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PVC-COVERED STEEL HALL AND THE EFFECTS OF THE SNOW LOAD ON THE PURLINS

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Construction and Civil Engineering Abstract
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The commissioner of this thesis is AFRY Finland Oy. The aim of this thesis was to investigate the effect of the snow load on the purlins of a steel structured PVC hall. The purlins are affected by the normal snow load, and the additional snow load caused by the bagging of the PVC fabric and the accumulated snow on the bags, which is usually not considered when dimensioning the purlins of the steel hall. At the moment there are no guidelines in the Eurocodes on how to design a PVC covered steel hall, which could be used as an aid when investigating or designing a hall.

PVC halls have collapsed under excessive snow load in Finland. Usually, they are caused by poorly designed steel structures and underestimated snow loads on them. If designed correctly, PVC halls are cost effective and durable options for different kind of use.

The goal was to find a method that can be used when evaluating the effect of the snow load on the purlins when designing and inspecting PVC halls. As steel structures come in different forms and PVC material has different mechanical properties, the method used here is simplified, but it can give valuable information when inspecting existing halls or designing a new hall.

Keywords PVC hall, snow load, steel hall
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Työn nimi PVC-covered Steel Hall and the Effects of the Snow Load on the Purlins
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Tämän opinnäytetyön toimeksiantaja on AFRY Finland Oy. Opinnäytetyön tavoitteena oli tutkia lumikuorman vaikutusta PVC-katteisen teräshallin orsiin. Orsiin vaikuttaa normaali lumikuorma, sekä PVC-kankaan pussittamisesta ja pusseihin kerääntyvästä lumesta aiheutuva lisälumikuorma, jota ei tavallisesti oteta huomioon teräshallin orsia mitoitettaessa. Tällä hetkellä Eurokoodeista ei löydy tietoa, kuinka PVC-halli suunnitellaan, eikä muutakaan tietoa, mitä voisi käyttää apuna PVC-katteista hallia tutkittaessa tai suunniteltaessa.

Suomessa PVC-halleja on romahtanut, kun katolle on kertynyt suuri määrä lunta. Tavallisesti romahdukset ovat johtuneet puutteellisesti suunnitelluista teräsrakenteista ja liian pieniksi mitoitetuista lumikuormista. Jos PVC-halli suunnitellaan oikein, se on edullinen ja kestävä vaihtoehto moniin käyttötarkoituksiin.

Tavoitteena oli löytää metodi, jolla lumen pussittamisesta orsille aiheutuvaa taipumaa voidaan arvioida PVC-halleja suunniteltaessa ja mitoittaessa. Koska teräshalleissa on erilaisia rakenneratkaisuja ja PVC-kankaiden mekaaniset ominaisuudet vaihtelevat kankaan toimittajien ja erilaisten kangaslaatujen välillä, tässä esitelty laskentametodi on erittäin yksinkertaistettu. Siitä saa kuitenkin arvokasta tietoa, jota voi käyttää hyväksi tutkittaessa olemassa olevia halleja tai uusia halleja suunniteltaessa.

Avainsanat PVC-halli, teräshalli, lumikuorma
Sivut 27 sivua ja liitteitä 6 sivua

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1 Introduction

PVC halls are widely used in Finland because they are cost effective and quick to construct. One-storey PVC halls are mainly used as warehouses, production and sport facilities. They are durable when properly designed and maintained. They can be a safety risk if poorly designed, as the structures are unstable and not able to withstand snow or wind loads (Heima, 2017).

In 2013 a steel structured indoor riding arena collapsed in Laukaa, which lead to the death of a child. The accident in Laukaa led to the enactment of so-called Hall Act in 2015. The law stipulates the obligation of the building owner to ensure that the safety of building has been assessed by an expert (Laki laajarunkoisten rakennusten rakenteellisen turvallisuuden arvioinnista 20.3.2015/300). The Finnish Safety and Chemical Agency Tukes has been particularly concerned about the safety of PVC halls, due to defects found in the design of load bearing steel structures (Tukes, 2019). After many assignments to inspect the PVC halls, it became clear that there was not enough information available about the bagging of the PVC cover under the snow load, and the effects of the resulting additional snow load on the purlins.

The design of a PVC covered steel hall differs from the design of a hard covered steel hall. PVC, being a textile material, behaves differently compared to conventional building materials. At the moment there are no comprehensive guidelines for designing a PVC hall, and Eurocode for Design of Tensioned Membrane Structures is still under way (Milošević & Marković, 2020). Material about form finding tensile textile structures can be found in literature, but the challenge with PVC halls is that they are not tensile or form finding structures, although the PVC cover must have some tension in it to resist snow and wind loads.

The stability of a PVC halls depends on many factors. The topic of this thesis is to investigate how the bagging of the PVC cover under snow load affects the purlins and thereby the stability of the PVC hall. The thesis is limited to a one-storey steel truss frame hall with pitched roof. The focus is on the snow load, and other types of loads are not considered in thesis. The problem is investigated by searching information from literature, calculating the effects of the snow load by hand, and verifying the hand calculations with Dlubal RFEM 5 Structural Analysis and Design Software.

This thesis is done for AFRY Finland Oy. The target group of this thesis are structural engineers who inspect and design steel halls.

2 A Typical PVC Steel Frame Hall

A PVC hall is a steel truss structured hall covered with PVC fabric. They have a simple design, and they are available in different sizes and shapes. The advantage of the combination of a steel structure and lightweighted PVC cover is lightness of the structure and long spans, which create a lot of free space on the floor. PVC hall is cost-effective and easy to transport to the building site.

The disadvantage is that the designer may not understand how the steel structure remains stable under different loads, which can lead to the collapse of the hall at the worst. Steel structures are easy to repeat in the design, which sometimes leads to copying and varying old designs without a deeper understanding of how the structure works properly. Design errors in the steel structures typically start to appear when the terrain’s snow load increases to around 100kg/m^2. Usually, the problem of the collapsed halls is insufficient stiffening of the steel structure. (Tukes, 2022).

At the present the steel structures are dimensioned according to the Eurocodes SFS-EN-1993-1-1, but there are no guidelines in the Eurocodes on how the snow load should be considered in the design when the steel structure is covered with a thin textile membrane, PVC. Textile membrane can take tension loads only, and it is not a part of the stiffening or load-bearing system, which is the case when, for example, corrugated sheets are used.

Even though textiles have been used as a building material for thousands of years, they have evolved into more complicated form-finding tensile structures only recently. Unfortunately, the obtained information from the studies of the tensile structures does not apply in the PVC halls, as the PVC cover does not act as a tensile structure. Currently, the design and manufacture of a PVC hall depends mainly on the designer’s experience and knowledge, but the advanced FEM programs may help in the design process.

2.1 The Steel Truss Structure

The steel truss structure in a PVC hall acts as a load bearing structure. The waterproof PVC fabric protects the building from weather conditions, and distributes wind and snow loads to the load bearing steel structure. The structure must be stable enough to withstand the loads without collapsing.

A steel truss structure is made of several steel truss frames that are placed adjacent to each other and tied together with longitudinal secondary beams, purlins. The columns at the end of the hall transfer horizontal wind loads to the foundation and support the PVC cladding. Diagonal members, bracings, transfer loads to the foundations and stabilize the hall.

Steel frame structures, where the frames can be separated into entities, work well in the hall structures. The joints in the frame corners are easy to make, and stability of the hall is easy to adjust by strengthening the frame with stiffening the joints or with diagonal and horizontal bracings.

There are different types of steel frame structures used in a single-aisle steel hall. A simple frame consists of two columns and a beam. This structure can be modified in different ways by using different types of joints between foundation and a column, and between a column and a beam. The column and the beam can be replaced by a truss. The roof truss can be straight, pitched or curved.

In the fixed column base, the columns are rigidly connected to the foundation and the truss is hinged to the columns. In hinged base frames, a rigid frame is connected to the foundations via hinged joints. Three-hinged frames have hinges in the foundation and in the ridge of the roof. Frames with hinged column bases need smaller foundation sizes in comparison to fixed bases. (SteelConstruction.info, n.d.) Anchoring the hall to the ground must be done carefully to avoid the light-built hall being detached from the foundations due to wind or frost. Figure 1 shows a fixed column base frame, where the truss is hinged to the columns. In figure 2, there are different types of frames with rigid corner joint.

Figure 1. A fixed column base frame (Kaitila, 2014, s. 119).

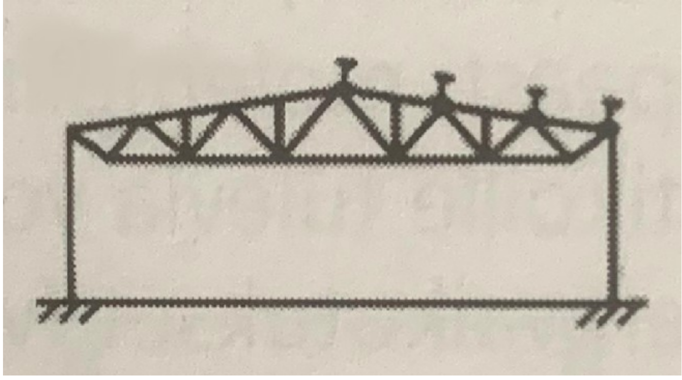
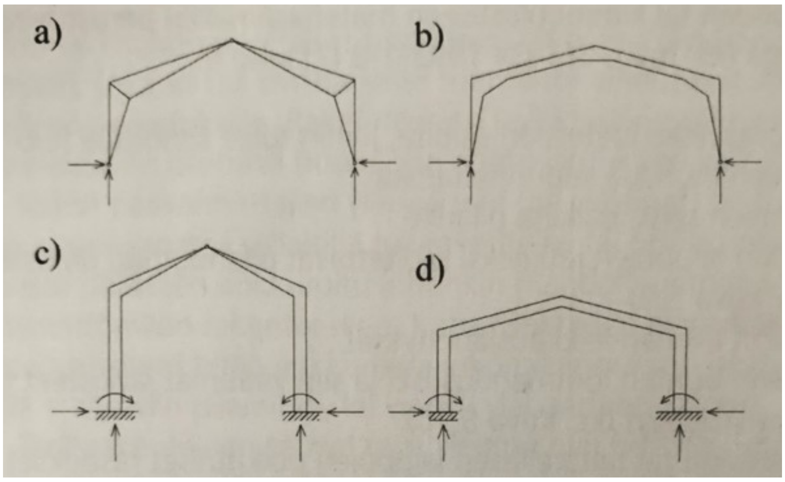


Figure 2. a) Three-hinged frame b) Hinged base frame c) Rigid base with ridge joint d) Frame with rigid base. (Kaitila, 2014, s. 119).



Bracings are the diagonal members between the columns and at each floor or roof level. Bracing system transfer loads to the foundations and reduce the buckling length of the column or the beam by offering support to the member. The bracings are dimensioned for the axial force only, and they must be rigid enough so that they do not buckle under compression.

A truss is built with diagonal and vertical rods that form one or more triangles. Rods in the truss frame can carry only axial loads, while the truss frame structure can carry vertical and horizontal loads. The chords are also subjected to minor bending moment, the top cord under compression and the lower cord under tension.

Purlins can be placed on top of the truss, or the purlins top side can be at the same or lower level of the top of the truss. The purlins bind truss frames on their places and prevent them from buckling to the sides. They support roof cladding and transfer vertical loads from the roof to the trusses, and wind loads to the horizontal bracings. The purlins must be continuous structures along their entire length and should be placed on the nodes of the truss. The purlins are dimensioned for the axial force and bending moment. In the figure 3, the purlin is placed on the same level with the top of the truss, and it supports the PVC cover on the ridge of the roof.

Figure 3. The purlin on the ridge of the roof and trusses.

2.2 Stability of a Steel Frame Structure

A steel structure must maintain its stability under different loads. Steel parts are strong but slender, and the disadvantage of the steel structure is that it can lose its stability easily due to the failing of a part. The structure is subjected to natural loads, whose values are taken from the statistics, and sometimes the loads may exceed their design values. Deflection is usually not a problem, if the deflection or deformation is eliminated when the load is removed. Any permanent deformation of the structure must be fixed, or the structural element replaced immediately to avoid serious accidents, as it is difficult to say how close the steel part was to a fracture. (RIL 246-2008, s. 67). If the structure has been designed correctly according to the Eurocodes, they have sufficiently high safety factors, and even a poorly designed steel hall remains upright until the loads increase too high.

Steel parts can carry a lot of loads relative to their weight, but because an individual part consists of thin plates, the parts lose their stability easily. Loss of stability is affected by dimensions, cross section and supports of the part. Closed cross-sections are stiffer than open cross-sections. It is essential to note which part of the structure is exposed to the compression, because it is prone to buckling.

Buckling of a part is the biggest problem in losing structural stability. Buckling is a determining factor in the dimensioning of columns. Buckling occurs when the compression on a slender member exceeds the normal strength of the material, and the member bends. The main way to prevent the loss of stability of the member is by reducing the buckling length.

Warping torsion is a combination of torsion and bending. It occurs when the member is subjected to excessive bending moment, and the member overturns. Warping torsion is often the determining factor in dimensioning of the beams. It can be prevented with supports on the beam’s top flange. Open cross-sections are sensitive to overturning. Square or circular hollow sections have sufficient restrain on the compression flange, and the warping torsion will not occur.

Frames are load bearing structures, and they carry vertical and horizontal loads. A truss frame is a rigid and strong structure when all the members work in a single plane, and they must be supported against buckling to the side from their plane with the purlins. Frames with pinned column base are non-sway parallel to the frame, and sway perpendicular to the frame. They require vertical and horizontal bracing system in the walls and in the roof to stabilize the hall longitudinally. Lateral displacements of structures must be controlled by stiffening elements (RIL 246-2008 s. 75).

Most common problems in the failure of the steel hall are incorrectly dimensioned loads, discontinuous load paths, insufficient number of purlins and bracings or their wrong placement and incorrect design of joints. If the steel hall is moved to a new location, it must be ensured that the steel parts are installed correctly, and the loads originally used in the design phase are not undersized in the new location.

2.3 The Load Path

All horizontal and vertical loads must be transferred to the foundations with continuous flow. Load paths are used to describe how loads are transferred through the structures. A continuous load path is ensured by members that are placed in the correct places. The members must be joined together so that the center lines of the members intersect at the nodes. Connections must be designed to transfer loads between structural elements.

Horizontal loads parallel to frames are transferred to the foundations via the frames. The frame must be stiff enough to carry the loads without excess lateral movements. Horizontal loads transverse to the truss travel along the purlins until they hit the horizontal bracings. The loads travel then to the vertical bracing and to the foundations. Vertical loads are transferred from the roof to the purlins, from purlins to the trusses and to the foundation via columns of the trusses.

3 Design of a PVC Hall

Design of a PVC hall differs from the design of a hard covered hall. Differences are found in the load bearing and stiffening structures, loads that are considered in the design, and the different behavior of the roofing material.

3.1 Main Differences Between PVC Covered and Hard Covered Hall

In general, the structure of a PVC covered, and a hard covered steel hall is the same. The same rules about load paths apply in both cases. In the PVC hall only the steel structure works as a load bearing and stiffening structure. In the hard covered hall, corrugated boards on the roof and walls can be used as load bearing and stiffening structures together with a steel structure.

Snow load and wind load are the most important loads to be considered when designing a PVC hall. Self-weight of the PVC fabric is negligible, and there is no live load on the roof. In the hard covered wall, the self-weight, live load and possibly a crane load must also be considered in addition to snow and wind loads. Dead load, live load, wind load and snow load are usually calculated as a distributed load. In a PVC hall, the cover blown by the wind also causes point loads to the steel structure at the attachment points of the fabric.

The main difference between a hard covered and a PVC covered steel hall is the different behavior of the roofing material under the snow load, and different pattern of snow accumulation on the roof. Corrugated board act as a load bearing structure, and in general, the snow load is distributed evenly on the roof and the load is easy to calculate. The problem with the PVC hall is bagging of the cover, which leads to bigger snow accumulation in the bags, and bigger snow load in general. Also, the snow may not be distributed evenly on the roof due to different size of bags.

3.2 Snow Load on the PVC Hall

The bagging of the PVC cover occurs when the polyester base of the PVC material yields over the time, and snow and ice gathers in the bag that the stretched material forms. The weight of the snow stretches the bag even deeper, which lead to bigger snow accumulation. Eventually, the surplus snow load in the bag may tear the PVC fabric, or exceed the loads dimensioned for the structure and the steel structure can lose its stability.

There are no guidelines in the Eurocodes on how to determine snow load accumulation on the PVC hall. Usually, the snow slides off the slippery PVC roof, but ageing of the material affects the slipperiness of the fabric, as UV radiation brittles the surface. Figure 4 shows an example of old PVC cover. The surface of the cover is roughened by the age, and the snow can no longer slide down from the roof. The snow stays on the roof, stretches the fabric and gives additional stress to the structures.

Figure 4. An old PCV cover.

The longitudinal purlins may also act as snow fences on the roof, especially if the fabric is already bagging. Risk of bagging due to creep increases when the material ages. If the purlins and trusses are too far apart, the PVC cover will not have enough support and there is greater risk that the fabric will creep under a snow load.

The snow load in the PVC hall may be spread unevenly on the roof, as snow is gathered in the bags in a mosaic-like form. Sometimes the snow load is only on one side of the hall due to wind, or when the roof is incorrectly cleared of snow one side at the time. In addition to excess snow load on the whole structure, problems arise when the snow load is pressed against the purlins. They are not dimensioned to have significant axial and bending moment at the same time, and the utilization ratio of the purlins increase.

The bagging can be avoided by tensioning the PVC cover regularly, but in general the bagging under snow load is expected to happen. The designer should consider the extra snow loads when designing a PVC hall.

The snow load on a roof, which is used when dimensioning a steel hall, is obtained from the Eurocodes SFS-EN 1991-1-3, and it is used to calculate snow load on the hard cover roof. Snow load on the PVC roof is affected by the location of the building, the shape and slope of the roof, indoor heating of the hall and the roughness of the fabric. To simplify the calculations, snow load on roof is determined according to equation 1.

Equation 1. Snow load on the roof.

$$s = \mu i \ Ce \ Ct \ sk$$

where:

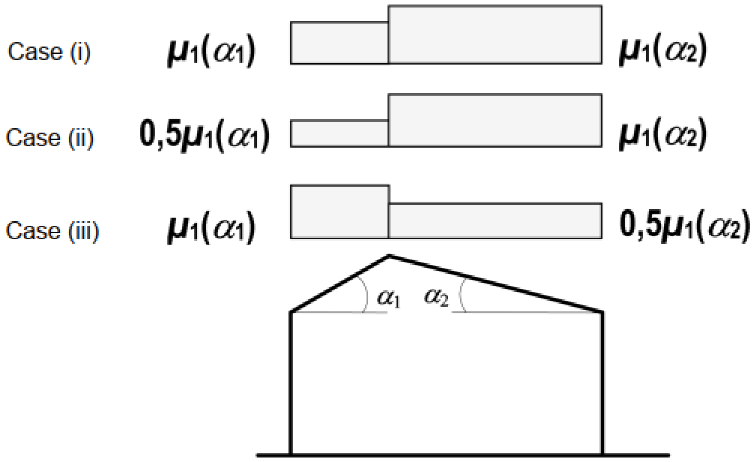
s	is the snow load on the roof	(kN/m^2)
μ_i	is the snow load shape coefficient	
C_e	is the exposure coefficient	
C_t	is the thermal coefficient	
s_k	is the characteristic value of snow load on the ground	(kN/m^2)

(SFS-EN 1991-1-3 + AC + A1, s. 29)

The value of $C_e = 1$, unless otherwise specified. Usually used value of $C_t = 1$. (SFS-EN 1991-1-3 + AC + A1, s. 31)

For determining the snow load on the roof, the snow load shape coefficient μ_i is obtained from figures 5 and 6. The snow load cases in pitched roof are given in figure 5. The undrifted load arrangement is shown in case (i), and the drifted load arrangements are shown in cases (ii) and (iii). (SFS-EN 1991-1-3 + AC + A1, s. 35).

Figure 5. Snow load shape coefficients for pitched roofs (SFS-EN 1991-1-3 + AC + A1, s. 35).



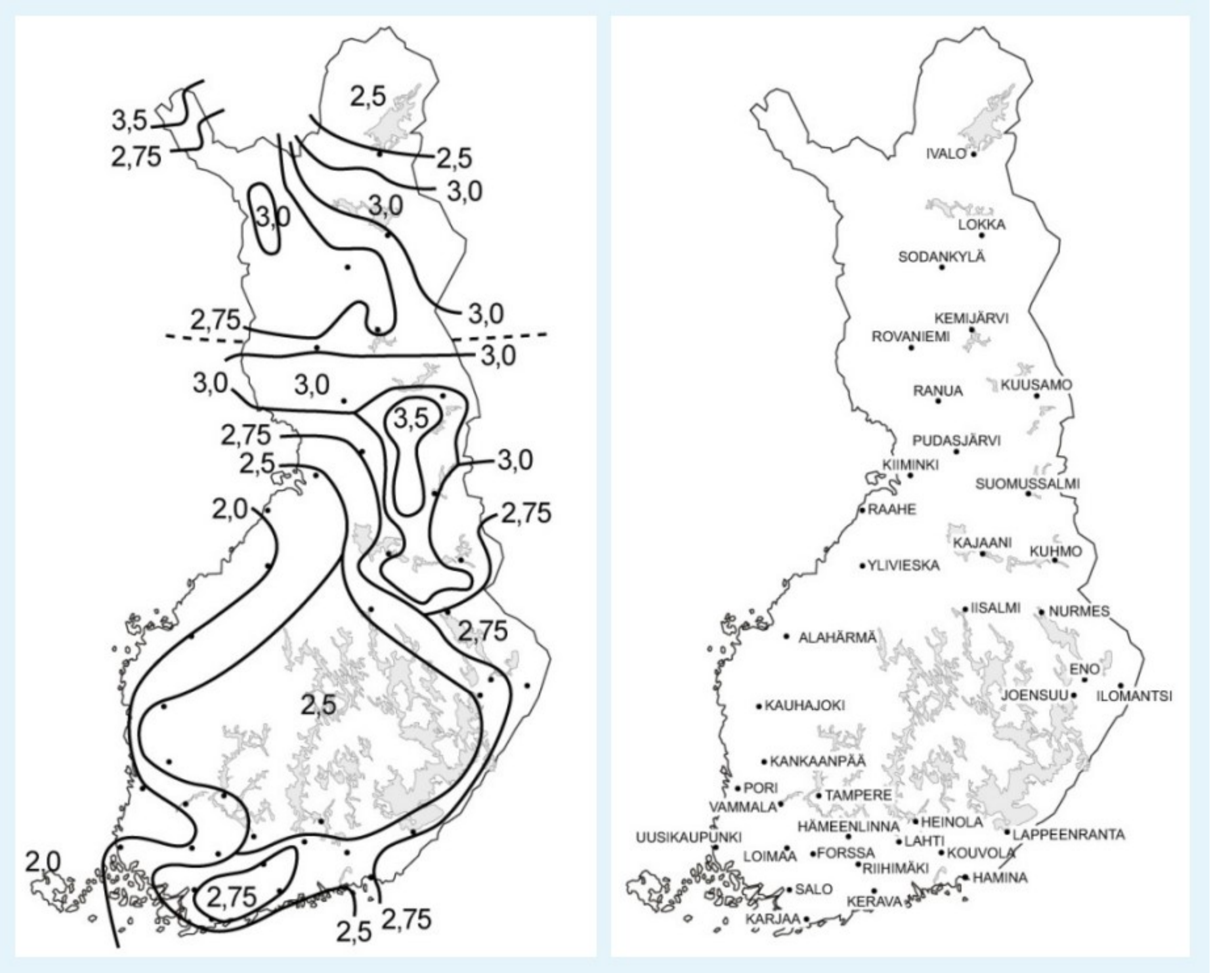
Snow load shape coefficient μ_i is given in figure 6. In the pitched roof PVC hall, the snow may be prevented from sliding off the roof due to purlins, and the snow load shape coefficient should not be reduced below 0,8 (SFS-EN 1991-1-3, s. 35).

Figure 6. Snow load shape coefficients, value of μ_i. (SFS-EN 1991-1-3 + AC + A1, s. 33).

Angle of pitch of roof α	$0° \leq \alpha \leq 30°$	$30° < \alpha < 60°$	$\alpha \geq 60°$
$\mu_1(\alpha)$	$\mu_1(0°) \geq 0,8$	$\mu_1(0°)\frac{(60° - \alpha)}{30°}$	0,0
$\mu_2(\alpha)$	0,8	$0,8\frac{(60° - \alpha)}{30°}$	0,0
$\mu_3(\alpha)$	$0,8 + 0,8\,\alpha/30°$	1,6	--

The amount of snow load is obtained from statistics, and the amount of snow may vary from year to year. Variations in regional snow loads must be considered when designing a hall. Figure 7 represents the minimum values of the snow on the ground.

Figure 7. Snow load on the ground in Finland. (Ympäristöministeriö, 2019, s. 15).



Snow load values can be increased in the regions where rain falls on top of the snow, which then melts and freezes. Especially in the spring, the water content of snow is high, and snow bulk weight density can be as high as 4,0 kN/m^3. Figure 8 shows values for different snow densities.

Figure 8. Mean bulk density of the snow. (SFS-EN 1991-1-3 + AC + A1, s. 81).

Type of snow	Bulk weight density [kN/m^3]
Fresh	1,0
Settled (several hours or days after its fall)	2,0
Old (several weeks or months after its fall)	2,5 - 3,5
Wet	4,0

The best way to prevent snow from accumulating on a PVC roof is to tighten the cover regularly. If the PVC cover is old and worn, it should be replaced. When the snow load on the roof is close to the bearing capacity of the hall, the snow should be removed carefully according to manufacturer’s instructions.

4 PVC Cover

Textiles offer a good alternative to conventional building materials, as their properties can be varied to suit different uses. PVC, polyvinyl chloride laminated polyester, is a commonly used textile cover in the steel hall. The PVC cover is light and cost effective, easy and fast to install, and it can be replaced easily if necessary. At the moment textile as a building material is not widely used in Nordic countries, as cold winters, wind and snow loads are challenging for the materials. The textile material also offers challenges to the design due to its orthotropic nature and different properties in the weft and warp direction. In addition, their elongation is not linear and may vary with the age of the fabric.

The PVC cover is manufactured at the factory by welding the fabric seams together to make a tight cover over the steel frame. The cover is assembled in the construction site by spreading it on the hall by cranes and attached to the frame. The cover is supported by the trusses, purlins and wind columns. It is not completely attached to the steel frame, and it can move slightly on the steel frame due to wind and snow loads, which may wear the PVC fabric. It is important to repair any damage of the cover at once to prevent microdamage and enlargement of the hole. The cover should be inspected once a year minimum or according to the manufacturer’s instructions.

4.1 PVC Material

PVC is a thin textile membrane that can carry tensile forces only. The base material consists of longitudinal (warp) and transverse (weft) polyester yarns. Polyester as the base material transfer loads. PVC coating makes the fabric waterproof and protects the base material from environmental impacts. The thicker the PVC layer is, the better it protects the base material. Unprotected base material will absorb moisture and dirt, which damage and weaken the base material. PVC layer is lacquered with acrylic varnish on both sides to ensure better UV resistance and colorfastness. The lacquering also ensures fabric to stay cleaner and prevent micro damages in the base material.

Other fibers can also be used as a base material, such as glass fibers with PTFE coating. Aramid (such as Kevlar, DuPont) or carbon fibers (CF) have outstanding characteristics which make them suitable for use in building, but they are not commonly used because of their high cost. (Pohl, 2010, p. 53).

4.2 Mechanical Properties of the PVC Fabric

Tensile strength and tear strength are the most important properties of the PVC fabric. Tensile strength is an important parameter of the material, and it measures the force required to rupture the fabric. (Euni Son, 2007, s. 16). The fabric has higher tensile strength in the warp direction than in weft direction, and it stretches more in the weft direction. Tear strength is the resistance to propagate an existing tear (Euni Son, 2007, s. 16). Tear propagation is the most common failure mode for fabrics (Seidel & Sturge, 2009, s. 47). The tear is usually caused by sharp objects, for example when removing snow with a shovel.

The welded seams of the cover form a waterproof and windproof seam, as the overlapped edges of the fabric strip melt together due to heat. If the weld is done correctly, it has higher tensile strength and lower elasticity than PVC fabric itself. The seams run in the same longitudinal direction of the hall as the warp.

The weight of the PVC fabric used in tensile structures in Europe is 750–1800g/m² and tensile strength in warp and weft directions 56–160 kN/m. (Stranghöner ym., 2023, s. 37). Over time, the properties of PVC material deteriorate due to external stresses such as UV-radiation and air pollution, but usually PVC cover lasts 25–35 years, especially if it is maintained regularly.

PVC fabric manufacturers do not usually provide information required in FEM modelling such as modulus of elasticity, shear modulus and Poisson’s ratio, as they are not needed in the fabric industry. The information is also hard to find from literature, as the properties of the fabric vary between manufacturers and different fabric quality.

4.3 Tensioning the PVC Cover

Proper tension in the PVC cover gives support against snow and wind load and helps the snow to slide off from the roof. The most importantly tensioning prevents the fabric from bagging. The tension system is critical to the structural stability of the hall, and it must distribute loads across the fabric evenly.

The PVC cover must be tensioned after installation. Creep is a permanent deformation of a material under constant stress, and it is affected by time, temperature and load. The material stretches with time even at relatively low loads, and the cover must be re-tensioned regularly. Re-tensioning can also expand the lifespan of the PVC cover.

The cover is attached to the steel frame by threading a steel bar to a welded fabric pocket and attaching the steel bar in the frame. In figure 9 is a steel bar attachment point to the frame and an example of the tightening system.

Figure 9. Attachment points of the PVC cover in the frame and the tensioning system of the cover.

It is difficult to estimate the tension force with which the PVC fabric is tightened over the hall, as it is not easy to measure. According to the hall manufacturers and different sources in the literature, it is safe to say that the prestress forces in PVC membrane are typically between 1.0 and 3.0 kN/m², as the tightening is done with the manpower only.

5 Bagging and the Effects of Snow Load on the Purlins

There are no ready-made guidelines in the literature that can be used for calculating the effects of the bagging on the steel structures. The problem with finding the correct calculating method was that the steel structures come in different forms, and the properties of the PVC fabrics vary. Therefore, the calculating method used here is very general and it relies on simplifications and assumptions.

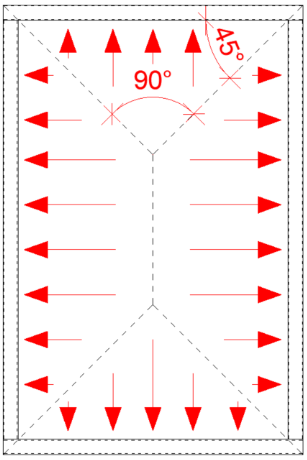
In this thesis, the distribution of a snow load between trusses and purlins was calculated with the different size of example quadrilaterals. The horizontal beams represented trusses and the vertical beams represented purlins. The bending moment of the purlins under the snow load was calculated according to the Eurocodes. Next, the deflection at the center of quadrilaterals due the snow load was calculated. After estimating the volume of the bag with the elongation of the PVC fabric and the weight of the extra snow load, the bending moment of the purlins was calculated again. These were calculated by hand.

5.1 Distribution of Snow Load and the Bending Moment of Purlins

The distribution of the snow load between purlins and trusses depends on the distance between purlins and trusses, their cross sections and length, and vertical placement of the purlins in relation to the trusses. If the purlin’s cross section is smaller than the cross section of the truss, more loads will be distributed to the truss. To simplify the load distribution calculations, it was assumed that upper chords of the trusses and the purlins have the same size hollow core cross-section, and that the top surfaces of the upper chord and purlins are in the same plane.

With these simplifications the snow load distribution between trusses and purlins were calculated as a two-way slab. The definition of the two-way slab is that the ratio of the longer side to the shorter side is 2 at the most. The load is transferred to the frames and purlins as triangular tributary load on the short side, and trapezoidal tributary load on the long side as shown in the Figure 10.

Figure 10. The load distribution in two-way slab.



The equations used in calculating triangular tributary load and trapezoidal tributary load are found in equation 2 and equation 3.

Equation 2. Triangular tributary load.

$$s * b/3$$

Equation 3. Trapezoidal tributary load.

$$s * b * (3 - 1/(l/b)^2)/6$$

where

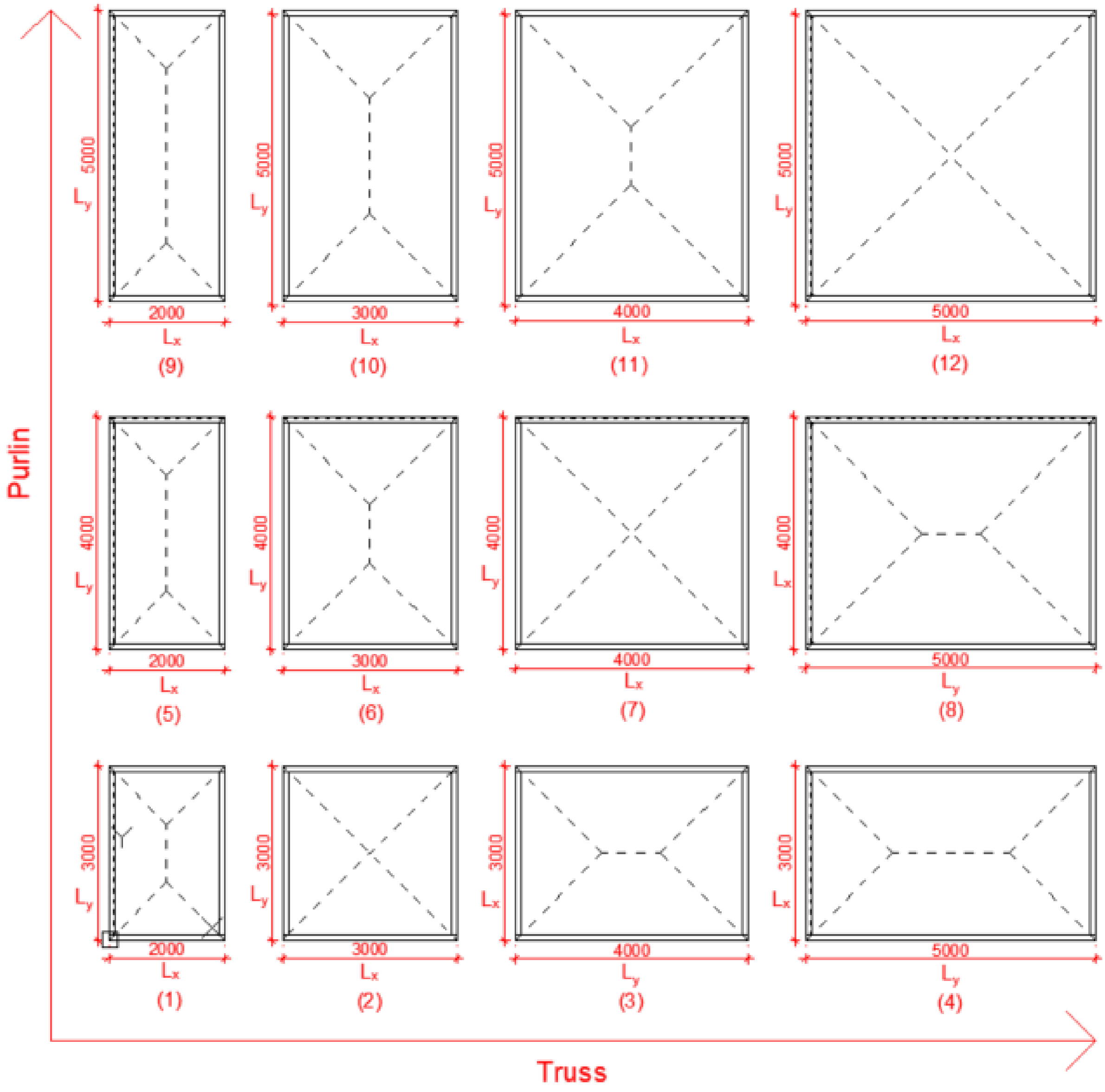
s	is snow load
l	is long side of slab
b	is short side of slab

These formulas calculate the loads as uniformly distributed load.

In the calculations of the snow load on the roof, the starting values of the different snow loads corresponded to the snow load on the ground values used in Finland. As the snow load was calculated according to the equation 1, the results and values of snow loads used in the calculations later were 1,6, 2,0, 2,2, 2,40 and 2,8 kN/m².

The distances used in the quadrilaterals vary between 2000–5000 mm between purlins and 3000–5000 mm between frames. The dimensions of the quadrilaterals and load distribution patterns are described in figure 11, where the horizontal beams represent a part of the truss, and the vertical beams represent purlins. Lx is the short side of the quadrilateral.

Figure 11. The different sizes and the load patterns of the example quadrilaterals.



The results of the snow load distribution between purlins and trusses are found in table 1. Even though different values snow loads were used, the load distribution remained the same as a percentage between the trusses and purlins.

Table 1. Distribution of the snow load.

Case	Truss lenght mm	Purlin lenght mm	Load distribution truss	Load distribution purlin
1	2000	3000	33 %	67 %
2	3000	3000	50 %	50 %
3	4000	3000	62 %	38 %
4	5000	3000	70 %	30 %
5	2000	4000	25 %	75 %
6	3000	4000	38 %	62 %
7	4000	4000	50 %	50 %
8	5000	4000	60 %	40 %
9*	2000	5000	20 %	80 %
10	3000	5000	30 %	70 %
11	4000	5000	40 %	60 %
12	5000	5000	50 %	50 %

9* The ratio between purlins and trusses is 2,5, and it is not a two-way slab. In this case, however, it is treated like a two-way slab to simplify the calculations.

Depending on the size of the example quadrilateral, up to 70 % of the snow load was distributed to the purlins. The greater the length of the purlin was compared to the truss length, the larger the snow load.

The bending moment of the purlins and trusses were calculated as uniformly distributed snow load according to the equation 4.

Equation 4. The maximum bending moment of the uniformly distributed load.

$$M_{max} = \frac{qL^2}{8}$$

The results of the bending moment calculations are found in the appendix 1.

5.2 Deflection at the Center of a Quadrilateral and the Elongation of the PVC

The elongation of the PVC fabric was estimated based on the data achieved from the results of tensile strength tests of the fabrics. The values differ depending on the different fabrics and if the tests were conducted in the warp or the weft directions. The ultimate elongation of the fabric, which is the elongation until the fabric rips, is 15 % in the warp direction, and 20–25 % in the weft direction. (Stranghöner ym., 2023, s. 37) It was assumed here, that the elongation of the fabric is 5 % in an authentic environment, regardless of how much load is applied to the fabric, and which is the warp/weft direction.

The center deflection is calculated according to the equation 5.

Equation 5. The center of deflection.

$$\delta = n_1 a \sqrt[3]{\frac{pa}{Et}}$$

where

a	is longitudinal dimension of membrane
p	is snow load
E	is modulus of elasticity
t	is thickness of a membrane

The deformation at center of the example quadrilaterals with the snow load and the estimated elongation of the PVC fabric are found in the appendix 2.

The volume of the bag is calculated according to the surface area of the quadrilateral, and the depth of the deformation in the center of the quadrilateral. There are no geometrical formulas how to calculate the bag, as it is not a dome or a half ellipsoid. Here, the volume of the bag is estimated based on the volume of the half ellipsoid. The volume is used when calculating the extra snow load in the final calculations. The snow density used here is 2,75 kN/m³, which is the mean value of the settled and old snow densities according to the figure 8. The results of the volume and the total snow load with the extra weight from the bag is found from appendix 2.

5.3 The Final Calculations of the Bending Moment on the Purlins

After the volume calculations, the extra snow load was added to the snow load obtained from the Eurocodes. The bending moment of the trusses and purlins were calculated with the extra load. The results are found in the appendix 1.

The extra snow load added the bending moment of the purlins 9–23 %. The bigger the quadrilateral was, the greater was the extra bending moment overall. The extra bending moment was bigger when smaller values of snow load were used.

6 Verifying the Results with Dlubal RFEM 5 Calculations

Dlubal RFEM 5 was chosen to verify the results of the hand calculations, even though RFEM 6 has some interesting new features that help with analyzing tensile structures. The properties of the membrane that is used in the models by default had to be modified to match the physical properties of the PVC fabrics found in the market. The values chosen for the modification are mean values of the properties of the PVC fabrics, as they vary between different fabrics. Some values are given by the fabric manufacturers, but for example, values of shear modulus and Poisson’s ratio were not found, and the presets of the membrane in RFEM 5 had to be used. The effect of the prestress was neglected here, as it was not used in the hand calculations neither.

The following values for the modelling was found from the literature and received from the fabric manufacturers:

Modulus of elasticity:	720 N/mm²
Thickness of the membrane:	0,7 mm
Specific weight:	12,80 kN/m³

Shear modulus and Poisson's ratio had to be used as the membrane's presets in RFEM 5.

The snow load used in the modelling was 2,0 kN/m². Every quadrilateral had its own extra snow load based on the volume of a bag which was calculated earlier, and it was added to the snow load value. The results of the hand calculations were verified with 3 different sizes of quadrilaterals. They were selected according to their size, since the smaller sizes are likely to be used in the design of the hall.

Figure 12 shows bending moment of the purlins and trusses under a normal snow load, and figure 13 shows the deformation at the center of the membrane with the same snow load. Figure 14 shows the bending moment with the extra snow load, and figure 15 shows the deformation with the extra snow load. The extra snow loads used in quadrilaterals were 2,21, 2,29 and 2,33 kN/m².

Figure 12. The bending moment with a snow load of 2,0 kN/m².

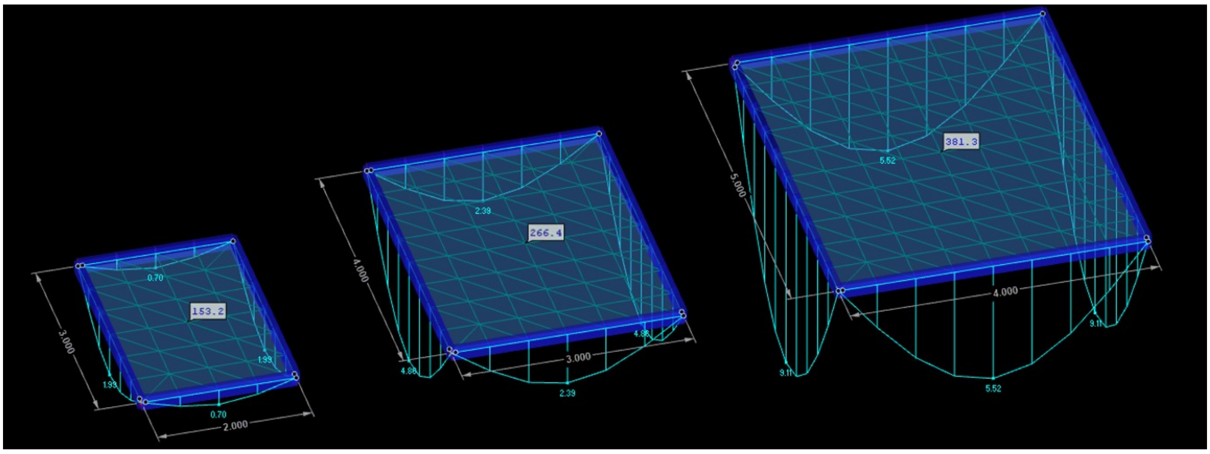


Figure 13. The deformation at the center of the quadrilateral with a snow load of 2,0 kN/m².

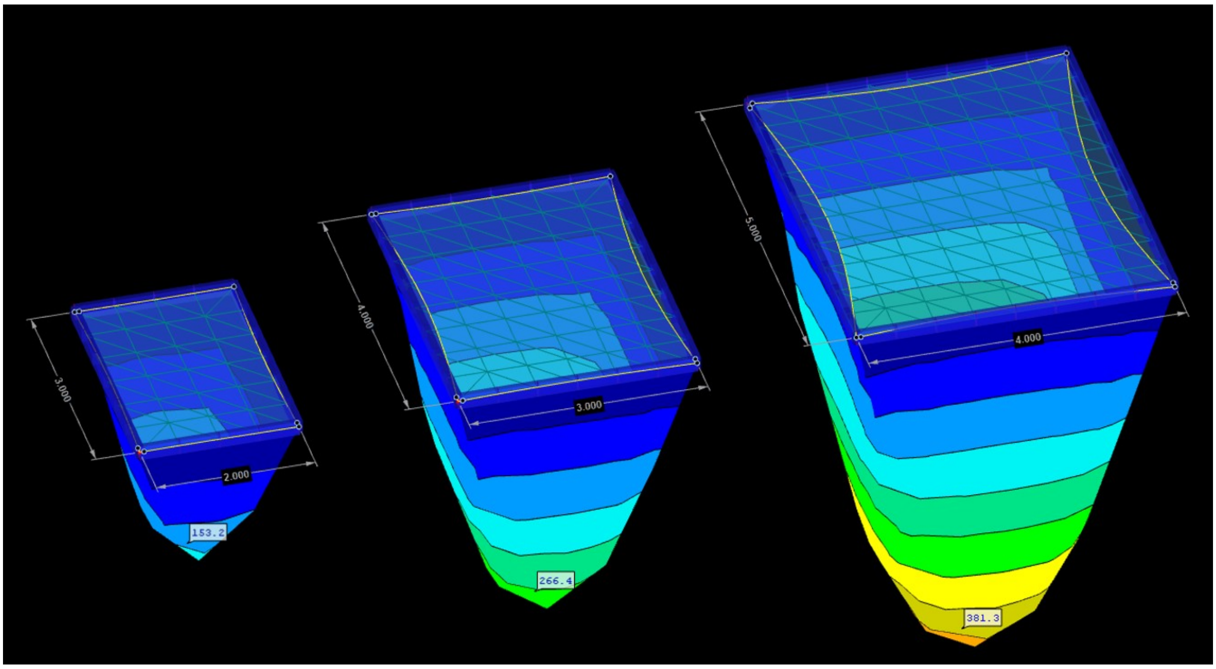


Figure 14. The bending moment with the extra snow load.

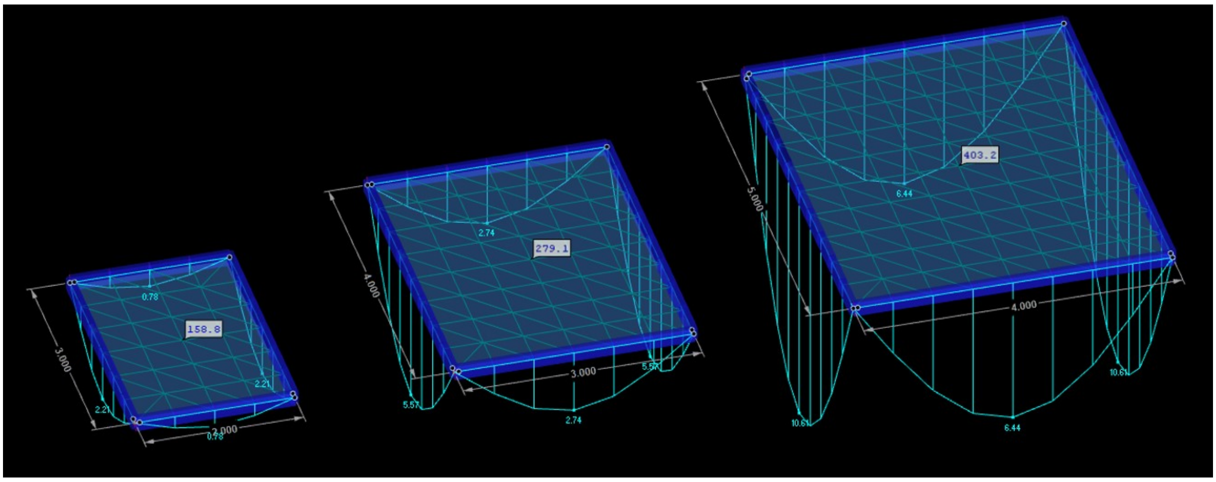
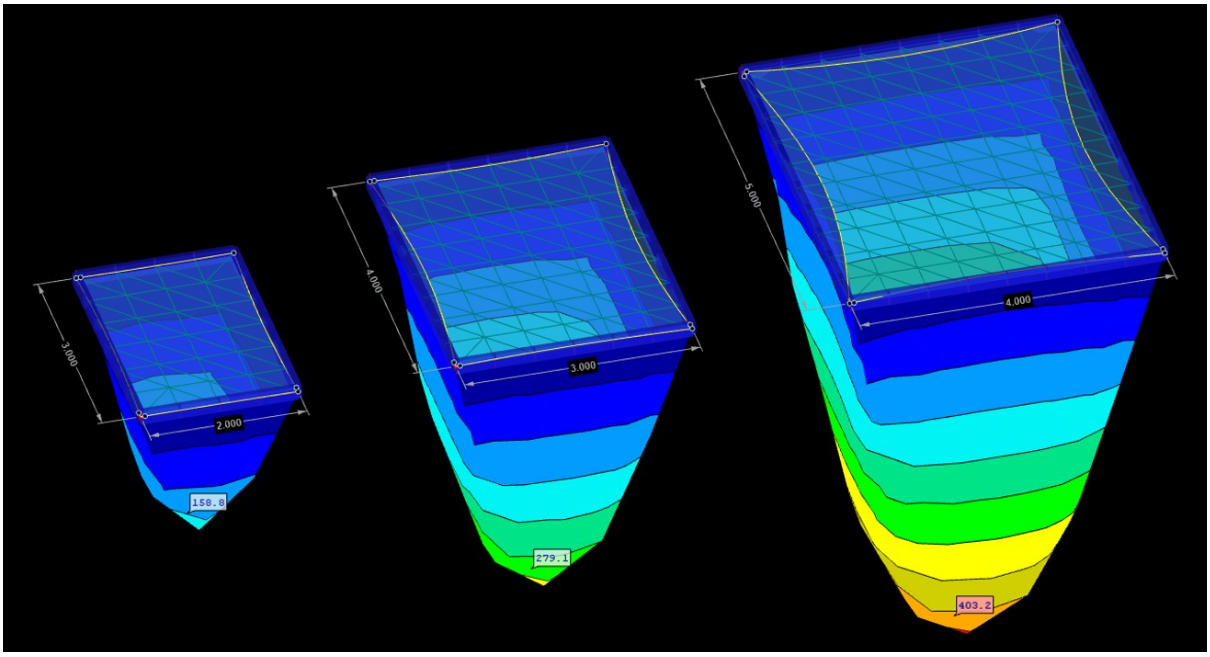


Figure 15. The deformation at the center of the quadrilateral with the extra snow load.



The results from the RFEM 5 were verified with the results from the hand calculations. They are found in the following table 2.

Table 2. Verification of the results of hand calculations and the results of RFEM calculations.

	Hand calculations			**RFEM calculations**		
Size of the quadrilateral mm	2000 x 3000	3000 x 4000	4000 x 5000	2000 x 3000	3000 x 4000	4000 x 5000
Bending moment of the purlin kNm	1,92	4,88	9,83	1,99	4,86	9,11
Deformation at the center mm	165	285	370	153	266	381
Snow load + extra snow load kN/m²	2,22	2,29	2,33	2,22	2,29	2,33
Bending moment of the purlin, extra snow load kN/m²	2,13	5,58	11,49	2,21	5,57	10,61
Difference between the bending moments	+11 %	+14 %	+17 %	+11 %	+15 %	+16 %

The differences between the hand calculations and RFEM calculations are small. The problem with the RFEM is that modelling the membrane is quite complicated, and RFEM may give wrong answers, as it is not designed to calculate this type of membrane structure. Nevertheless, it is a useful tool to verify the results of the hand calculations.

The increase in the bending moment of the purlins with the extra snow load from bagging is significant. With the bigger size quadrilaterals, the difference is even more, and it should be considered in designing.

7 Conclusion

The aim of this thesis was to inspect the effects of bagging of the cover of a PVC hall. The effect of the extra snow load on the purlins was studied particularly closely. The goal was to find a method that can be used when evaluating the snow load on the purlins. Snow accumulation on the bags and the extra snow load due to bagging can be a problem when the snow load exceeds the bearing capacity of the steel frame.

There are studies about the textile membranes used in the building industry, but those studies are focused mainly on the tensile fabric structures. The PVC covered steel hall is not a tensile structure, and the source data had to be applied. Due to the lack of proper data, the calculations are based on assumptions and simplifications. Despite that, it was possible to get reasonable results that can be used in the design and inspection of the hall.

In the history of design of these types of structures, the effect of the snow load on purlins has not been considered in the design. The purlins are usually dimensioned for the axial force only. According to my calculations, the deflection of the purlins is too much regardless of the creep and bagging of the ageing PVC material. In the PVC cover, the creep, bagging and the additional snow load accumulation is a self-feeding process, which leads to more load coming to the purlins, which are not designed for that kind of behavior.

We advise designers who are using PVC as a covering layer in the steel structures, to consider designing the purlins far from the top chord (even 500–600 mm), so they would not take any vertical load. That kind of design may cause problems, as the PVC cover lacks the necessary support to prevent bagging. If the purlins are designed close to the top chord, they should be designed to carry also vertical loads coming from the top due to the snow load. This type of detailing gives support to the PVC cover against bagging.

Pre-tension and tensioning of the cover during its life cycle is necessary to prevent the formation of the bags. According to hall manufacturers and experts, tensioning the PVC cover is still done with the manpower, and it is difficult to measure its force. If pre-tension of the PVC membrane is included in the more detailed calculations, we advise designers not to overestimate the value of the tension. Usually 1–2 kN/m^2 is good estimation for the tensile force in the PVC hall.

The effect of the bagging must be considered in the design, because it is an inevitable phenomenon. According to my calculations, and when comparing the results to the information obtained from a hall manufacturer, the deflection of the PVC is considerable. To slow down the process of bagging, the steel structure on the roof should be dense enough to give sufficient support to the PVC cover. The tensioning system of the cover should be easy to use, as there should be constant tension on the PVC fabric. Removing excessive snow from the roof is important, especially in heavy snow winters.

The stability of the steel hall also depends on the design of the steel structure. If the loads are sized correctly and attention is paid to the structural stability of the steel hall, the PVC hall is a durable and long-lasting option for various purposes.

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Appendix 1. The bending moment of the trusses and purlins with the snow load and with the extra snow load due to bagging.

Case	Truss lenght mm	Purlin lenght mm	Snow load kN/m²	Truss M_{max} kNm	Purlins M_{max} kNm	Snow load + the bag load kN/m²	Truss with bag load M_{max} kNm	Purlins with bag load M_{max} kNm	Difference in the bending moment Truss	Difference in the bending moment Purlins
1	2000	3000	1,6	0,53	1,53	1,77	0,59	1,70	11 %	11 %
			2,0	0,67	1,92	2,22	0,74	2,13	11 %	11 %
			2,2	0,73	2,11	2,43	0,81	2,33	11 %	11 %
			2,4	0,80	2,30	2,64	0,88	2,53	9 %	10 %
			2,8	0,93	2,68	3,05	1,02	2,92	9 %	9 %
2	3000	3000	1,6	1,80	1,80	1,85	2,08	2,08	16 %	16 %
			2,0	2,25	2,25	2,27	2,55	2,55	13 %	13 %
			2,2	2,48	2,48	2,48	2,79	2,79	13 %	13 %
			2,4	2,70	2,70	2,68	3,02	3,02	12 %	12 %
			2,8	3,15	3,15	3,10	3,49	3,49	11 %	11 %
3	4000	3000	1,6	3,90	1,80	1,87	4,56	2,10	17 %	17 %
			2,0	4,88	2,25	2,30	5,60	2,58	15 %	15 %
			2,2	5,36	2,48	2,49	6,08	2,80	13 %	13 %
			2,4	5,85	2,70	2,71	6,60	3,05	13 %	13 %
			2,8	6,83	3,15	3,12	7,61	3,51	12 %	12 %
4	5000	3000	1,6	6,60	1,80	1,85	7,65	2,09	16 %	16 %
			2,0	8,25	2,25	2,27	9,38	2,56	14 %	14 %
			2,2	9,08	2,48	2,55	10,52	2,87	16 %	16 %
			2,4	9,90	2,70	2,76	11,39	3,11	15 %	15 %
			2,8	11,55	3,15	3,18	13,12	3,58	14 %	14 %

Case	Truss lenght, mm	Purlin lenght, mm	Snow load kN/m²	Truss M_{max}	Purlins M_{max}	Snow load + the bag load kN/m²	Truss with bag load M_{max}	Purlins with bag load M_{max}	Difference in the bending moment Truss	Difference in the bending moment Purlins
5	2000	4000	1,6	0,53	2,93	1,79	0,60	3,28	12 %	12 %
			2,0	0,67	3,67	2,20	0,73	4,04	10 %	10 %
			2,2	0,73	4,03	2,41	0,80	4,42	9 %	9 %
			2,4	0,80	4,40	2,61	0,87	4,79	9 %	9 %
			2,8	0,93	5,13	3,03	1,01	5,55	8 %	8 %
6	3000	4000	1,6	1,80	3,90	1,87	2,10	4,56	17 %	17 %
			2,0	2,25	4,88	2,29	2,58	5,58	15 %	15 %
			2,2	2,48	5,36	2,50	2,81	6,09	14 %	14 %
			2,4	2,70	5,85	2,71	3,05	6,60	13 %	13 %
			2,8	3,15	6,83	3,12	3,51	7,61	12 %	12 %
7	4000	4000	1,6	4,27	4,27	1,90	5,08	5,08	19 %	19 %
			2,0	5,33	5,33	2,33	6,20	6,20	16 %	16 %
			2,2	5,87	5,87	2,54	6,77	6,77	15 %	15 %
			2,4	6,40	6,40	2,75	7,32	7,32	14 %	14 %
			2,8	7,47	7,47	3,16	8,44	8,44	13 %	13 %
8	5000	4000	1,6	7,87	4,27	1,91	9,38	5,09	19 %	19 %
			2,0	9,83	5,33	2,33	11,46	6,21	17 %	17 %
			2,2	10,82	5,87	2,54	12,49	6,77	15 %	15 %
			2,4	11,80	6,40	2,75	13,52	7,33	15 %	15 %
			2,8	13,77	7,47	3,17	15,57	8,45	13 %	13 %

Case	Truss lenght, mm	Purlin lenght, mm	Snow load kN/m^2	Truss M_{max}	Purlins M_{max}	Snow load + the bag load kN/m^2	Truss with bag load M_{max}	Purlins with bag load M_{max}	Increase in the bending moment Truss	Increase in the bending moment Purlins
9	2000	5000	1,6	0,53	4,73	1,77	0,59	5,25	11 %	11 %
			2,0	0,67	5,92	2,19	0,73	6,47	9 %	9 %
			2,2	0,73	6,51	2,39	0,80	7,08	9 %	9 %
			2,4	0,80	7,10	2,60	0,87	7,69	8 %	8 %
			2,8	0,93	8,28	3,01	1,00	8,90	7 %	7 %
10	3000	5000	1,6	1,80	6,60	1,85	2,09	7,65	16 %	16 %
			2,0	2,25	8,25	2,27	2,56	9,38	14 %	14 %
			2,2	2,48	9,08	2,48	2,79	10,23	13 %	13 %
			2,4	2,70	9,90	2,69	3,03	11,09	12 %	12 %
			2,8	3,15	11,55	3,10	3,49	12,80	11 %	11 %
11	4000	5000	1,6	4,27	7,87	1,91	5,09	9,38	19 %	19 %
			2,0	5,33	9,83	2,33	6,21	11,46	17 %	17 %
			2,2	5,87	10,82	2,54	6,77	12,49	15 %	15 %
			2,4	6,40	11,80	2,75	7,33	13,52	15 %	15 %
			2,8	7,47	13,77	3,17	8,45	15,57	13 %	13 %
12	5000	5000	1,6	8,33	8,33	1,97	10,27	10,27	23 %	23 %
			2,0	10,42	10,42	2,40	12,49	12,49	20 %	20 %
			2,2	11,46	11,46	2,61	13,60	13,60	19 %	19 %
			2,4	12,50	12,50	2,82	14,70	14,70	18 %	18 %
			2,8	14,58	14,58	3,24	16,90	16,90	16 %	16 %

Appendix 2. The deformation at center of the example quadrilaterals and the deformation with estimated elongation of the PVC fabric.

Case	Truss lenght, mm	Purlin lenght, mm	Snow load kN/m²	Volume m³	Total snow load weight kN/m²	Deformation at the center mm	Estimated elongation 5 % + deformation at the center
1	2000	3000	1,6	0,37	1,77	146	154
			2,0	0,49	2,22	158	165
			2,2	0,51	2,43	163	171
			2,4	0,52	2,64	167	176
			2,8	0,55	3,05	176	185
2	3000	3000	1,6	0,82	1,85	210	220
			2,0	0,88	2,27	226	237
			2,2	0,90	2,48	233	245
			2,4	0,93	2,68	240	252
			2,8	0,98	3,10	253	266
3	4000	3000	1,6	1,18	1,87	252	265
			2,0	1,24	2,28	271	285
			2,2	1,28	2,49	280	294
			2,4	1,35	2,71	288	303
			2,8	1,41	3,12	304	319
4	5000	3000	1,6	1,39	1,85	251	264
			2,0	1,49	2,27	271	284
			2,2	1,53	2,55	279	293
			2,4	1,58	2,76	288	302
			2,8	1,66	3,18	303	318

5	2000	4000	1,6	0,55	1,79	149	157
			2,0	0,59	2,20	161	169
			2,2	0,61	2,41	166	174
			2,4	0,62	2,61	171	179
			2,8	0,66	3,03	180	189
6	3000	4000	1,6	1,18	1,87	252	265
			2,0	1,27	2,29	271	285
			2,2	1,31	2,5	280	294
			2,4	1,35	2,71	288	303
			2,8	1,41	3,12	304	319
7	4000	4000	1,6	1,77	1,90	308	323
			2,0	1,90	2,33	332	348
			2,2	1,96	2,54	342	360
			2,4	2,01	2,75	353	370
			2,8	2,12	3,16	371	390
8	5000	4000	1,6	2,23	1,91	327	343
			2,0	2,40	2,33	352	370
			2,2	2,47	2,54	363	381
			2,4	2,54	2,75	374	393
			2,8	2,67	3,17	394	413

9	2000	5000	1,6	0,63	1,77	151	158
			2,0	0,68	2,19	162	171
			2,2	0,70	2,39	168	176
			2,4	0,72	2,60	173	181
			2,8	0,76	3,011	182	191
10	3000	5000	1,6	1,39	1,85	251	264
			2,0	1,49	2,27	271	284
			2,2	1,53	2,48	279	293
			2,4	1,58	2,69	288	302
			2,8	1,66	3,10	303	318
11	4000	5000	1,6	2,23	1,91	327	343
			2,0	2,40	2,33	352	370
			2,2	2,47	2,54	363	381
			2,4	2,54	2,75	374	393
			2,8	2,67	3,17	394	413
12	5000	5000	1,6	3,37	1,97	415	435
			2,0	3,63	2,40	447	469
			2,2	3,74	2,61	461	484
			2,4	3,84	2,82	475	498
			2,8	4,04	3,24	500	525