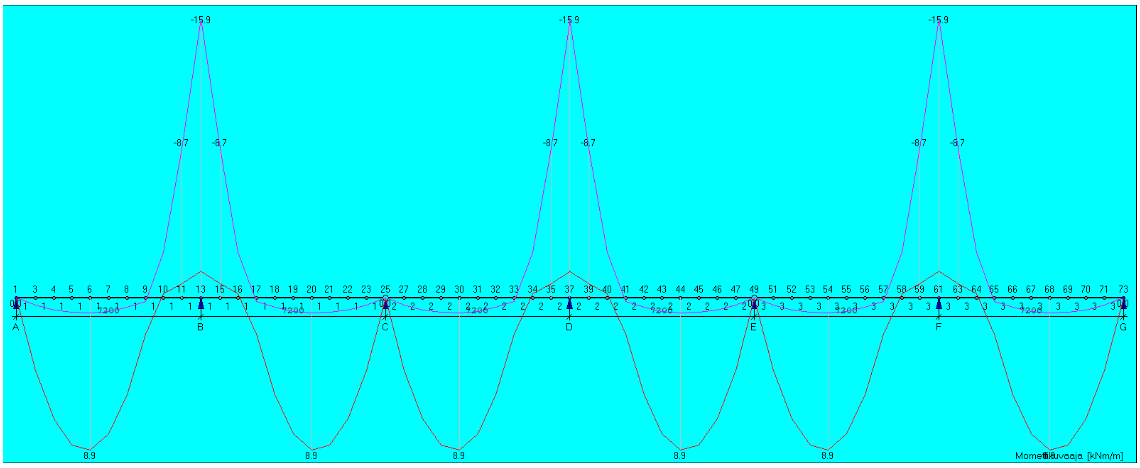


Thickness	1,2/350	1,2/350	1,2/350	1,2/350	1,2/350	1,2/350	1,2/350
Length (mm)	7290	7180	7180	7180	7180	7180	7290
Utilization rate between supports (%)	60,9	60,9	60,9	60,9	60,9	60,9	60,9
Utilization rate on supports (%)	36,3	36,3	36,3	36,3	36,3	36,3	36,3
Utilization rate of deflection (%)	104,3	104,3	104,3	104,3	104,3	104,3	104,3

➔ Utilization rate of deflection is under given terms

Steel consumption 15,16 kg /m^2

Double span

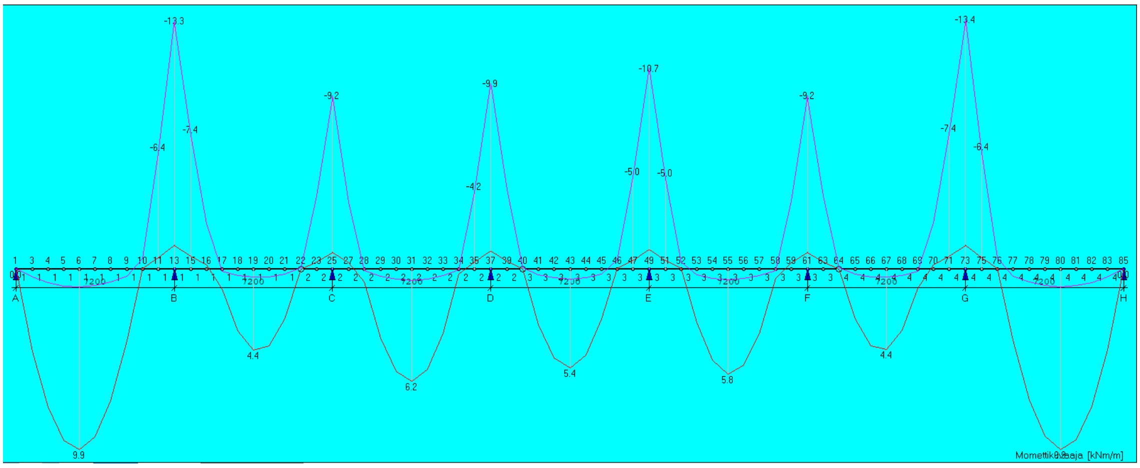


Thickness	0,8/350	0,8/350	0,8/350
Length (mm)	14490	14380	14490
Utilization rate between supports (%)	66,7	66,7	66,7
Utilization rate on supports (%)	85,1	85,1	85,1
Utilization rate of deflection (%)	62,4	62,4	62,4

➔ OK

Steel consumption 10,12 kg /m^2

Gerber joint



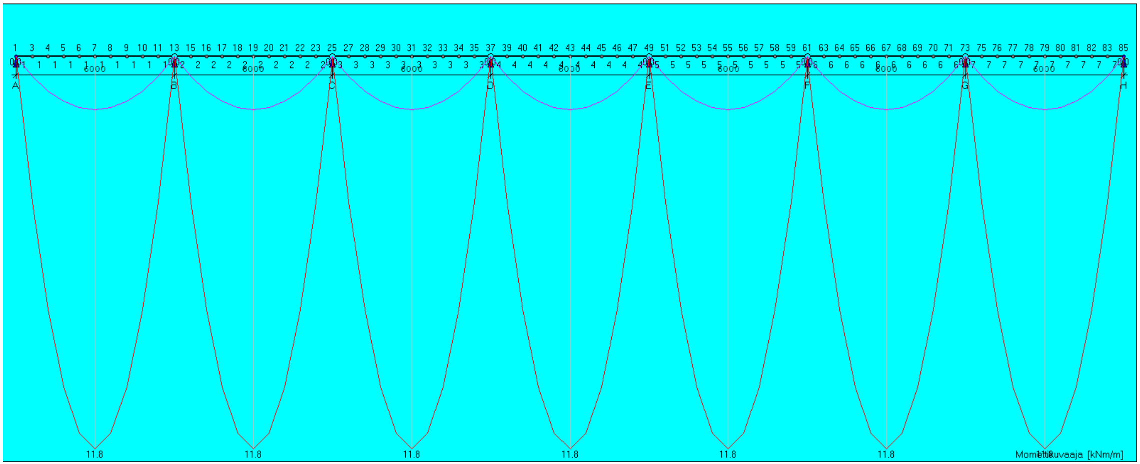
Thickness	0,8/350	0,8/350	0,8/350	0,8/350
Length (mm)	13135	10230	14550	13135
Utilization rate between supports (%)	74,5	46,4	43,2	74,3
Utilization rate on supports (%)	72,4	55,4	59,4	72,7
Utilization rate of deflection (%)	75,6	40,1	35,4	75,2

➔ OK

Steel consumption 10,22 kg /m^2

Built-up roof structure 6000 mm

Single span

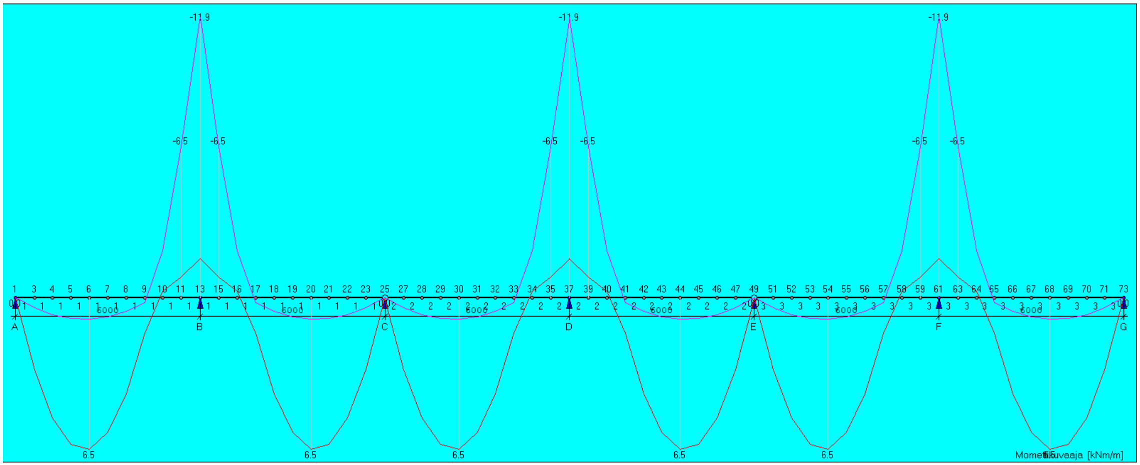


Thickness	0,8/350	0,8/350	0,8/350	0,8/350	0,8/350	0,8/350	0,8/350
Length (mm)	6175	6150	6150	6150	6150	6150	6175
Utilization rate between supports (%)	88,4	88,4	88,4	88,4	88,4	88,4	88,4
Utilization rate on supports (%)	69,9	69,9	69,9	69,9	69,9	69,9	69,9
Utilization rate of deflection (%)	101,0	101,0	101,0	101,0	101,0	101,0	101,0

➔ OK

Steel consumption 10,35 kg /m^2

Double span

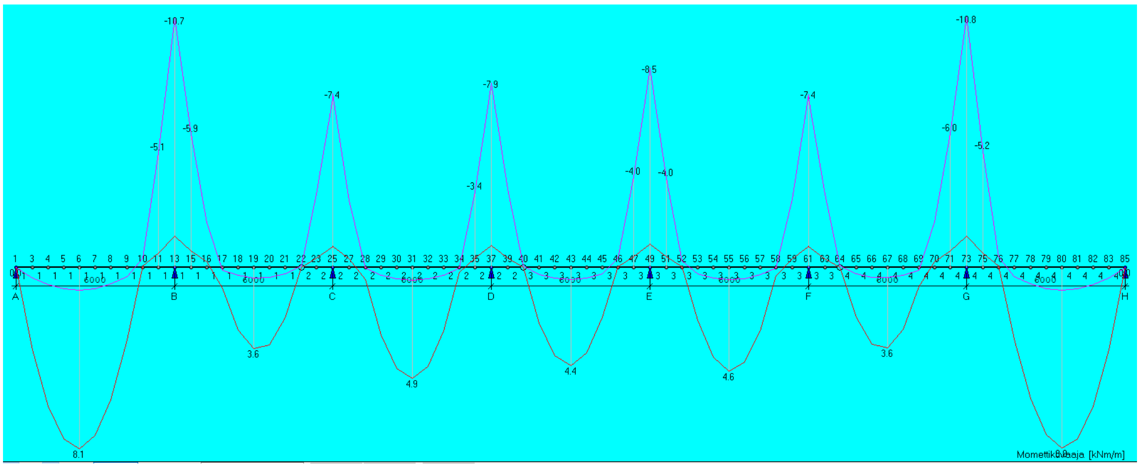


Thickness	0,9/350	0,9/350	0,9/350
Overlapping	-	-	-
Length (mm)	12175	12150	12175
Utilization rate between supports (%)	40,2	40,2	40,2
Utilization rate on supports (%)	85,9	85,9	85,9
Utilization rate of deflection (%)	37,3	37,3	37,3

➔ OK

Steel consumption 11,47 kg /m^2

Gerber joint

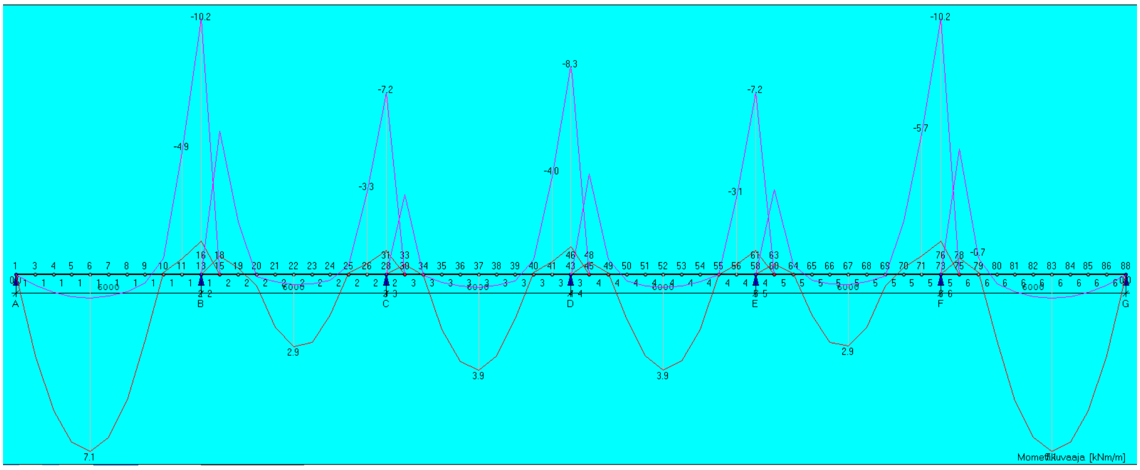


Thickness	1,0/350	0,8/350	0,8/350	1,0/350
Overlapping	-	-	-	-
Length (mm)	10975	8550	12150	10975
Utilization rate between supports (%)	41,1	36,9	34,5	41,0
Utilization rate on supports (%)	61,2	77,7	80,3	61,5
Utilization rate of deflection (%)	97,0	62,9	55,6	96,6

➔ OK

Steel consumption 11,55 kg /m^2

Continuous structure



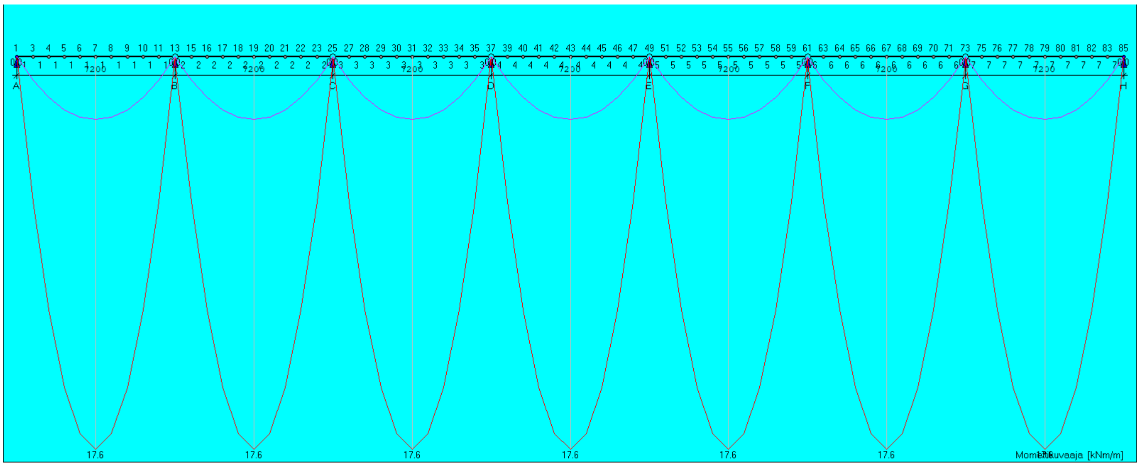
Thickness	0,7/350	0,7/350	0,7/350	0,7/350	0,7/350	0,7/350	0,7/35
Overlapping	-	-	-	-	-	-	-
Length (mm)	6725	6650	6650	6650	6650	6650	6125
Utilization rate between supports (%)	68,7	31,6	37,9	35,9	37,9	53,2	68,7
Utilization rate on supports (%)	95,6	68,2	75,2	75,3	68,1	95,7	47,5
Utilization rate of deflection (%)	53,9	11,4	23,4	19,1	23,5	11,2	54,7

➔ OK

Steel consumption 9,68 kg /m^2

Built-up roof structure 7200 mm

Single span

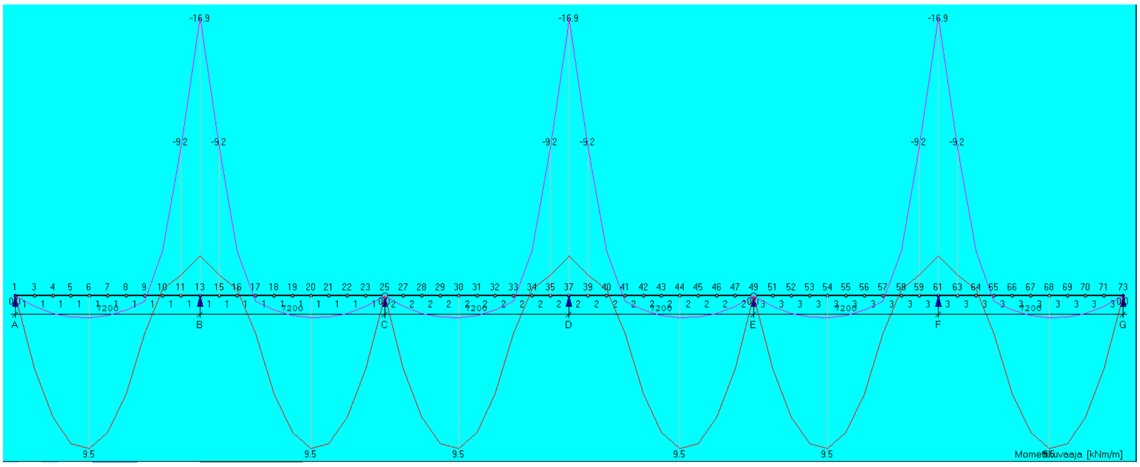


Thickness	1,5/350	1,5/350	1,5/350	1,5/350	1,5/350	1,5/350	1,5/35
Overlapping	-	-	-	-	-	-	-
Length (mm)	7375	7350	7350	7350	7350	7350	7375
Utilization rate between supports (%)	44,4	44,4	44,4	44,4	44,4	44,4	44,4
Utilization rate on supports (%)	25,2	25,2	25,2	25,2	25,2	25,2	25,2
Utilization rate of deflection (%)	94,9	94,9	94,9	94,9	94,9	94,9	94,9

➔ OK

Steel consumption 19,33 kg /m^2

Double span

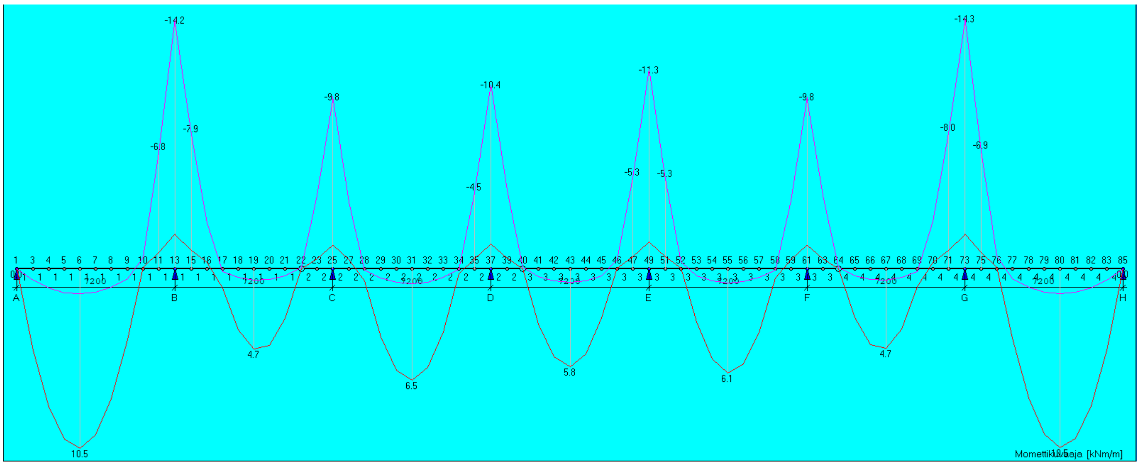


Thickness	1,0/350	1,0/350	1,0/350
Overlapping	-	-	-
Length (mm)	14575	14550	14575
Utilization rate between supports (%)	48,7	48,7	48,7
Utilization rate on supports (%)	88,5	88,5	88,5
Utilization rate of deflection (%)	58,4	58,4	58,4

➔ OK

Steel consumption 12,75 kg /m^2

Gerber joint

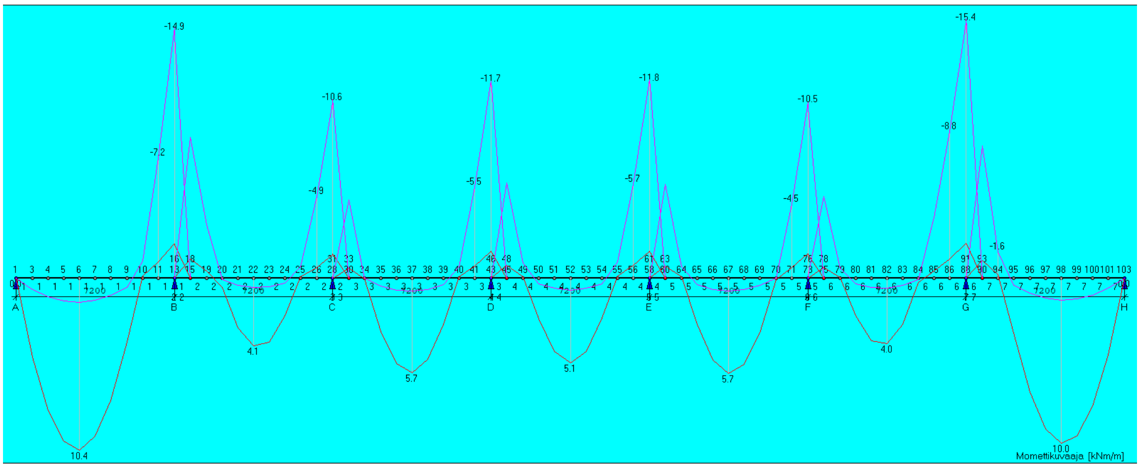


Thickness	0,9/350	0,8/350	0,8/350	0,9/350
Overlapping	-	-	-	-
Length (mm)	13675	10650	15150	13675
Utilization rate between supports (%)	64,7	49,0	45,7	64,5
Utilization rate on supports (%)	91,8	90,7	95,4	92,2
Utilization rate of deflection (%)	78,1	45,5	40,1	77,8

➔ OK

Steel consumption 10,88 kg /m^2

Continuous structure



Thickness	0,9/350	0,8/350	0,8/350	0,8/350	0,8/350	0,9/350	0,7/35
Overlapping	-	-	-	-	-	-	-
Length (mm)	8045	7970	7970	7970	7970	7970	7325
Utilization rate between supports (%)	63,6	32,2	42,6	41,6	42,9	53,3	95,9
Utilization rate on supports (%)	89,6	77,6	85,8	86,3	76,6	92,9	74,9
Utilization rate of deflection (%)	76,1	16,8	36,3	29,1	36,5	14,5	89,2

➔ OK

Steel consumption 11,27 kg /m^2