RESEARCH REPORT

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Optimization tools for steel portal frames – Optimization results

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Summary

The aim of the study was to optimize the shape of welded-tapered frames to achieve the lowest mass while all limit states conditions are satisfied according to the Eurocodes [1]. The AP-Frame optimization tool developed in VTT [2] was used to produce results presented in this report. Together with the detailed optimized frame configurations (Appendix A) frame mass and steel consumption curves are included (Chapter 5.1, Chapter 5.2) as well as the comparative study of different snow load distribution and seismic peak ground acceleration (Chapter 5.3).

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Preface

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Contents

1 Introduction

The aim of the study was to optimize the shape of welded-tapered frames to achieve the lowest mass while all limit states conditions are satisfied according to the Eurocodes [1]. Following load scenarios (Fig 1) were applied. The optimization was carried out using AP-Frame optimization software developed in VTT, Technical Research Centre of Finland for the Precasteel project [2] [3].

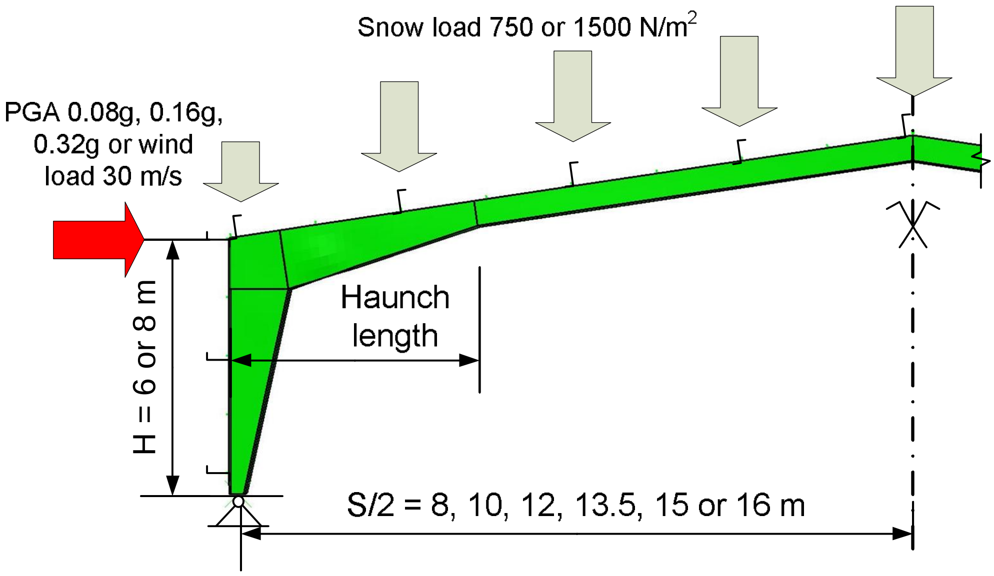


Fig 1 Frame loading and dimensions

2 Description

The study focuses on optimization of 96 cases of single-span or double-span welded tapered frames. The different eaves heights (6 m and 8 m) as well as different span lengths (varying from 16 to 32 m in case of single-span frames and 16 to 24 m in case of double-span frames) were considered. The loading scenarios included different characteristic snow loads (750 and 1500 N/m^2) and seismic loads originating from different peak ground accelerations (from 0,08g to 0,32g).

Variable parameters:
Number of bays: 1 or 2
Axis-to-axis span: 16 m, 20 m, 24 m, 28 m or 32 m
Eaves height: 6 m or 8 m
Characteristic snow load: 750 N/m2 or 1500 N/m^2
Peak ground acceleration: 0,32 g, 0,.16 g or 0,08 g

Table 1 Selected cases (PGA 0,32 g)

Case	Number of bays	Axis-to-axis span (m)	Eaves height (m)	Characteristic snow load (N/m^2)	Peak ground acceleration
1	1	16	6	750	0,32 g
2	1	20	6	750	0,32 g
3	1	24	6	750	0,32 g
4	1	28	6	750	0,32 g
5	1	32	6	750	0,32 g
6	1	16	6	1500	0,32 g
7	1	20	6	1500	0,32 g
8	1	24	6	1500	0,32 g
9	1	28	6	1500	0,32 g
10	1	32	6	1500	0,32 g
11	1	16	8	750	0,32 g
12	1	20	8	750	0,32 g
13	1	24	8	750	0,32 g
14	1	28	8	750	0,32 g
15	1	32	8	750	0,32 g
16	1	16	8	1500	0,32 g
17	1	20	8	1500	0,32 g
18	1	24	8	1500	0,32 g
19	1	28	8	1500	0,32 g
20	1	32	8	1500	0,32 g
21	2	16	6	750	0,32 g
22	2	20	6	750	0,32 g
23	2	24	6	750	0,32 g
24	2	16	6	1500	0,32 g
25	2	20	6	1500	0,32 g
26	2	24	6	1500	0,32 g
27	2	16	8	750	0,32 g
28	2	20	8	750	0,32 g
29	2	24	8	750	0,32 g
30	2	16	8	1500	0,32 g
31	2	20	8	1500	0,32 g
32	2	24	8	1500	0,32 g

Table 2 Selected cases (PGA 0,16 g)

Case	Number of bays	Axis-to-axis span (m)	Eaves height (m)	Characteristic snow load (N/m^2)	Peak ground acceleration
33	1	16	6	750	0,16 g
34	1	20	6	750	0,16 g
35	1	24	6	750	0,16 g
36	1	28	6	750	0,16 g
37	1	32	6	750	0,16 g
38	1	16	6	1500	0,16 g
39	1	20	6	1500	0,16 g
40	1	24	6	1500	0,16 g
41	1	28	6	1500	0,16 g
42	1	32	6	1500	0,16 g
43	1	16	8	750	0,16 g
44	1	20	8	750	0,16 g
45	1	24	8	750	0,16 g
46	1	28	8	750	0,16 g
47	1	32	8	750	0,16 g
48	1	16	8	1500	0,16 g
49	1	20	8	1500	0,16 g
50	1	24	8	1500	0,16 g
51	1	28	8	1500	0,16 g
52	1	32	8	1500	0,16 g
53	2	16	6	750	0,16 g
54	2	20	6	750	0,16 g
55	2	24	6	750	0,16 g
56	2	16	6	1500	0,16 g
57	2	20	6	1500	0,16 g
58	2	24	6	1500	0,16 g
59	2	16	8	750	0,16 g
60	2	20	8	750	0,16 g
61	2	24	8	750	0,16 g
62	2	16	8	1500	0,16 g
63	2	20	8	1500	0,16 g
64	2	24	8	1500	0,16 g

Table 3 Selected cases (PGA 0,08 g)

Case	Number of bays	Axis-to-axis span (m)	Eaves height (m)	Characteristic snow load (N/m^2)	Peak ground acceleration
65	1	16	6	750	0,08 g
66	1	20	6	750	0,08 g
67	1	24	6	750	0,08 g
68	1	28	6	750	0,08 g
69	1	32	6	750	0,08 g
70	1	16	6	1500	0,08 g
71	1	20	6	1500	0,08 g
72	1	24	6	1500	0,08 g
73	1	28	6	1500	0,08 g
74	1	32	6	1500	0,08 g
75	1	16	8	750	0,08 g
76	1	20	8	750	0,08 g
77	1	24	8	750	0,08 g
78	1	28	8	750	0,08 g
79	1	32	8	750	0,08 g
80	1	16	8	1500	0,08 g
81	1	20	8	1500	0,08 g
82	1	24	8	1500	0,08 g
83	1	28	8	1500	0,08 g
84	1	32	8	1500	0,08 g
85	2	16	6	750	0,08 g
86	2	20	6	750	0,08 g
87	2	24	6	750	0,08 g
88	2	16	6	1500	0,08 g
89	2	20	6	1500	0,08 g
90	2	24	6	1500	0,08 g
91	2	16	8	750	0,08 g
92	2	20	8	750	0,08 g
93	2	24	8	750	0,08 g
94	2	16	8	1500	0,08 g
95	2	20	8	1500	0,08 g
96	2	24	8	1500	0,08 g

Each frame was calculated twice during the optimization; loaded with fundamental combination [4] of dead, snow and reduced wind load, and seismic combination of accidental, dead and reduced snow load. Single-span frames were loaded with uniform snow load and the results checked with non-symmetric snow, where only one half of snow mass was applied on the downwind side. In case of double-span frames, the drifted snow load case [4] was used in optimization and the results were checked with uniform snow load.

Design situations:
Persistent and transient design situation with dead, snow and reduced wind load
Seismic design situations with seismic, dead and reduced snow load

The unique names of column and rafter are composed of their dimensions in mm (Fig 2). For example column 200x800x260x12x6 means that tapered section's shallow end is 200 mm high while the deep end is 800 mm high, flanges are 260x12 mm and web thickness is 6 mm. Also the length of the haunch (Lh) has to be provided as the rafter is tapered only at the frame corner. Sometimes the length is expressed as the haunch ratio (S/Lh).

Optimized variables:
Column bottom-end height (h_c)
Rafter constant part height (h_b),
Corner height of the haunches (hh_b, hh_c),
Flange width (b)
Flange thickness (t_f)
Web width (t_w)
Haunch ratio (S/L_h)

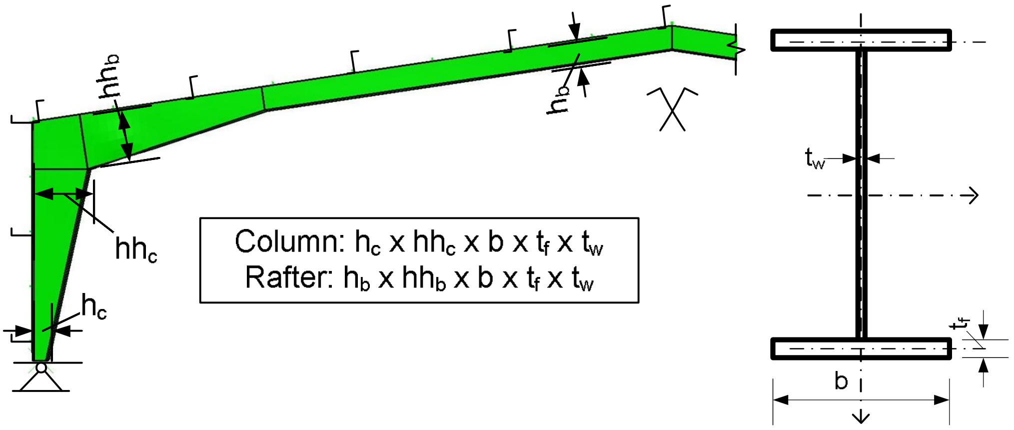


Fig 2 Column and rafter names

3 Limitations

The slenderness of frame cross-sections was limited to section class 3 and lower in order to effectively use shell FE models without need of local buckling calculation. Considering class 4 slender cross-sections could save an additional weight, however, very fine mesh needed for the local stability assessment makes the optimization computationally expensive. The steel grade of all calculated cases is S275.

All the optimization results presented in this report were calculated using Genetic Algorithm (GA) method with fixed number of 50 generations and population of 40 individuals in each generation. Although there is no guarantee that the best individual represents the global minimum at the same time, its weight is usually less than 5% higher than the minimal weight. In order to study this effect, each optimization was carried out twice and results were compared and manually refined to find the best frame in a close range near the optimized one. In later studies of double-span frames, the local search was implemented automatically into the optimization algorithm and there was no need for further refining of obtained results.

Constants:
Distance between frames: 6 m
Roof pitch: 15.0 % (8,53°)
Characteristic dead load: 380 N/m2
Wind load: 30 m/s, terrain type 1
Seismic load: spectrum type 1, ground type B, q = 1.5
Material: S275
Base support: Pinned

4 Methods

For the optimization we used the AP-Frame tool described in VTT Report [2], where the general method according to Eurocode 3 [1] was selected in combination with the genetic algorithm [3].

Design method:
General method: Linear or nonlinear in-plane analysis with global reduction for out-of-plane stability using beam model with stepped cross-sections and shell model

Optimization method:
Real coded genetic algorithm (RCGA) with local search in each generation

Optimization parameters:
Number of generations: 50
Population size: 40
Number of elite values: 1
Objective function evaluation: < 4000

Optimization operators:
Selection operator: tournament selection
Crossover operator: simulated binary crossover (SBX)
Mutation operator: polynomial mutation

5 Results

5.1 Optimized weight of welded-tapered frames

The lowest mass of one frame was calculated for selected spans from 16 to 32 m with different snow load (750 and 1500 N/m^2) and frame height (6 and 8 m). The results were interpolated with 2nd order polynomial approximation.

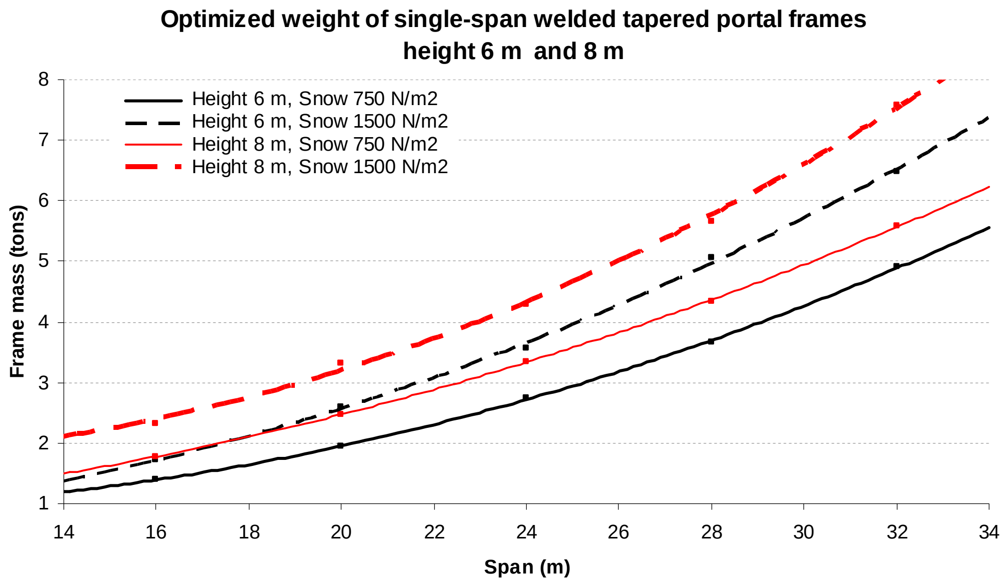


Fig 3 Optimized weight of single-span frames

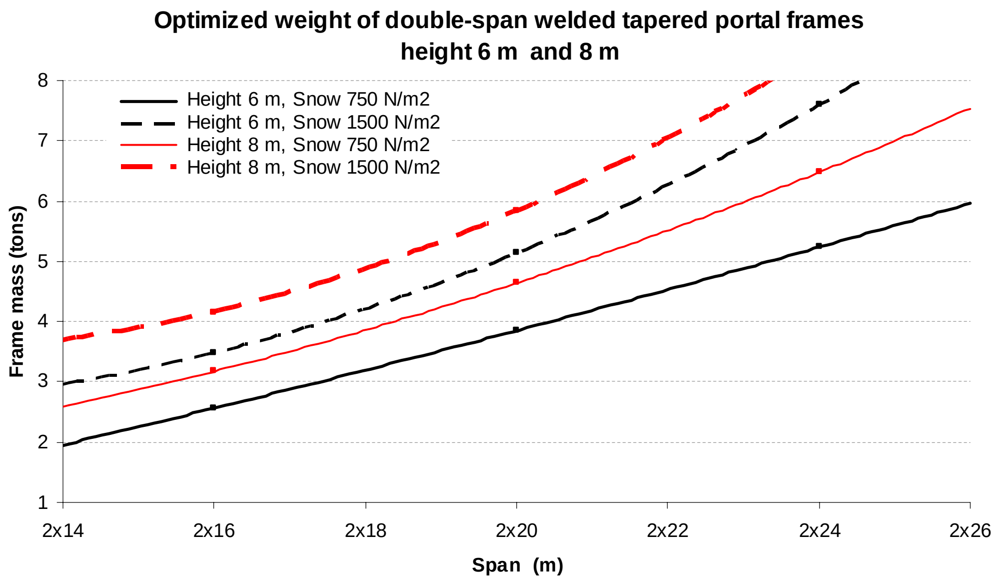


Fig 4 Optimized weight of double-span frames

5.2 Steel consumption of welded-tapered frames

From the optimized mass of single portal frame the steel consumptions in kg/m^2 were calculated including purlins, side rails, horizontal and vertical bracing. The results were interpolated with 2^{nd} order polynomial approximation. Purlins, side rails and bracing were used the same as in calculated hot-rolled frames [6] (Table 4, Table 5).

Table 4 Purlins and side rails

S (m)	H (m)	Snow load (N/m2)	Purlins	Rails	Horiz. beams
16	6	750	IPE140	IPE120	IPE160
20	6	750	IPE140	IPE120	IPE160
24	6	750	IPE140	IPE120	IPE160
28	6	750	IPE140	IPE120	IPE160
32	6	750	IPE140	IPE120	IPE160
16	6	1500	IPE180	IPE120	IPE180
20	6	1500	IPE180	IPE120	IPE180
24	6	1500	IPE180	IPE120	IPE180
28	6	1500	IPE180	IPE120	IPE180
32	6	1500	IPE180	IPE120	IPE180
16	8	750	IPE180	IPE120	IPE180
20	8	750	IPE180	IPE120	IPE180
24	8	750	IPE180	IPE120	IPE180
28	8	750	IPE180	IPE120	IPE180
32	8	750	IPE180	IPE120	IPE180
16	8	1500	IPE180	IPE120	IPE200
20	8	1500	IPE180	IPE120	IPE200
24	8	1500	IPE180	IPE120	IPE200
28	8	1500	IPE180	IPE120	IPE200
32	8	1500	IPE180	IPE120	IPE200
16	6	750	IPE140	IPE120	IPE160
20	6	750	IPE140	IPE120	IPE160
24	6	750	IPE140	IPE120	IPE180
16	6	1500	IPE180	IPE120	IPE200
20	6	1500	IPE180	IPE120	IPE200
24	6	1500	IPE180	IPE120	IPE200
16	8	750	IPE140	IPE120	IPE300
20	8	750	IPE140	IPE120	IPE300
24	8	750	IPE140	IPE120	IPE300
16	8	1500	IPE180	IPE120	IPE360
20	8	1500	IPE180	IPE120	IPE360
24	8	1500	IPE180	IPE120	IPE360

Table 5 Bracing

S (m)	H (m)	Snow load (N/m^2)	Vertical bracing (CHS)	Middle vertical bracing (CHS)	Horizontal bracing (CHS)
16	6	750	101.6x3.6		88.9x3.2
20	6	750	114.3x3.6		88.9x3.2
24	6	750	114.3x3.6		88.9x4
28	6	750	139.7x4		114.3x3.6
32	6	750	139.7x4		114.3x3.6
16	6	1500	114.3x3.6		88.9x4
20	6	1500	139.7x4		114.3x3.6
24	6	1500	139.7x4		114.3x3.6
28	6	1500	139.7x5		139.7x4
32	6	1500	139.7x5		139.7x4
16	8	750	168.3x4.5		88.9x3.2
20	8	750	168.3x6.3		88.9x4
24	8	750	139.7x8		88.9x4
28	8	750	168.3x6.3		139.7x5
32	8	750	168.3x6.3		139.7x5
16	8	1500	168.3x4.5		88.9x3.2
20	8	1500	168.3x6.3		101.6x3.6
24	8	1500	168.3x4.5		88.9x5
28	8	1500	168.3x6.3		139.7x5
32	8	1500	168.3x6.3		139.7x5
16	6	750	88.9x4	139.7x5	88.9x4
20	6	750	101.6x3.6	168.3x4.5	101.6x3.6
24	6	750	114.3x3.6	168.3x6.3	114.3x3.6
16	6	1500	101.6x3.6	168.3x4.5	101.6x3.6
20	6	1500	114.3x3.6	168.3x6.3	114.3x3.6
24	6	1500	139.7x4	168.3x6.3	139.7x4
16	8	750	139.7x4	139.7x6.3	101.6x3.6
20	8	750	139.7x4	139.7x6.3	101.6x3.6
24	8	750	139.7x4	139.7x6.3	101.6x3.6
16	8	1500	168.3x10	139.7x8	101.6x6.3
20	8	1500	168.3x10	139.7x8	101.6x6.3
24	8	1500	168.3x10	139.7x8	101.6x6.3

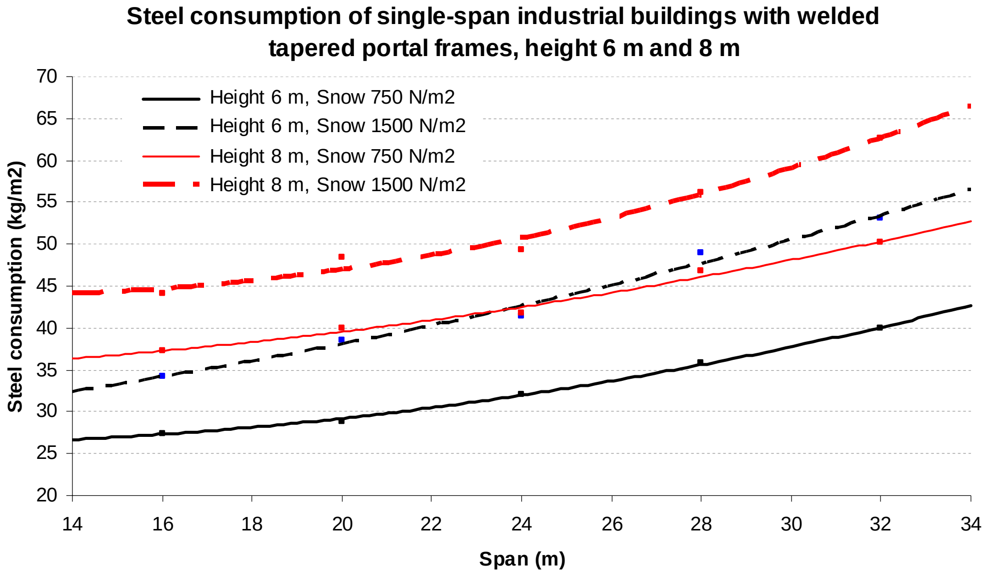


Fig 5 Steel consumption of single-span buildings

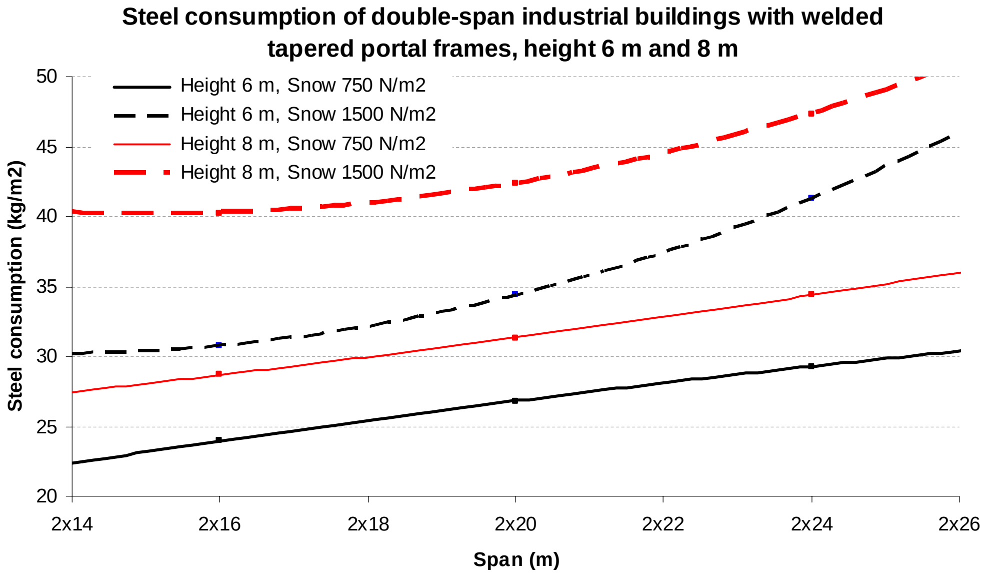


Fig 6 Steel consumption of double-span buildings

5.3 Limit states utilization

As the default output of AP-Frame software, the ultimate limit state (ULS) and serviceability limit state (SLS) capacities are stored either in N/m^2 of vertical load (in fundamental design situations) or in kN of horizontal load (in seismic design situations). The utilization is calculated using those capacities and corresponding (design or characteristic) load. Their physical meaning is, thus, related only to the vertical or horizontal component of load while the other actions on structure are considered to be constant.

The selected frames were optimized using fundamental design situation with symmetrical snow load and wind from the left side altogether with seismic design situation. Results were checked with unsymmetrical snow loads and in two cases (24/6 and 24/8) where the SLS check was failing, the frames were redesigned to satisfy limit states condition.

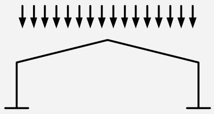
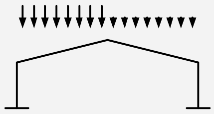
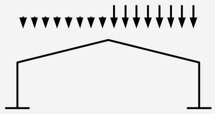
	Single span frame identification				Utilization in the fundamental design situation					
					 Symmetric snow		 Left side loaded		 Right side loaded	
	S/H	Cases			ULS	SLS	ULS	SLS	ULS	SLS
Low snow load 750 N/m^2	16/6	1	33	65	**0.97**	0.74	0.82	0.70	0.79	0.53
	20/6	2	34	66	**0.99**	0.76	0.92	0.84	0.84	0.52
	24/6	3	35	67	0.98	0.99	0.84	**1.00**	0.82	0.64
	28/6	4	36	68	**1.00**	0.95	0.86	0.99	0.84	0.59
	32/6	5	37	69	**1.00**	0.56	0.91	0.63	0.86	0.39
	16/8	11	43	75	**0.87**	0.78	0.80	0.76	0.78	0.71
	20/8	12	44	76	**0.93**	0.58	0.83	0.58	0.81	0.50
	24/8	13	45	77	0.94	**0.96**	0.79	0.89	0.78	0.69
	28/8	14	46	78	0.96	**0.97**	0.81	0.93	0.80	0.67
	32/8	15	47	79	**0.97**	0.70	0.89	0.76	0.84	0.45
High snow load 1500 N/m^2	16/6	6	38	70	**0.95**	0.49	0.92	0.55	0.82	0.42
	20/6	7	39	71	**0.99**	0.72	0.88	0.81	0.78	0.50
	24/6	8	40	72	**1.00**	0.58	0.81	0.60	0.80	0.45
	28/6	9	41	73	**0.98**	0.50	0.89	0.55	0.79	0.38
	32/6	10	42	74	**1.00**	0.69	0.91	0.83	0.81	0.51
	16/8	16	48	80	**0.94**	0.80	0.91	0.86	0.81	0.66
	20/8	17	49	81	**0.95**	0.71	0.90	0.77	0.80	0.54
	24/8	18	50	82	**1.00**	0.95	0.88	**1.00**	0.79	0.57
	28/8	19	51	83	**0.98**	0.77	0.81	0.83	0.78	0.53
	32/8	20	52	84	**0.99**	0.56	0.84	0.59	0.80	0.43
Minimum					0.87	0.49	0.79	0.55	0.78	0.38
Maximum					1.00	0.99	0.92	1.00	0.86	0.71
Average					0.97	0.74	0.86	0.77	0.81	0.53

Table 6 Utilization of single-span frames in the fundamental design situations

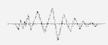
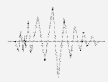
	Single span frame identification				Utilization in the seismic design situation					
					 Low seismicity		 Medium seismicity		 High seismicity	
	S/H	Cases			ULS	SLS	ULS	SLS	ULS	SLS
Low snow load 750 N/m²	16/6	1	33	65	0.18	0.20	0.25	0.40	0.39	**0.81**
	20/6	2	34	66	0.19	0.21	0.27	0.42	0.42	**0.85**
	24/6	3	35	67	0.15	0.22	0.21	0.44	0.34	**0.88**
	28/6	4	36	68	0.16	0.21	0.21	0.43	0.33	**0.88**
	32/6	5	37	69	0.19	0.16	0.24	0.32	0.35	**0.64**
	16/8	11	43	75	0.17	0.18	0.23	0.36	0.35	**0.72**
	20/8	12	44	76	0.19	0.17	0.25	0.33	0.36	**0.67**
	24/8	13	45	77	0.14	0.19	0.19	0.37	0.30	**0.75**
	28/8	14	46	78	0.14	0.19	0.19	0.38	0.29	**0.76**
	32/8	15	47	79	0.18	0.17	0.23	0.34	0.34	**0.69**
High snow load 1500 N/m²	16/6	6	38	70	0.16	0.18	0.24	0.37	0.41	**0.73**
	20/6	7	39	71	0.13	0.20	0.21	0.40	0.35	**0.83**
	24/6	8	40	72	0.12	0.17	0.18	0.34	0.30	**0.70**
	28/6	9	41	73	0.13	0.14	0.18	0.28	0.29	**0.55**
	32/6	10	42	74	0.12	0.17	0.17	0.35	0.28	**0.70**
	16/8	16	48	80	0.15	0.18	0.21	0.37	0.35	**0.74**
	20/8	17	49	81	0.13	0.18	0.20	0.36	0.33	**0.71**
	24/8	18	50	82	0.11	0.19	0.17	0.38	0.30	**0.76**
	28/8	19	51	83	0.12	0.18	0.17	0.35	0.28	**0.71**
	32/8	20	52	84	0.14	0.15	0.19	0.30	0.29	**0.60**
Minimum					0.11	0.14	0.17	0.28	0.28	0.55
Maximum					0.19	0.22	0.27	0.44	0.42	0.88
Average					0.15	0.18	0.21	0.36	0.33	0.74

Table 7 Utilization of single-span frames in the seismic design situations

Also double-span frames were checked with different loading situations. In that case they were optimized for the drifted snow load that was assumed to be the most critical load in fundamental combination and with high seismic load. The results are summarized in the following tables.

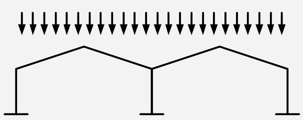
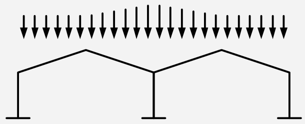
	Double span frame ientification				 Undrifted snow load		 Drifted snow load	
	S/H	Cases			ULS	SLS	ULS	SLS
Low snow load	2x16/6	21	53	85	0.94	0.89	**0.99**	0.94
	2x20/6	22	54	86	0.92	0.93	**0.98**	0.98
	2x24/6	23	55	87	0.90	0.87	**0.98**	0.93
	2x16/8	27	59	91	0.91	0.77	**0.96**	0.82
	2x20/8	28	60	92	0.90	0.92	0.98	**1.00**
	2x24/8	29	61	93	0.89	0.89	**0.97**	**0.97**
High snow load	2x16/6	24	56	88	0.90	0.58	**1.00**	0.64
	2x20/6	25	57	89	0.91	0.68	**0.97**	0.72
	2x24/6	26	58	90	0.90	0.70	**0.97**	0.74
	2x16/8	30	62	94	0.93	0.89	**1.00**	0.95
	2x20/8	31	63	95	0.94	0.55	**0.98**	0.58
	2x24/8	32	64	96	0.88	0.46	**0.98**	0.51
Minimum					0.88	0.46	0.96	0.51
Maximum					0.94	0.93	1.00	1.00
Average					0.91	0.76	0.98	0.82

Table 8 Utilization of double-span frames in the fundamental design situations

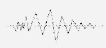
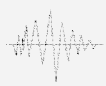
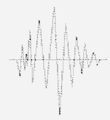
	Double span frame identification				 Low seismicity		 Medium seismicity		 High seismicity	
	S/H	Cases			ULS	SLS	ULS	SLS	ULS	SLS
Low snow load	2x16/6	21	53	85	0.13	0.17	0.19	0.35	0.30	**0.71**
	2x20/6	22	54	86	0.13	0.17	0.17	0.33	0.27	**0.67**
	2x24/6	23	55	87	0.14	0.14	0.17	0.29	0.26	**0.57**
	2x16/8	27	59	91	0.16	0.14	0.21	0.29	0.31	**0.58**
	2x20/8	28	60	92	0.13	0.15	0.17	0.31	0.27	**0.62**
	2x24/8	29	61	93	0.13	0.15	0.17	0.30	0.25	**0.60**
High snow load	2x16/6	24	56	88	0.13	0.18	0.17	0.36	0.25	**0.72**
	2x20/6	25	57	89	0.09	0.12	0.13	0.25	0.22	**0.49**
	2x24/6	26	58	90	0.10	0.11	0.13	0.23	0.20	**0.45**
	2x16/8	30	62	94	0.10	0.15	0.14	0.31	0.24	**0.62**
	2x20/8	31	63	95	0.12	0.12	0.17	0.23	0.27	**0.47**
	2x24/8	32	64	96	0.11	0.10	0.14	0.19	0.22	**0.39**
Minimum					0.09	0.10	0.13	0.19	0.20	0.39
Maximum					0.16	0.18	0.21	0.36	0.31	0.72
Average					0.12	0.14	0.16	0.29	0.25	0.57

Table 9 Utilization of double-span frames in the seismic design situations

6 Comparative study

The steel consumption of industrial buildings with tapered frames was compared to the same buildings with hot-rolled frames calculated in [6] and noticeable savings in weight were achieved (see Fig 7).

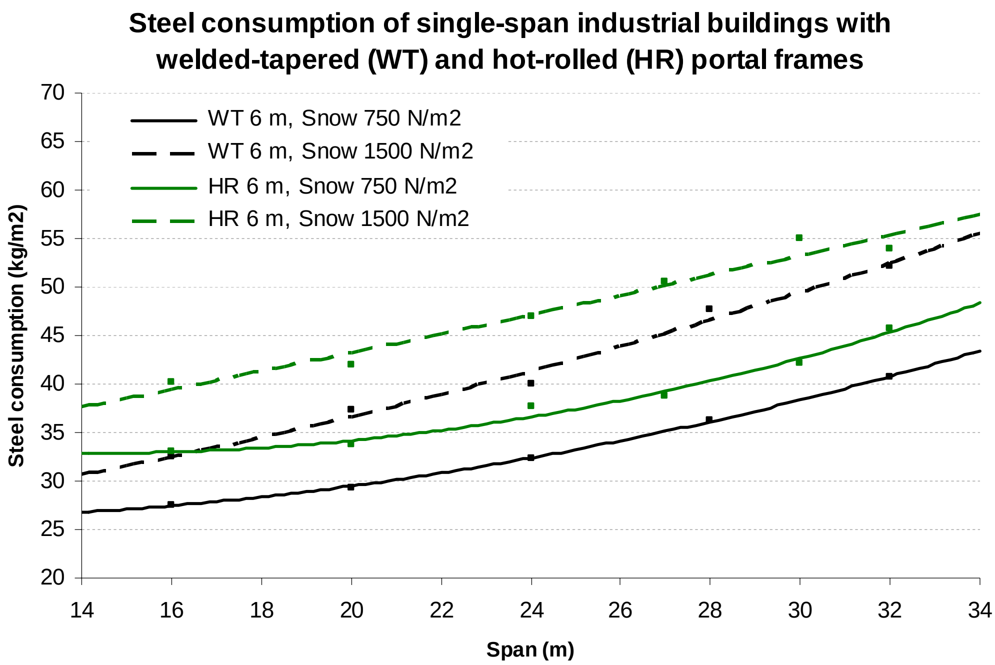


Fig 7 Steel consumption of optimized welded-tapered frames compared to hot-rolled frames optimized in [6]

7 Summary

The AP-Frame optimization tool was used to produce results presented in this report. Together with the detailed optimized frame configurations (Appendix A) frame mass and steel consumption curves are included (Chapter 5.1, Chapter 5.2) as well as the comparative study of different snow load distribution and seismic peak ground acceleration (Chapter 5.3).

References

[1] EN 1993:2005, Eurocode 3: Design of steel structures
[2] Hradil P., Mielonen M., Fülöp L., VTT-R-00524-10 Res. Report, *Optimization tools for steel portal frames – software documentation*, Espoo, 2009
[3] Mielonen M., *Optimization of steel portal frames using genetic algorithms*, Master of Science thesis, Aalto University, 2010.
[4] EN 1991, Eurocode 1: Actions on structures
[5] EN 1990, Eurocode: Basis of structural design
[6] Varelis G., Vasilikis D., Karamanos S., Tsintzos P.: *WP2: Performance analysis of selected steel types for one-storey industrial buildings*, Research report

Appendix A: Geometry of the frames

Frame 16/6 (Cases 1, 6, 33, 38, 65, 70)

Span (m)	Snow load (N/m^2)	Column	Rafter	Haunch ratio	Mass of the frame (tons)	Mass of the structure (tons)	Steel consumption (kg/m^2)
16	750	220x560x220x10x5	360x560x220x10x5	7	1.39	13.2	27.5
16	1500	260x660x260x10x6	400x660x260x10x6	9	1.72	15.6	32.4

Table 10 Frame 16/6

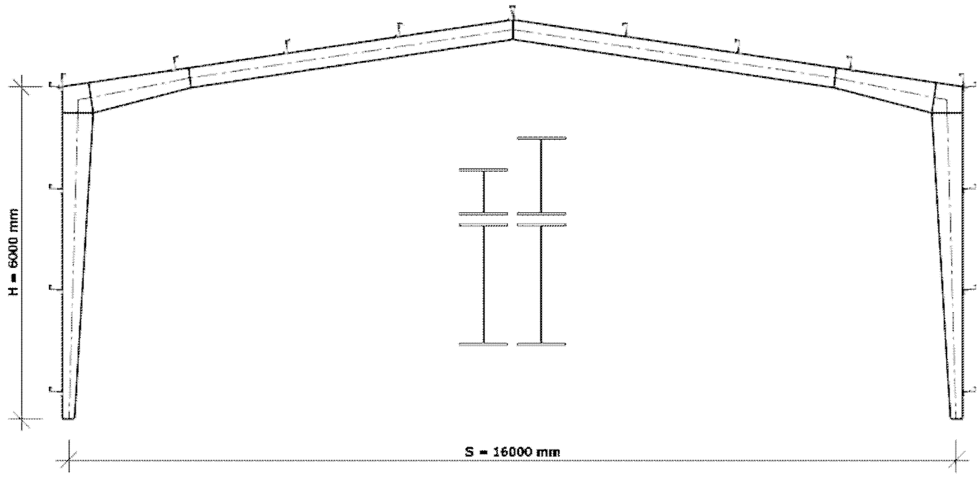


Fig 8 Frame 16/6, Snow 750 N/m2

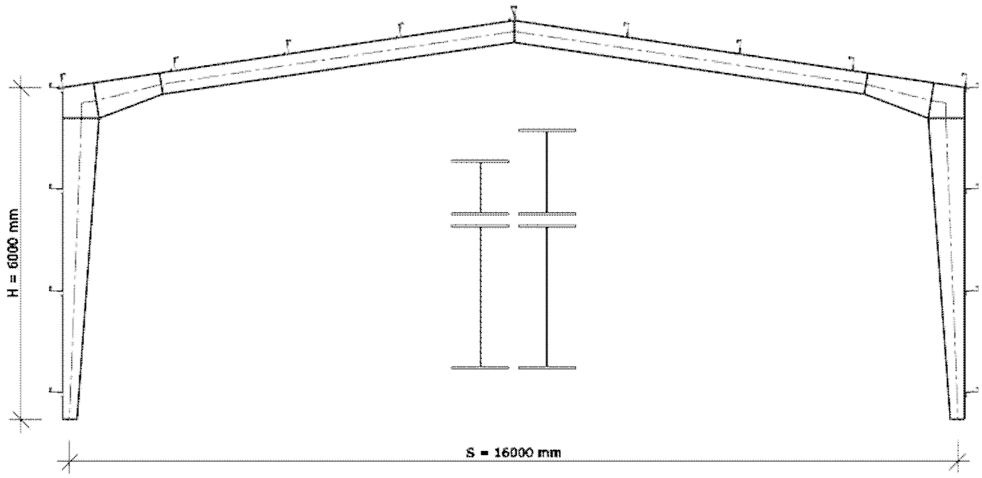


Fig 9 Frame 16/6, Snow 1500 N/m2

Frame 16/8 (Cases 11, 16, 43, 48, 75, 80)

Span (m)	Snow load (N/m^2)	Column	Rafter	Haunch ratio	Mass of the frame (tons)	Mass of the structure (tons)	Steel consumption (kg/m^2)
16	750	240x560x240x10x5	500x560x240x10x5	10	1.77	16.9	35.2
16	1500	280x620x280x12x6	380x620x280x12x6	9	2.33	20.2	42.1

Table 11 Frame 16/8

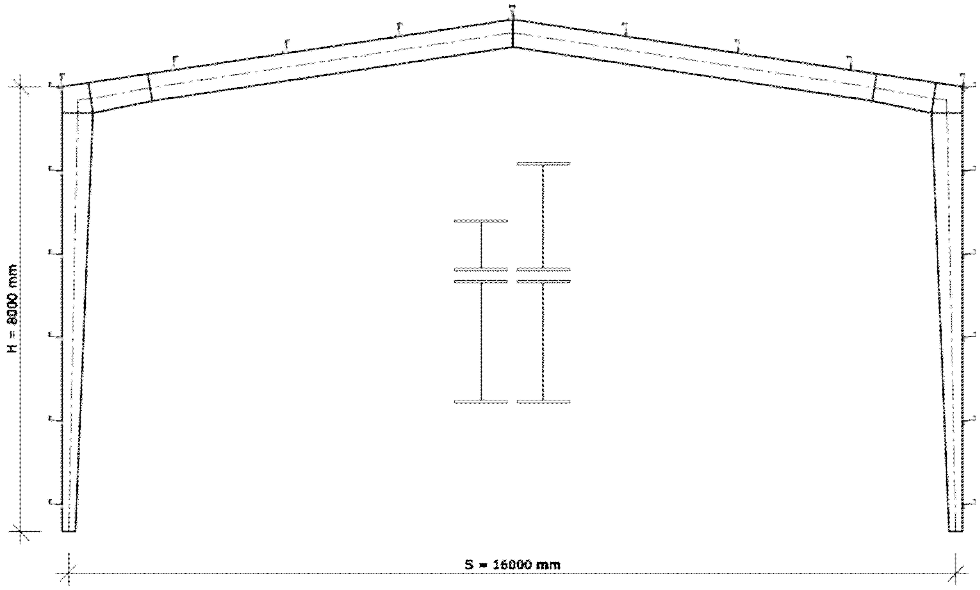


Fig 10 Frame 16/8, Snow 750 N/m2

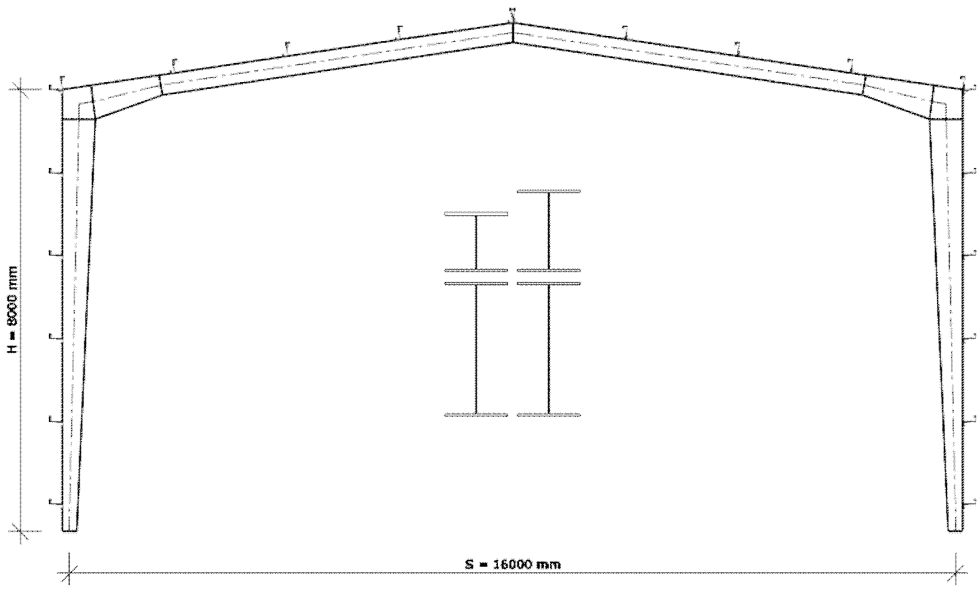


Fig 11 Frame 16/8, Snow 1500 N/m2

Frame 20/6 (Cases 2, 7, 34, 39, 66, 71)

Span (m)	Snow load (N/m^2)	Column	Rafter	Haunch ratio	Mass of the frame (tons)	Mass of the structure (tons)	Steel consumption (kg/m^2)
20	750	260x640x260x10x6	380x640x260x10x6	8	1.95	17.6	29.4
20	1500	320x640x320x12x6	380x640x320x12x6	9	2.59	22.4	37.3

Table 12 Frame 20/6

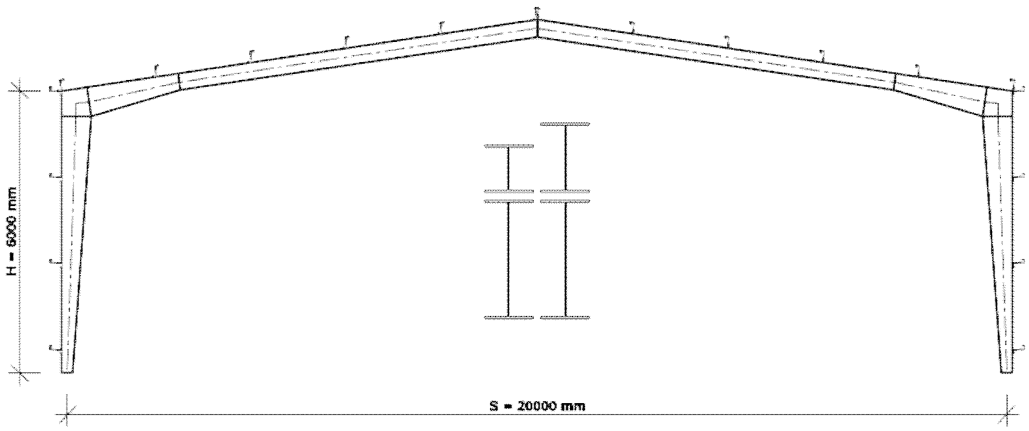


Fig 12 Frame 20/6, Snow 750 N/m2

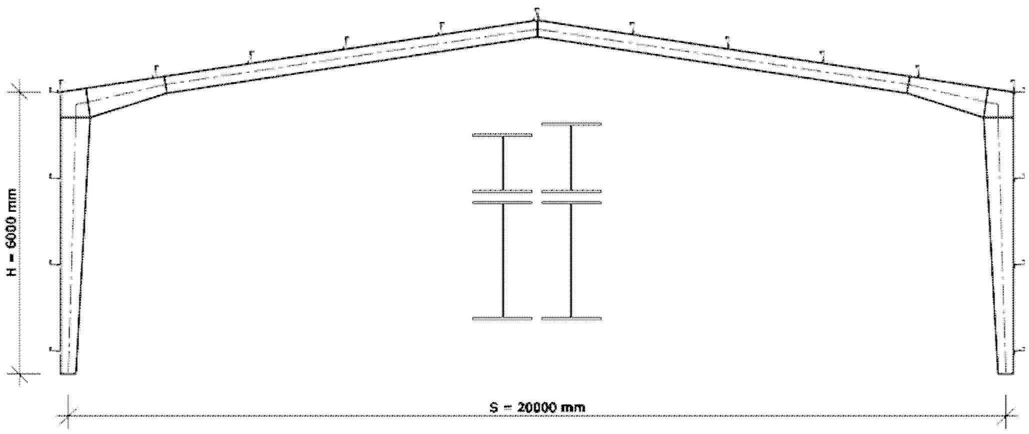


Fig 13 Frame 20/6, Snow 1500 N/m2

Frame 20/8 (Cases 12, 17, 44, 49, 76, 81)

Span (m)	Snow load (N/m^2)	Column	Rafter	Haunch ratio	Mass of the frame (tons)	Mass of the structure (tons)	Steel consumption (kg/m^2)
20	750	240x680x240x12x6	540x680x240x12x6	10	2.48	23.1	38.4
20	1500	320x680x320x14x6	420x680x320x14x6	10	3.32	28.2	46.9

Table 13 Frame 20/8

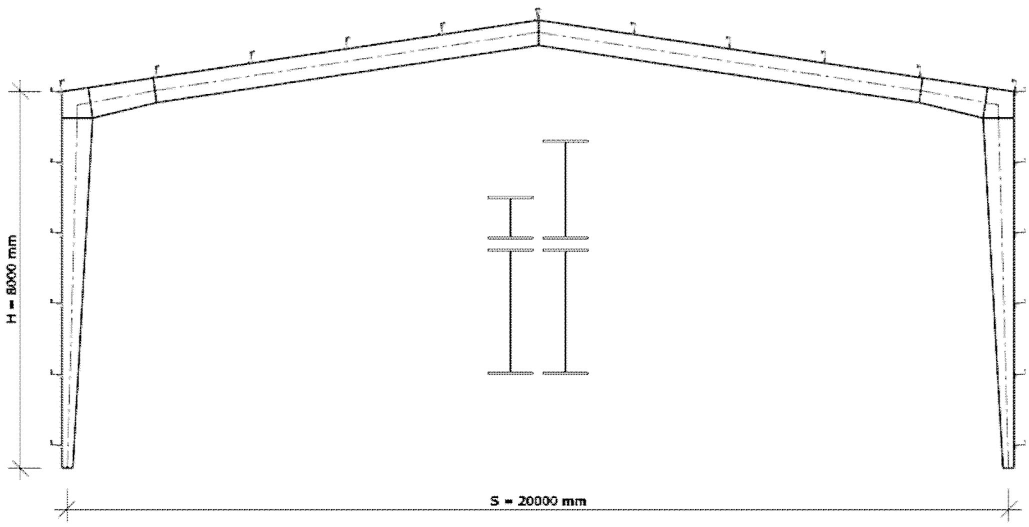


Fig 14 Frame 20/8, Snow 750 N/m2

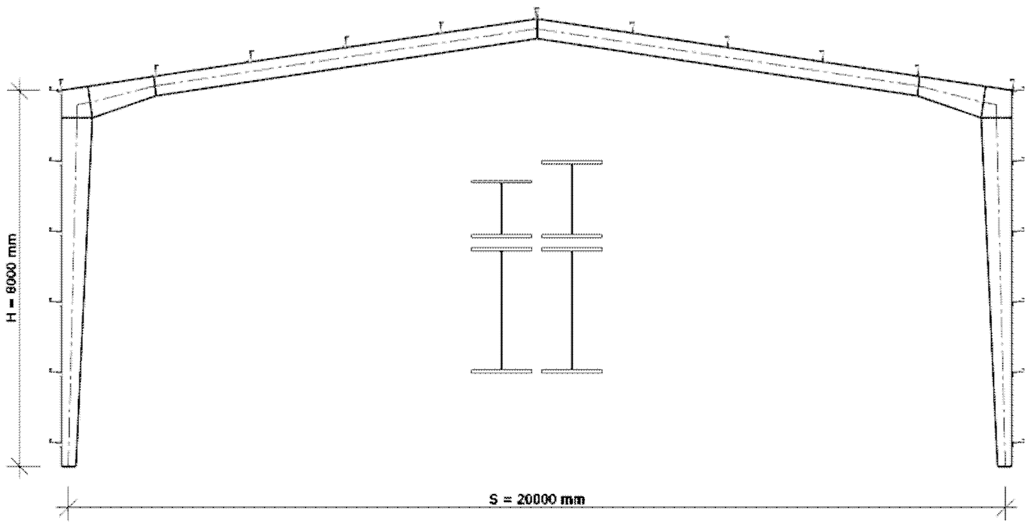


Fig 15 Frame 20/8, Snow 1500 N/m2

Frame 24/6 (Cases 3, 8, 35, 40, 67, 72)

Span (m)	Snow load (N/m^2)	Column	Rafter	Haunch ratio	Mass of the frame (tons)	Mass of the structure (tons)	Steel consumption (kg/m^2)
24	750	300x600x300x12x6	380x600x300x12x6	8	2.75	23.3	32.3
24	1500	340x680x340x14x6	500x680x340x14x6	10	3.57	28.8	40.0

Table 14 Frame 24/6

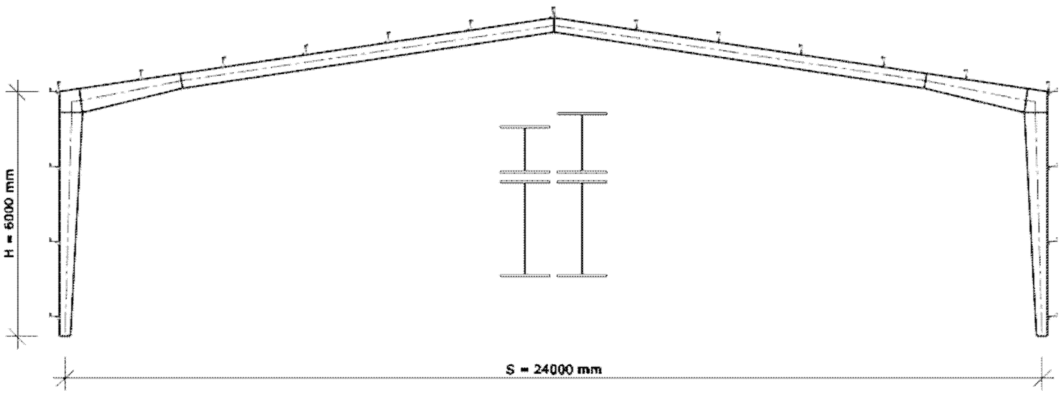


Fig 16 Frame 24/6, Snow 750 N/m2

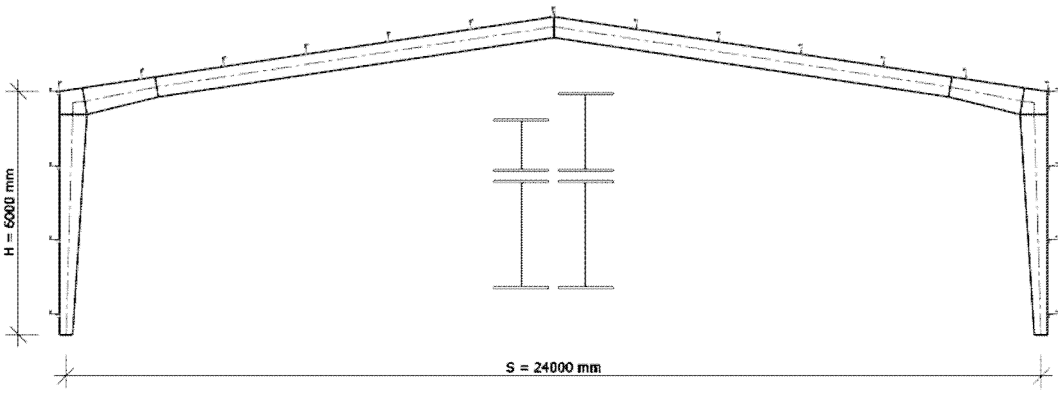


Fig 17 Frame 24/6, Snow 1500 N/m2

Frame 24/8 (Cases 13, 18, 45, 50, 77, 82)

Span (m)	Snow load (N/m^2)	Column	Rafter	Haunch ratio	Mass of the frame (tons)	Mass of the structure (tons)	Steel consumption (kg/m^2)
24	750	320x620x320x12x6	500x620x320x12x6	10	3.35	28.9	40.2
24	1500	360x640x360x15x6	440x640x360x15x6	11	4.29	34.3	47.7

Table 15 Frame 24/8

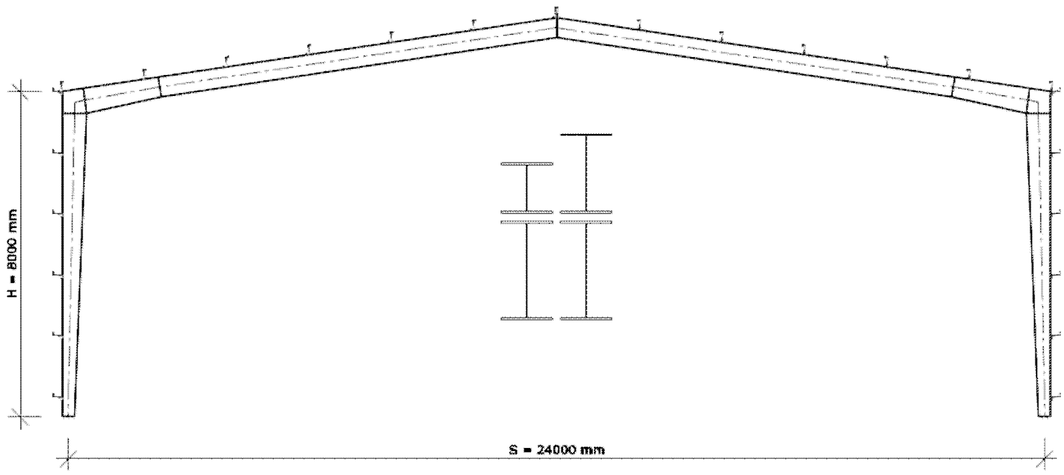


Fig 18 Frame 24/8, Snow 750 N/m2

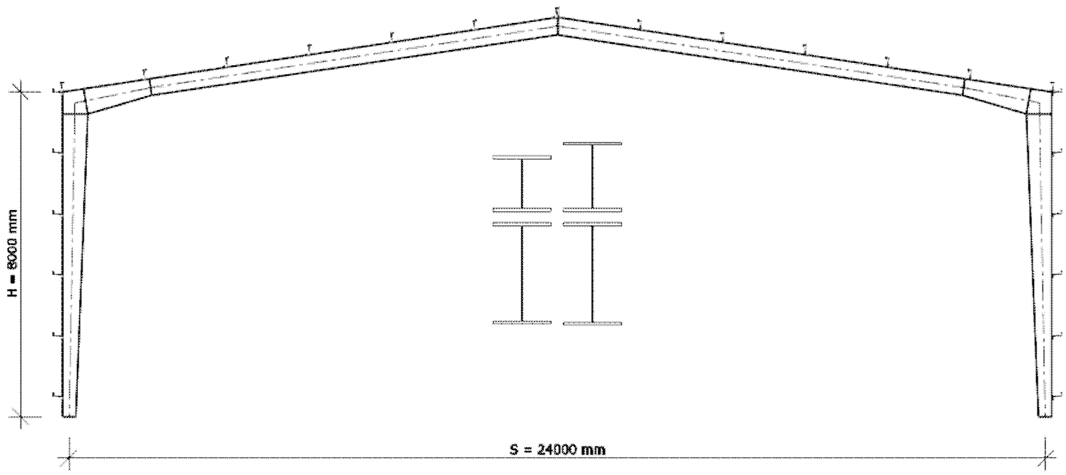


Fig 19 Frame 24/8, Snow 1500 N/m2

Frame 28/6 (Cases 4, 9, 36, 41, 68, 73)

Span (m)	Snow load (N/m^2)	Column	Rafter	Haunch ratio	Mass of the frame (tons)	Mass of the structure (tons)	Steel consumption (kg/m^2)
28	750	320x640x320x14x6	420x640x320x14x6	9	3.67	30.5	36.3
28	1500	380x860x380x15x8	540x860x380x15x8	10	5.06	40.1	47.8

Table 16 Frame 28/6

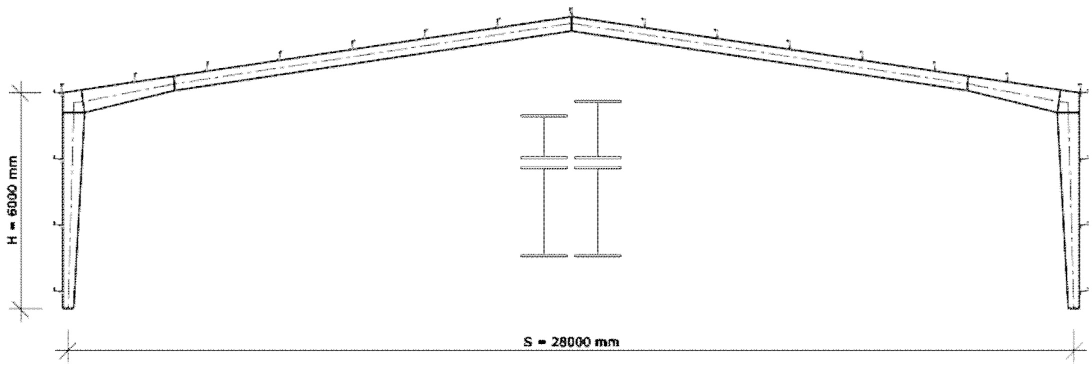


Fig 20 Frame 28/6, Snow 750 N/m2

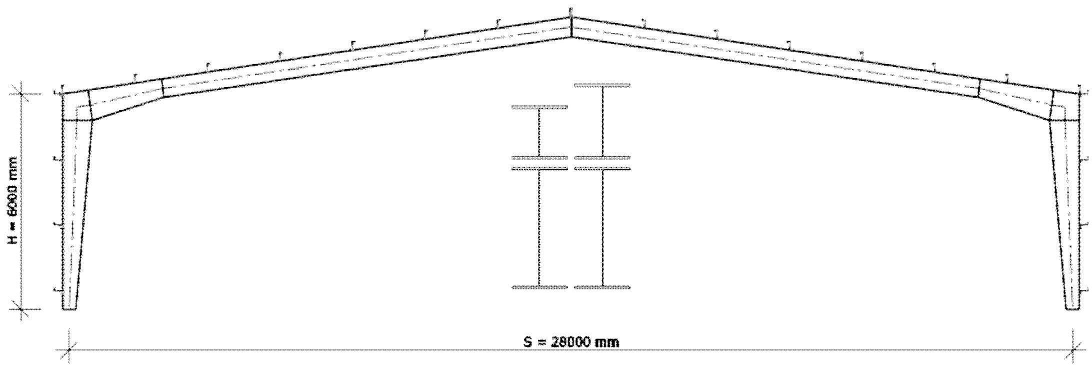


Fig 21 Frame 28/6, Snow 1500 N/m2

Frame 28/8 (Cases 14, 19, 46, 51, 78, 83)

Span (m)	Snow load (N/m²)	Column	Rafter	Haunch ratio	Mass of the frame (tons)	Mass of the structure (tons)	Steel consumption (kg/m²)
28	750	340x660x340x14x6	500x660x340x14x6	10	4.35	38.2	45.5
28	1500	400x800x400x15x8	480x800x400x15x8	8	5.67	46.1	54.9

Table 17 Frame 28/8

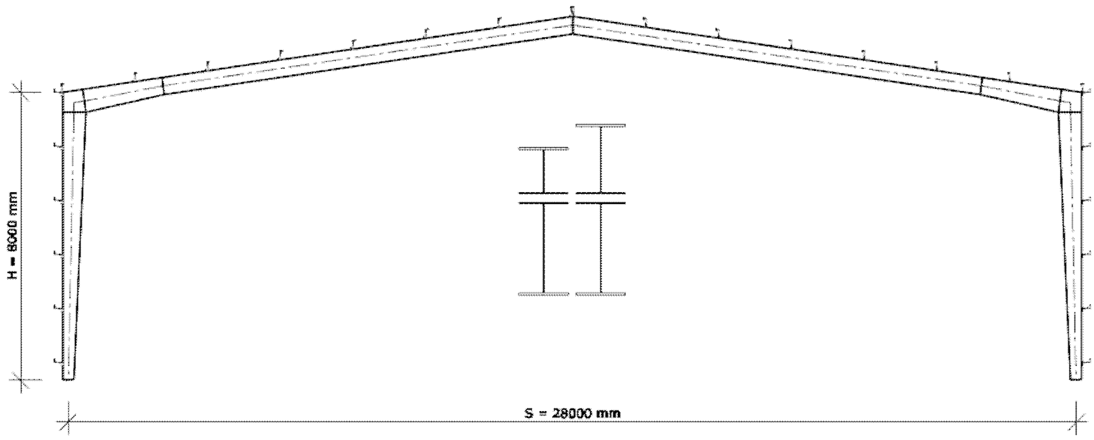


Fig 22 Frame 28/8, Snow 750 N/m2

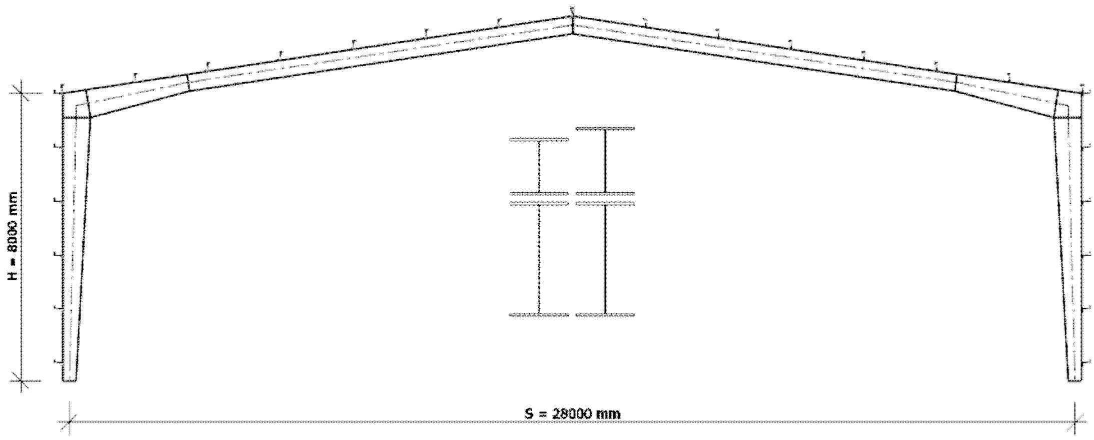


Fig 23 Frame 28/8, Snow 1500 N/m2

Frame 32/6 (Cases 5, 10, 37, 42, 69, 74)

Span (m)	Snow load (N/m^2)	Column	Rafter	Haunch ratio	Mass of the frame (tons)	Mass of the structure (tons)	Steel consumption (kg/m^2)
32	750	340x820x340x14x8	560x820x340x14x8	10	4.90	39.1	40.7
32	1500	400x800x400x18x8	500x800x400x18x8	10	6.48	50.0	52.1

Table 18 Frame 32/6

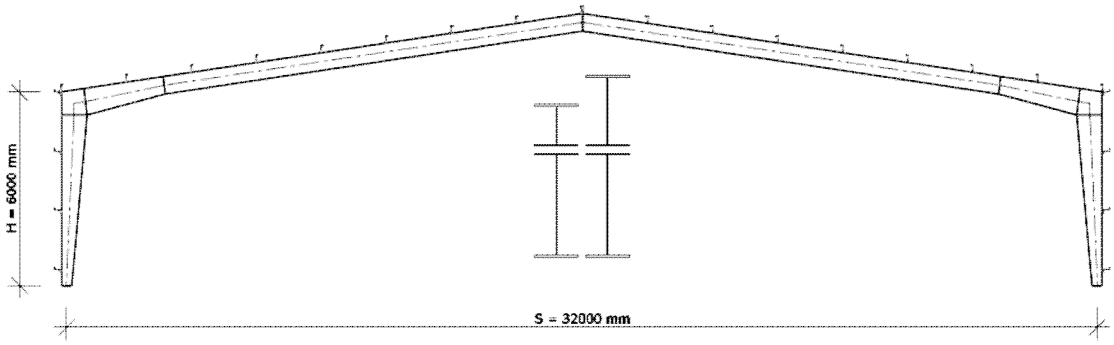


Fig 24 Frame 32/6, Snow 750 N/m2

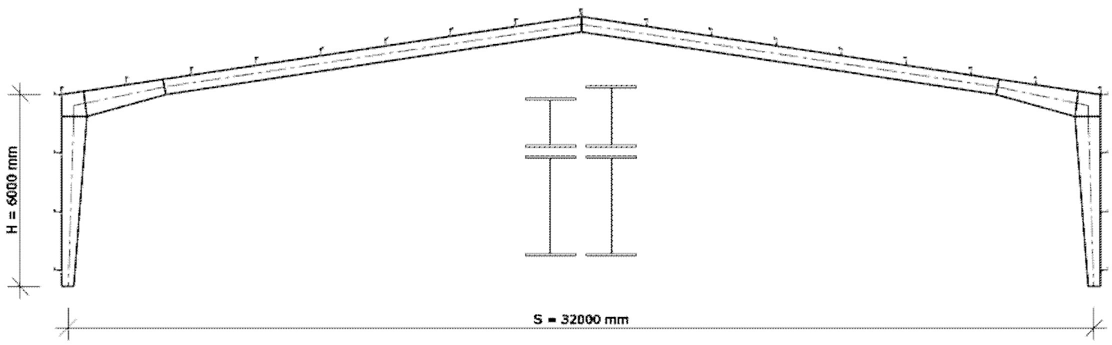


Fig 25 Frame 32/6, Snow 1500 N/m2

Frame 32/8 (Cases 15, 20, 47, 52, 79, 84)

Span (m)	Snow load (N/m^2)	Column	Rafter	Haunch ratio	Mass of the frame (tons)	Mass of the structure (tons)	Steel consumption (kg/m^2)
32	750	360x840x360x14x8	560x840x360x14x8	10	5.58	47.1	49.1
32	1500	380x920x380x20x8	580x920x380x20x8	9	7.58	59.1	61.6

Table 19 Frame 32/8

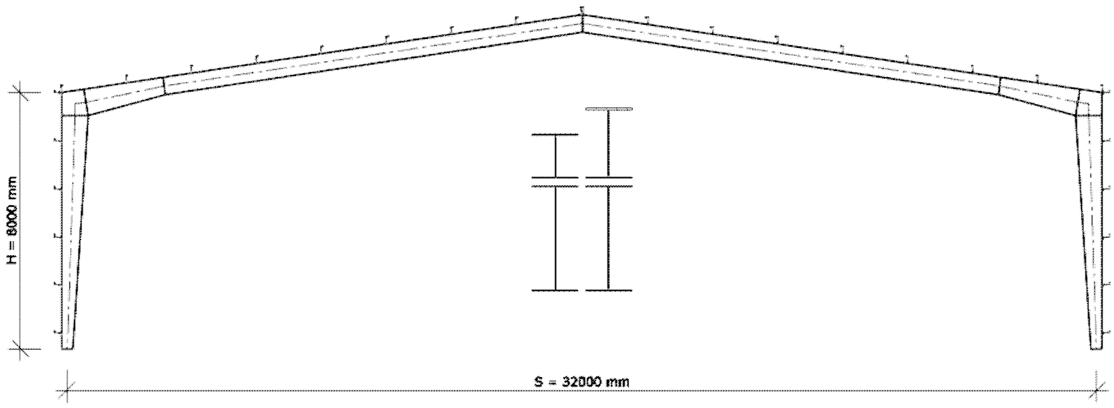


Fig 26 Frame 32/8, Snow 750 N/m2

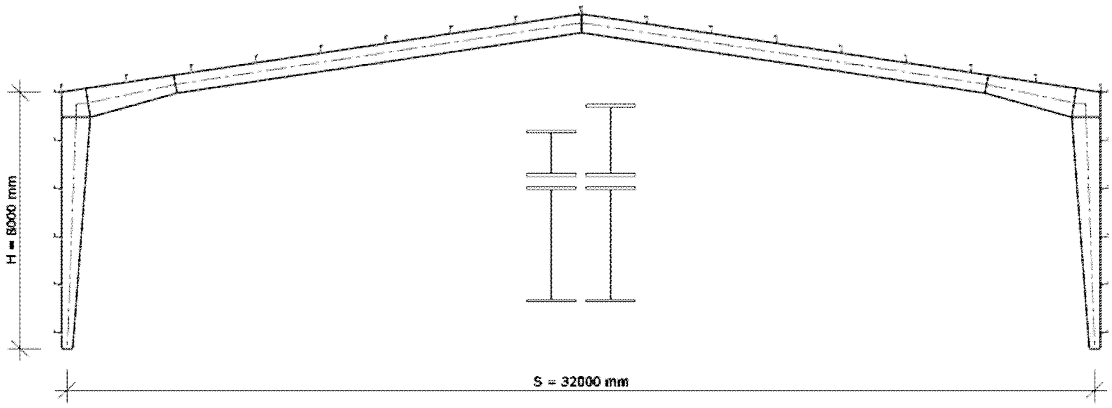


Fig 27 Frame 32/8, Snow 1500 N/m2

Frame 2x16/6 (Cases 21, 24, 53, 56, 85, 88)

Span (m)	Snow load (N/m^2)	Column	Rafter	Haunch ratio	Mass of the frame (tons)	Mass of the structure (tons)	Steel consumption (kg/m^2)
2x16	750	260x460x260x10x4	320x460x260x10x4	10	2.56	23.0	23.9
2x16	1500	220x600x220x14x8	300x600x220x14x8	7	3.49	29.6	30.8

Table 20 Frame 2x16/6

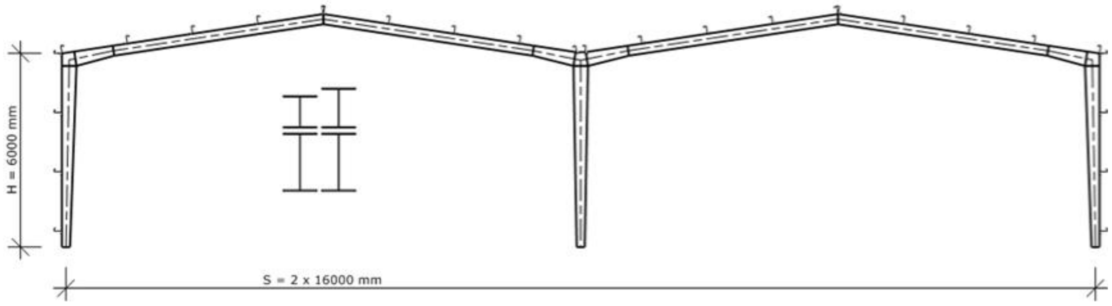


Fig 28 Frame 2x16/6, Snow 750 N/m2

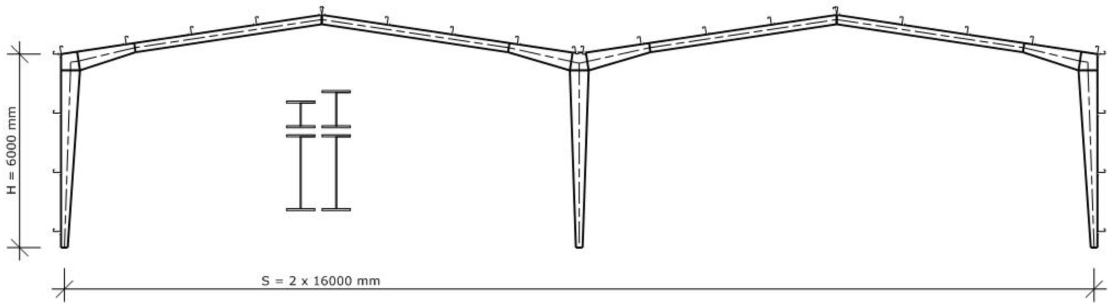


Fig 29 Frame 2x16/6, Snow 1500 N/m2

Frame 2x20/6 (Cases 22, 25, 54, 57, 86, 89)

Span (m)	Snow load (N/m^2)	Column	Rafter	Haunch ratio	Mass of the frame (tons)	Mass of the structure (tons)	Steel consumption (kg/m^2)
2x20	750	280x540x280x12x5	320x540x280x12x5	9	3.85	32.2	26.8
2x20	1500	320x640x320x14x6	340x640x320x14x6	8	5.14	41.3	34.4

Table 21 Frame 2x20/6

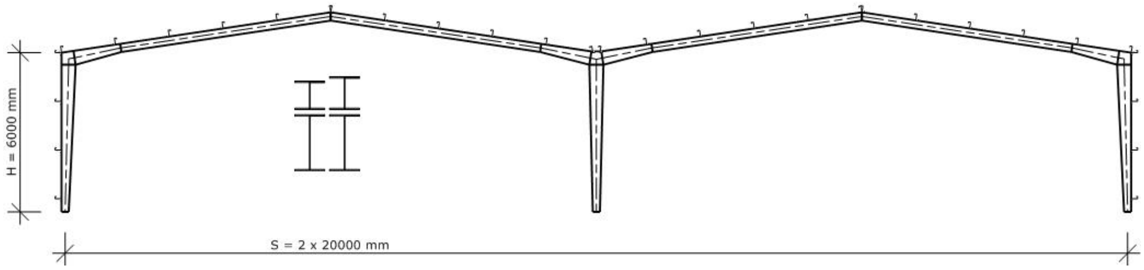


Fig 30 Frame 2x20/6, Snow 750 N/m2

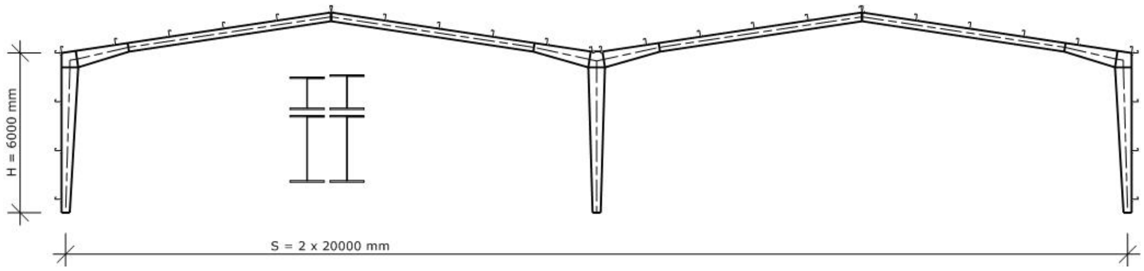


Fig 31 Frame 2x20/6, Snow 1500 N/m2

Frame 2x24/6 (Cases 23, 26, 55, 58, 87, 90)

Span (m)	Snow load (N/m^2)	Column	Rafter	Haunch ratio	Mass of the frame (tons)	Mass of the structure (tons)	Steel consumption (kg/m^2)
2x24	750	320x640x320x12x6	360x640x320x12x6	8	5.24	42.2	29.3
2x24	1500	340x660x340x18x6	380x660x340x18x6	9	7.59	59.5	41.3

Table 22 Frame 2x24/6

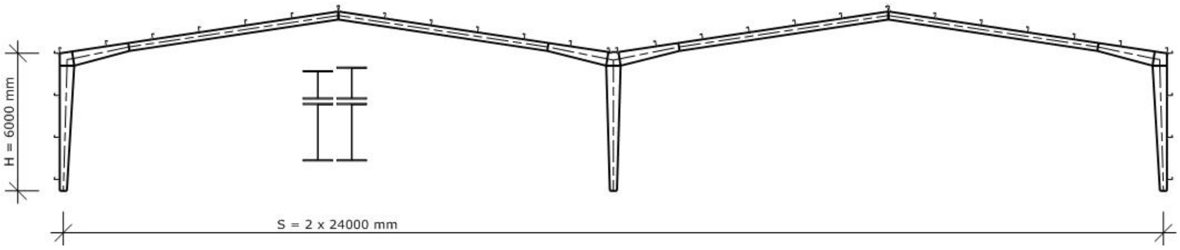


Fig 32 Frame 2x24/6, Snow 750 N/m2

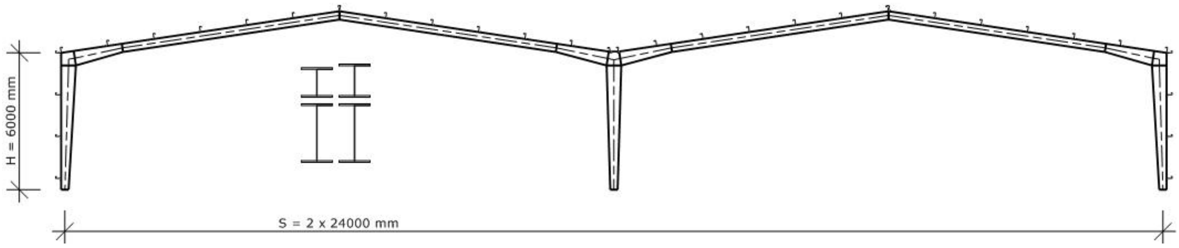


Fig 33 Frame 2x24/6, Snow 1500 N/m2

Frame 2x16/8 (Cases 27, 30, 59, 62, 91, 94)

Span (m)	Snow load (N/m^2)	Column	Rafter	Haunch ratio	Mass of the frame (tons)	Mass of the structure (tons)	Steel consumption (kg/m^2)
2x16	750	240x620x240x10x6	380x620x240x10x6	8	3.17	27.5	28.7
2x16	1500	300x580x300x12x6	320x580x300x12x6	7	4.16	38.6	40.3

Table 23 Frame 2x16/8

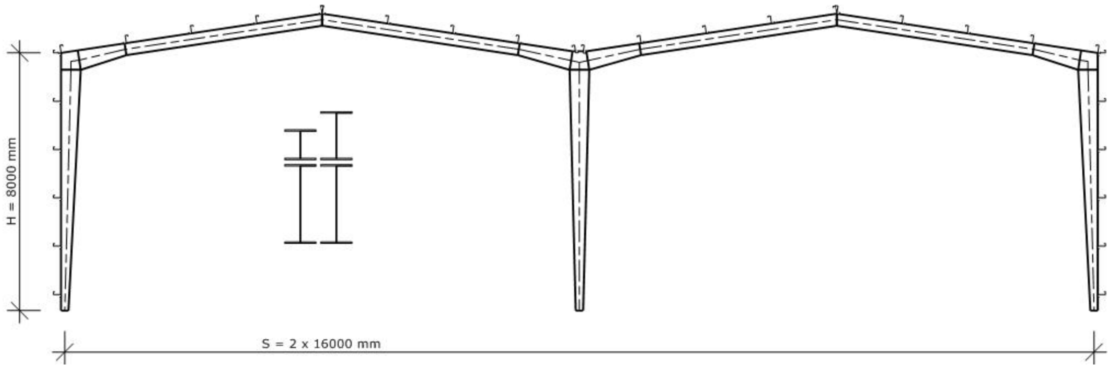


Fig 34 Frame 2x16/8, Snow 750 N/m2

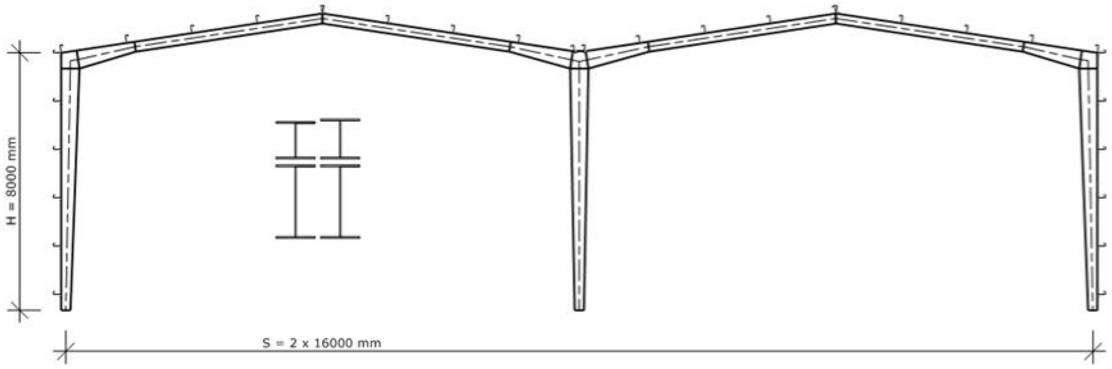


Fig 35 Frame 2x16/8, Snow 1500 N/m2

Frame 2x20/8 (Cases 28, 31, 60, 63, 92, 95)

Span (m)	Snow load (N/m^2)	Column	Rafter	Haunch ratio	Mass of the frame (tons)	Mass of the structure (tons)	Steel consumption (kg/m^2)
2x20	750	300x560x300x12x5	400x560x300x12x5	10	4.64	37.6	31.3
2x20	1500	320x860x320x12x8	380x860x320x12x8	6	5.83	50.8	42.4

Table 24 Frame 2x20/8

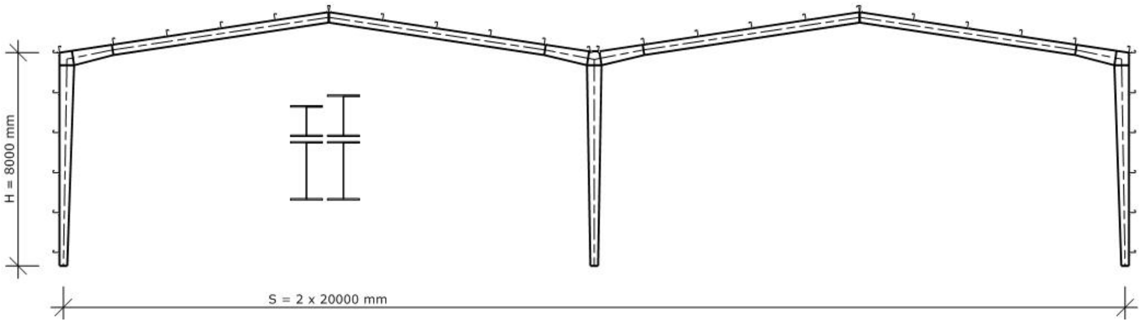


Fig 36 Frame 2x20/8, Snow 750 N/m2

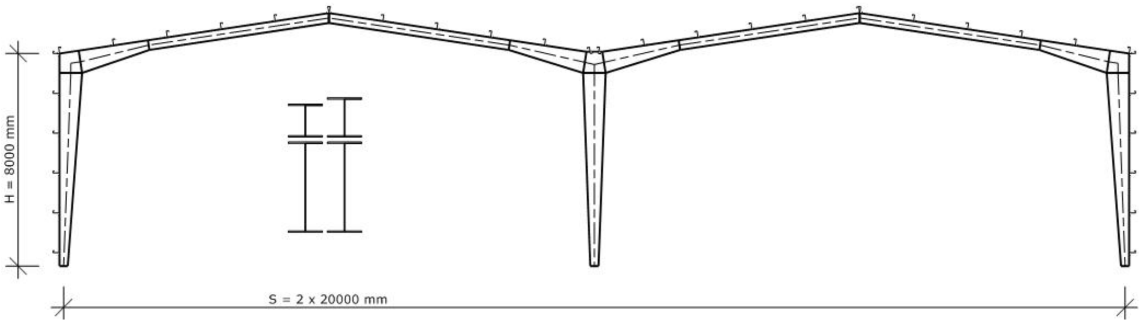


Fig 37 Frame 2x20/8, Snow 1500 N/m2

Frame 2x24/8 (Cases 29, 32, 61, 64, 93, 96)

Span (m)	Snow load (N/m^2)	Column	Rafter	Haunch ratio	Mass of the frame (tons)	Mass of the structure (tons)	Steel consumption (kg/m^2)
2x24	750	320x640x320x14x6	380x640x320x14x6	7	6.48	49.5	34.4
2x24	1500	360x900x360x15x8	440x900x360x15x8	6	8.49	68.2	47.3

Table 25 Frame 2x24/8

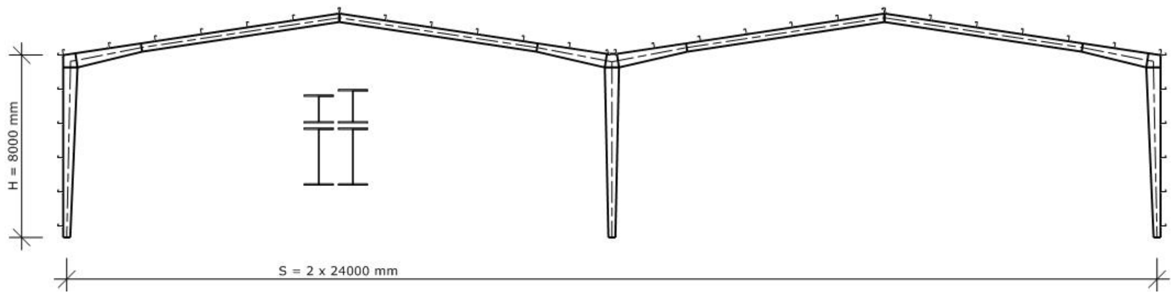


Fig 38 Frame 2x24/8, Snow 750 N/m2

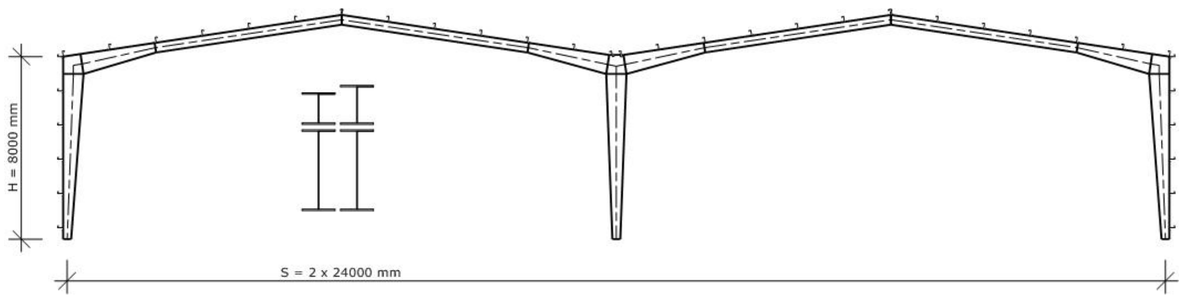


Fig 39 Frame 2x24/8, Snow 1500 N/m2