Stabilization of volumes – optimization

Final Report

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Preface

Building with volume technology has several advantages that are not always fully utilized. By building houses with prefabricated three-dimensional units, it is considered that an “extra” stability is obtained which is not always reflected in dimensioning rules.

The effect that a three-dimensional approach has is not taken into account due to the difficulty and little experience of any added value with a three-dimensional considerations of building volumes.

In this project, the possibility of determining a 3D factor with which manufacturing companies can optimize their solutions has been investigated.

The work has been financed by TräCentrum Norr and participating companies. The project has been implemented as a complementary project to Interreg received by RISE and LTU. Nord project “TallWood – Wood Solutions in Tall Hybrid Building”. The TallWood project aims to develop new solutions for hybrid constructions for the benefit of building tall wooden houses and among other things, its goal is to develop calculation aids, processes and systems based on hybrid constructions to increase the competitiveness of wooden construction.

A big thanks to the industry reference group’s participants for valuable views and efforts during the work’s planning and implementation: Per-Olov Landstedt and Jamal Alipour, Derome-Plusshus, Lars Oscarsson and Ida Edskär, Lindbäcks Bygg.

Other participants and implementers of the project have been Anders Gustafsson, Urban Häggström and Jörgen Olsson all at RISE and Sven Berg, LTU.

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1. Background, purpose and boundaries

Construction of multi-story wooden houses is growing with an increasing rate in Sweden. In order to maintain and improve competitiveness, it is important to constantly develop new products but also to improve existing products. An important part is also to improve calculation methods and verify the capacity of existing products.

Dimensioning of stabilizing walls is usually only done at subcomponent level (sum of individual walls' capacity). The effect that a three-dimensional approach entails is not taken into account due to the difficulty and little experience of any added value that can be obtained with a three-dimensional approach.

If there were an opportunity to create a "3D factor", it would be of great importance to manufacturers of building volumes. This may mean that it is possible to build higher than today, but also that the amount of stabilizing boards can be reduced while maintaining total stability.

The project is based on the latest development in wood construction technology and the construction technology that enabled building of several floors up to 8-10.

The purpose of the project is to optimize existing constructions and development of design tools/ methods, processes and building system technology to thereby increase the competitiveness of wood construction.

The following sub-goals have been set:

- Compilation of previous work and results.
- Presentation of calculation hypothesis for "3D factor".
- Results of stability tests.
- Compilation of FEM model.
- Evaluation and adaptation of hypotheses.

2. Work methodology and hypotheses

The principle for determining a 3D factor has been to show, based on tests, differences between the results in pressure testing of individual walls and pressure testing of volumes with similar walls. The comparison has been made analytically and with the help of FEM calculations.

2.1 Load bearing capacity

The most common method, elastic dimensioning, for dimensioning the stability and load-bearing capacity of a wall is to calculate the load-bearing capacity of the boards attached to a rule structure according to current calculation standards. The calculations are based on the capacity of the included boards, the capacity of the fastening elements and the interaction between boards. The capacity of the wall panels is often based on tests where the results have been recalculated to apply per meter of wall or equivalent. The results are reported as the permissible horizontal load per panel width and the capacity of the entire wall is the sum of the capacity of all panels. The horizontal capacity if a volume is determined by the number of walls acting in the direction of force.

The plastic method /1/ provides the ability to control the forces and take greater account of transverse walls and usually provides higher calculated capacities.

2.2 Deformation criteria in serviceability limit

The deformation criteria applied, is decided by the designer and there are no specific criteria in current standards. Recommendations and previous versions of standards have been used deformation limitations $u \leq {}^{h}/_{300}$ which h indicates the current height (previous version of Eurocode 5) and $u \leq {}^{h}/_{500}$ (German DIN standard).

If a change in slope results in damage to walls and frame complements without special investigation, a change of 0.2% of ${}^{h}/_{500}$ is accepted /2/. If there is not a risk of damage, slope changes of no more than 0.7% or ${}^{h}/_{143}$ are accepted /2/.

2.3 Working methodology

The working method within the project has been to:

a) Determine the capacity of retaining walls by testing.
b) Determine the holding capacity of the volume by testing.
c) Evaluate the results analytically and with FEM calculations.
d) Determination of 3D Factor.

3. Components

3.1 Walls

In the project, a total number of 16 wall elements have been built and tested with different constructions. The wall elements have been manufactured and supplied by Derome AB and Lindbäcks Bygg AB, respectively. Construction of walls is shown in Appendix 1, testing of wall rigidity, RISE report 2P00662-01.

3.2 Volumes

In the project, two volumes have been built with a similar floor plan but with company-specific wall constructions. The volumes have been manufactured and provided by Derome AB and Lindbäcks Bygg AB, respectively. The description of the volumes can be found in Appendix 2, testing of wall stiffness, volumes, RISE report 2P00662-02.

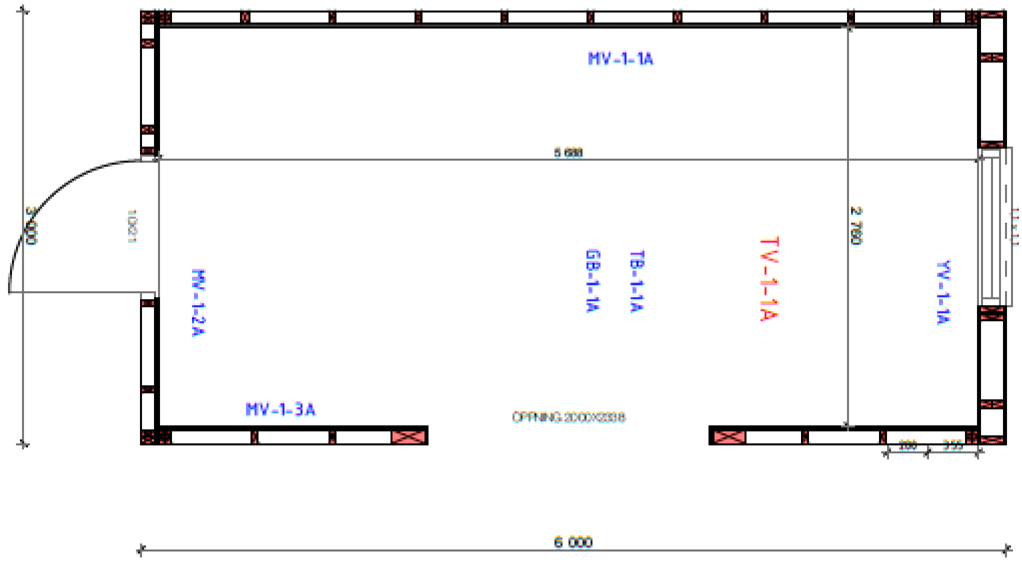

Figure 1 Volume floor plan

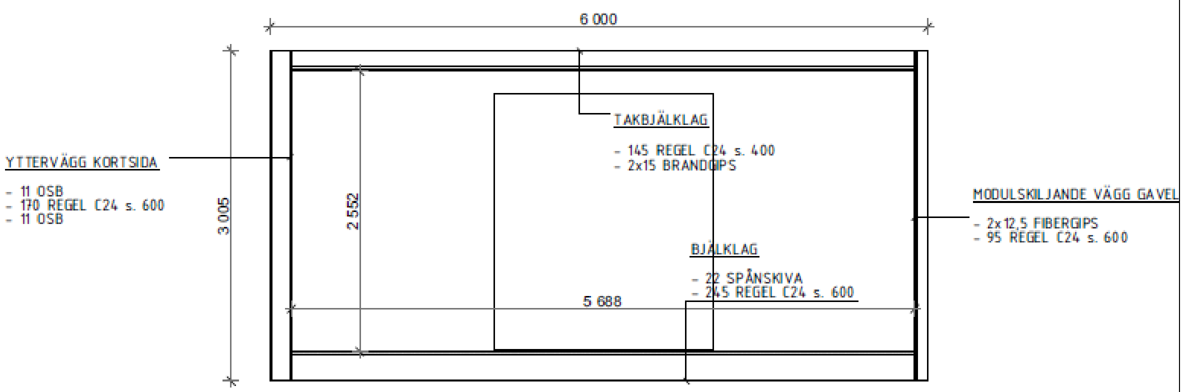

Figure 2 Example of wall construction and size

4. Results

4.1 Results of wall tests

Complete results and description of wall tests are given in the report Wall stiffness test, RISE report 2P00662-01.

Table 1 Summary of results from testing of walls only

Stiffness determination

Table 1: results of stiffness (R) of wall elements

Wall:	*R (N/mm)	R valid for interval (N)	**F_{max} (N)	Def at 10 KN (mm)
K1 (3m)	2459	4 500 – 25 000	37 237	3,37
Y1 (3m)	1421	3 400 – 10 000	27 065	3,71
LS1 (6m)	2578	2 200 – 30 000	46 394	3,55
LS2 (6m)	717	2 000 – 8 000	19 534	9,63
YV (3m)	2 265	2 000 – 22 000	47 039	3,67
MV-1-2A (3m)	1 494	2 500 – 10 000	24 278	3,67
MV-1-1A (6m)	3 279	18 000 – 32 000	51 451	0,09
MV-1-3A (6m)	1 970	7 500 – 20 000	41 304	1,58

4.2 Results from testing of volumes

Complete results and description of tests of volumes are given in report Test of wall stiffness, volumes RISE report 2P00662-02.

Table 2 Summary of displacements at different loads applied.

Table 2: Displacements across volumes

	Lindbäcks		Derome	
Load (kN)	Position 3 (mm)	Position 5 (mm)	Position 3 (mm)	Position 5 (mm)
25	0,19 v	0,36 h	2,45 h	1,12 h
50	1,24 v	1,90 h	4,45 h	1,72 h
75	1,79 v	0,97 h	5,86 h	2,35 h
100	2,89 v	5,64 h	6,75 h	2,23 h

position 3 = back / top / left
position 5 = above the side opening
v = displacements at left side from the pressure side

5. Evaluation of test results

5.1 Analytical evaluation of tests

Applied and resisting forces must cancel out each other. Applied force was applied at one point, see test report, and distributed to longitudinal walls via a distribution beam. To determine how much goes to each wall, horizontal forces were also recorded in the support. Together with friction against steel beams, the total restraining force must be equal to the total force applied.

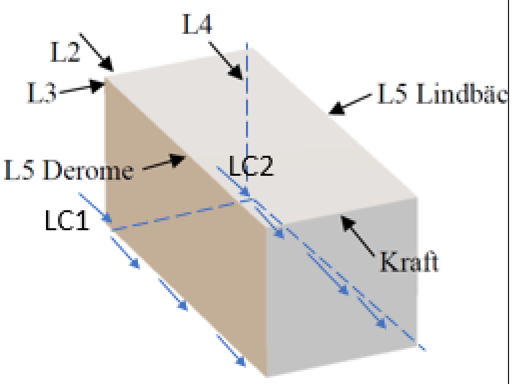	
Figure 3 Principle figure placement of applied loads and placement of position sensors. LC1, LC2 Loaders L1-L5 Position sensor	Figure 4 Image from test setup volumes.

5.2 Resistant force due to friction, coefficients of friction

In the contact surface between the steel frame and the volume sill plate, restraining forces arise. The magnitude of restraining forces is determined by the coefficient of friction between the surfaces. During the test, there was plastic between the volume and the steel rig, which gives a restraining force due to friction, that can be determined according to:

$F_{friction} = N \mu_f$

Coefficient of friction was checked experimentally and determined to

Wood- steel $\mu_f = 0.485 - 0.490$
Plastic- steel $\mu_f = 0.330 - 0.340$
Solymer- wood $\mu_f = 0.73 - 0.78$

The dead weight of the volume amounts to approximately 2900 kg and the load applied in the form of thick steel plates amounts to 7600 kg. Total restraining force will then be approximately 35 kN.

$F_{friction} = N \mu_f = (76000 + 29000) \times 0.335 = 35.18$ kN to be distributed equally on both long sides.

5.3 Selected walls and designations

The comparison between wall and volume is made at wall level, i.e. the results from the walls' capacity during wall testing are compared with the walls' capacity during the testing of the volume. The comparison is made for each individual wall.

The 3D factor has been calculated to be obtained according to: $F_{3D} = F_{wall} / F_{volume}$ at deformation of 5 mm, 10 mm, 15 and 20 mm.

In order to be able to determine in which areas (deformation limits) the factors apply, linear relationships have been established between force and deformation, see figures below.

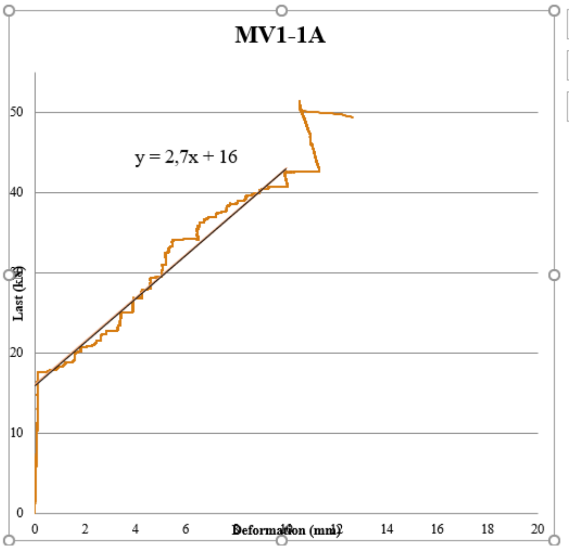	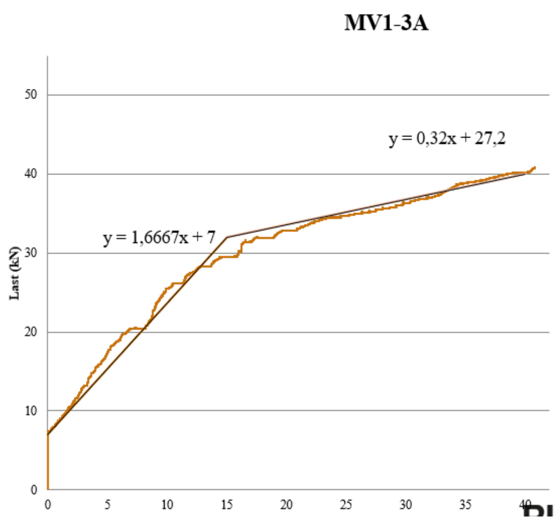
Figure 5 Graph from wall test. Long side wall without openings, Derome AB.	Figure 6 Graph from wall test. Long side wall with openings, Derome AB.

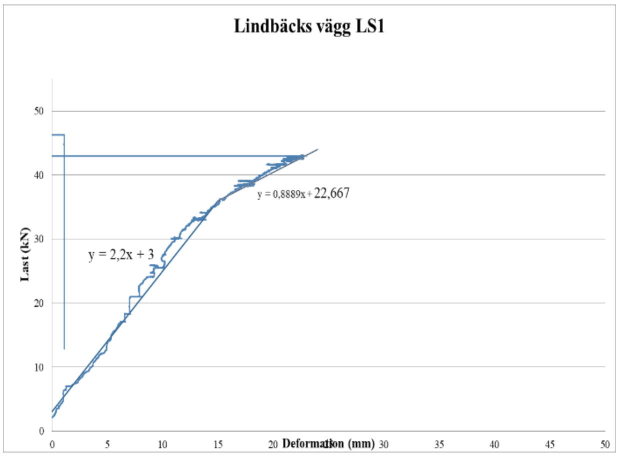

Figure 7 Graph from wall test. Long side wall without openings, Lindbäcks Bygg AB.

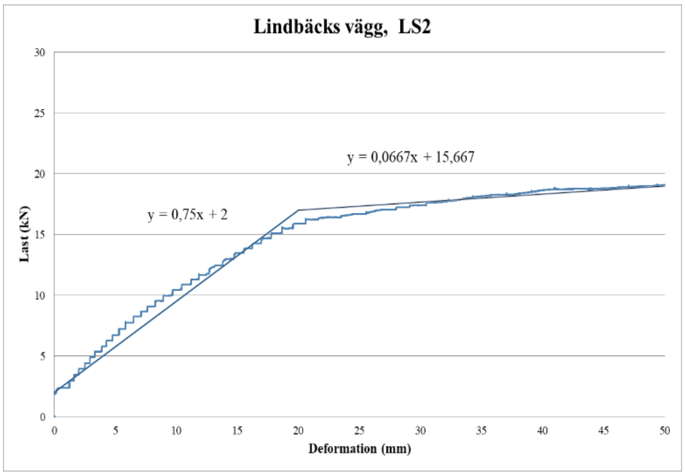

Figure 8 Graph from wall test. Long side wall with openings, Lindbäcks Bygg AB.

In a similar way, graphs are produced for long sides when testing volume, see Figure 9.

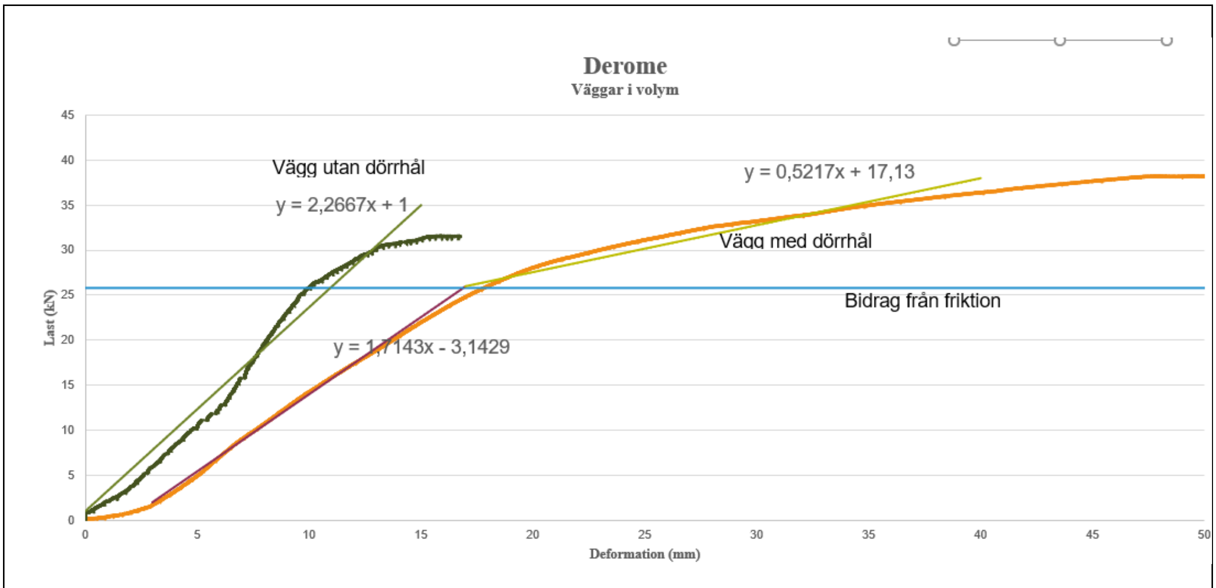

Figure 9 Graphs from volume testing. Walls with and without opening. Derome AB

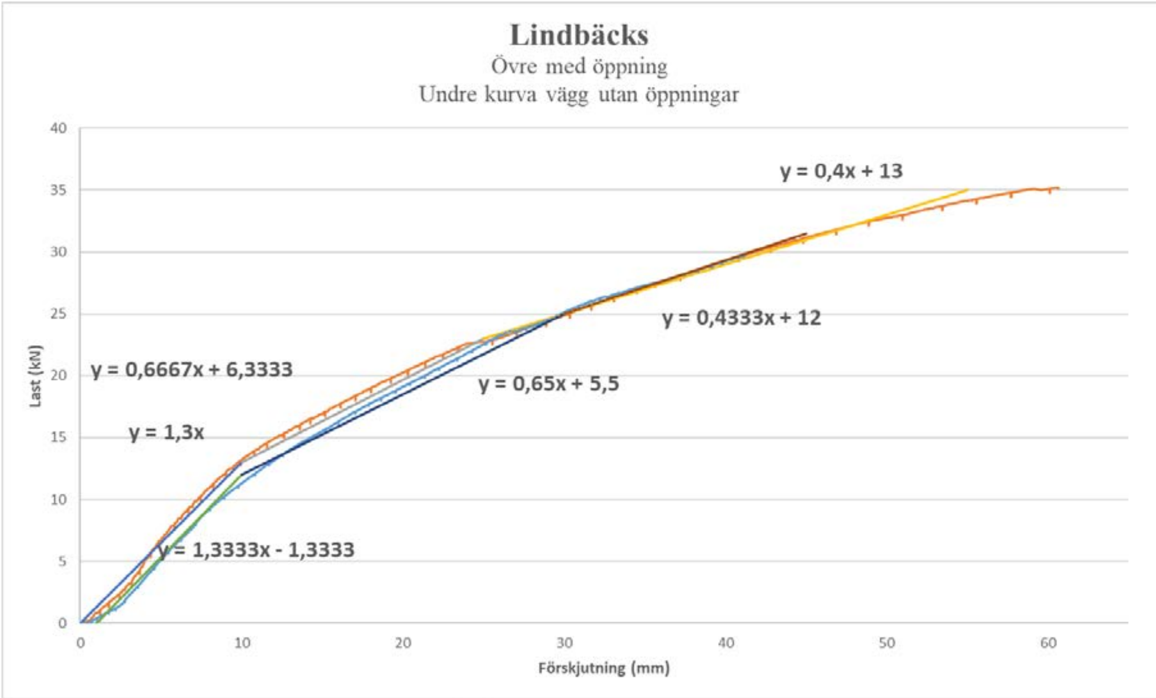

Figure 10 Graphs from volume testing. Walls with and without opening, Lindbäcks Bygg AB.

If values are entered for the different graphs and a comparison is made, the following values are obtained according to Table 3-Table 8.

Table 3 Comparison wall MV1-1A, long side without opening, Derome AB.

R=3279 N/mm	**5 mm**	**10 mm**	**15 mm**	**20 mm**
MV1-1A, Wall smaple	*29,5* kN	43 kN	Around 55 kN*	Around 70*
MV1-1A, Volume sample	12,3+17,6 =29,9 kN	23,7+17,6 =41,3 kN	34,0+17,6 =51,6 kN	-
Factor	1,01	0,96	0,94	

- Values calculated linearly based on values between 0-10 mm.

Table 4 Comparison wall MV1-3A, long side with opening, Derome AB.

R=1970 N/mm	**5 mm**	**10 mm**	**15 mm**	**20 mm**
MV1-3A, Wall sample	*15,3* kN	*23,7* kN	32,0 kN	33,6 kN
MV1-3A, Volume sample	5,4+17,6 =23 kN	14,0+17,6 =31,6 kN	22,6+17,6 =40,2 kN	27,6+17,6=45,2 kN -
Factor	1,50	1,33	1,26	1,35

Table 5 Total volume, Derome AB.

	5 mm	**10 mm**	**15 mm**	**20 mm**
MV1-1A+MV1-3A Wall sample	44,8 kN	66,7 kN	87,0 kN	103,6 kN
Volume sample	50,6 kN	72,3 kN	92,7 kN	101,2 kN
Factor	1,13	1,08	1,06	0,98

Table 6 Comparison wall LS1, long side without opening, Lindbäcks Bygg AB.

R=2578 N/mm	**5 mm**	**10 mm**	**15 mm**	**20 mm**
LS1, Wall sample	*14,0* kN	*25,2* kN	36,1 kN	40,5 kN
LS1, Volume sample	5,3+17,6=22,9	12,0+17,6 =29,6 kN	15,3+17,6 =32,9	18,5+17,6=36,1
Factor	1,63	1,17	0,91	0,89

Table 7 Comparison wall LS2, long side with opening, Lindbäcks Bygg AB.

R=717 N/mm	**5 mm**	**10 mm**	**15 mm**	**20 mm**
LS2, Wall sample	*5,8* kN	*9,5* kN	13,25 kN	17,0 kN
LS2, Volume sample	6,5+17,6 =24,1 kN	12,0+17,6 = 29,6 kN	16,3+17,6 =33,9 kN	19,7+17,5=37,2 kN
Factor	4,16	3,12	2,56	2,19

Table 8 Total volume, Lindbäcks Bygg.

	5 mm	**10 mm**	**15 mm**	**20 mm**
LS1+LS2 Wall sample	19,8 kN	34,7 kN	49,4 kN	57,5 kN
Volume sample	45,3 kN	57,7 kN	67,2 kN	75,2 kN
Factor	2,28	1,67	1,36	1,31

5.4 Error sources

During the testing of the volumes, the main beam of the rig was curved, which meant an angular change of the applied load. The beam was curved upwards a maximum of 50 mm at the load point. This means that vertical reaction forces also arise in the supports and that the horizontal restraining forces decrease. Vertical forces and reduced horizontal forces can be estimated at:

Angle change of the load: change of angle α= arctan50 / 6000 gives about 0.5 degrees.

Vertical force at applied load of 100 kN gives 0.9 kN.

Horizontal change due to angular change: about 0.1 kN.

The specific gravity between the long-side walls differs, which affects the magnitude of the frictional force. However, the difference is so small that it has been considered negligible.

The applied force F1 should be equal to the measured forces at end supports LC1 and LC3 added with abrasive forces due to friction. A comparison is shown in Table 9 and Table 10

Table 9 Comparison between applied horizontal load and measured force, Derome.

	5 mm	10 mm	15 mm	20 mm	25 mm	60 mm
F1	53,6	65,4	80,0	92,7	98,7	116,4
LC1+LC2 +$F_{friction}$	10,4+7,76 +35,2=53,4	15,5+14,3 +35,2=65,0	22,0+21,4 +35,2=78,6	28,0+25,9 +35,2=89,1	31,2+27,7 +35,2=94,1	38,9+31,5 +35,2=105,6
Difference	-0,2 (0,4%)	-0,4	-1,4	-3	-4,6 (4,6%)	-10,8 (9,3%)

Tabell 10 Comparison between applied horizontal load and measured force, Lindbäcks Bygg.

	5 mm	10 mm	15 mm	20 mm	25 mm	50 mm
F1	50,0	62,1	70,8	78,0	82,5	98,3
LC1+LC3 +$F_{friction}$	9,9+6,7 +35,2=51,8	15,0+13,2 +35,2=63,4	18,6+17,0 +35,2=70,8	21,8+20,3 +35,2=77,3	23,6+22,7 +35,2=81,5	28,3+32,7 +35,2=96,2
Difference	1,8	1,3	0	-0,7	-1,0	-2,1

The difference between the applied horizontal load and the measured horizontal load is less than 5% for loads below 100 kN.

Tests of individual walls are not performed in exactly the same way as when the wall is attached to the volume and that the deflection of individual walls to the side may have affected the measurement results. This may have meant that the stiffness of individual walls has been underestimated.

5.5 Evaluation using FE calculations

Models of the walls and Deromes and Linbäck's test modules were made according to drawings, figure 11. For drawings, see appendix.

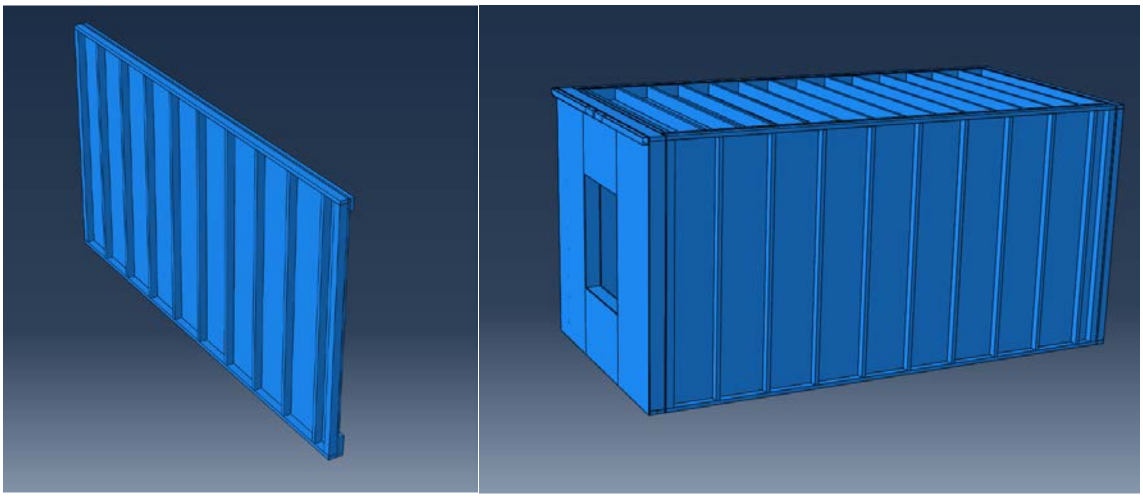

Figure 11. Example of modeled wall and volume

Both wooden joists and gypsum board were modeled as elastic. The steel beam used in the experiments was modeled as elastoplastic. See Table 11 for material data. Poisson's ratio was set to zero for wood and 0.3 for gypsum and steel.

Table 11. Material data for wood, gypsum and steel in MPa

	E1	E2	E3	G1	G2	G3
wood	11000	370	370	690	690	69
gypsum	2500					
Steel	210 000					

The contact conditions used were cohesion-controlled, where the stiffnesses in the main directions were adjusted so that the model would follow the experiments' global load-displacement curve, up to 10 mm displacement. In other respects, "hard contact" and "Allow separation after contact" were used. The elements used were C3D8. The load was simulated with a displacement instead of a force due better convergence.

Contact stiffness was the same for drywall as wood-wood, no roof load module. The boundary conditions of the model were freely supported on beams below the volume and walls as well as support in the direction of force on the beam at the back of the volume and wall. To compare the rigidity of the module with the rigidity of the walls, a model was made where the rigidity of the two long side walls was tested together, see figure 12. This model was also made with a boundary condition that prevented buckling of the walls; the gypsum board was held out of the plane.

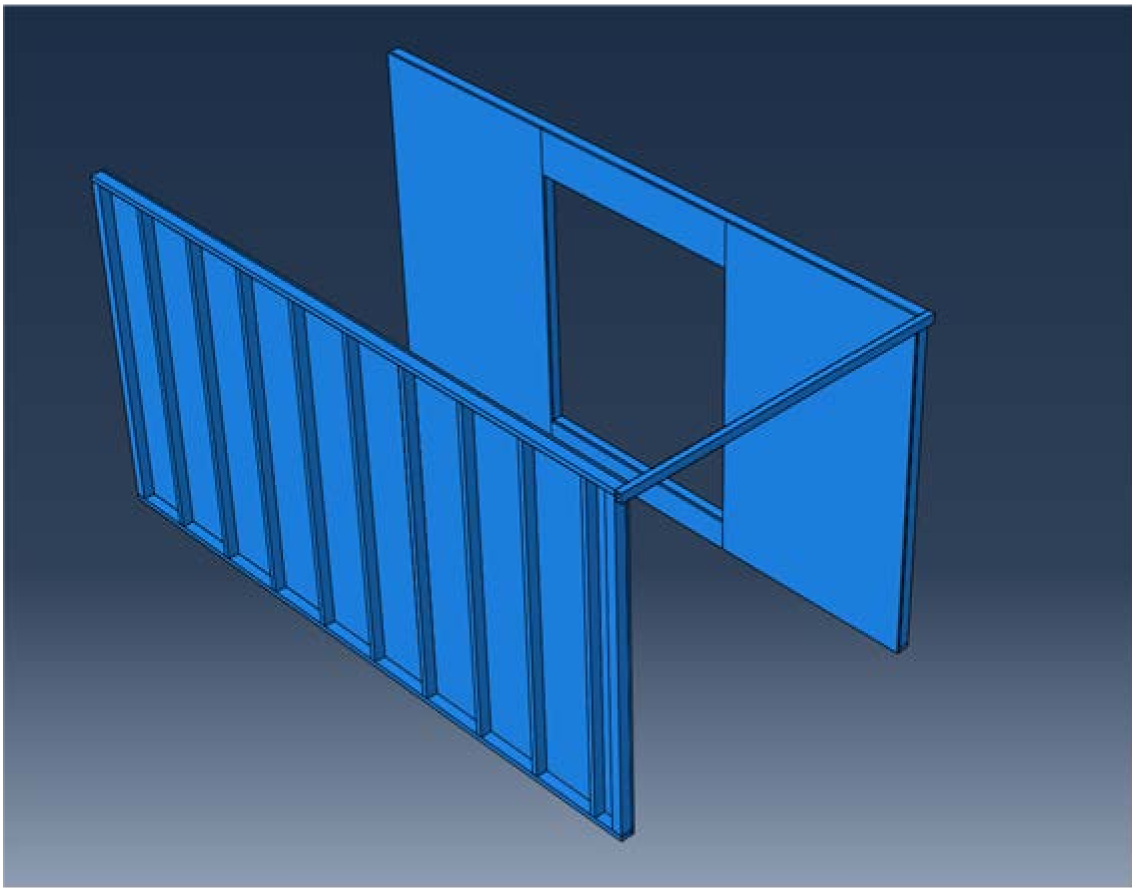

Figure 12. Model testing the two long side walls together.

5.5.1. Models and model calibration

To calibrate the model against the wall tests, the test results were approximated to a linear stiffness up to 10 mm, see figure 3. For the module the same was done, but the model was calibrated against two different stiffnesses, see figure 13. For the volumes called the stiffness starting from zero, 1:a stiffness and the subsequent 2:a stiffness.

A model of the volume in which the calibrated wall stiffeners were used was made. In this case, no calibration was performed against the load-displacement curve of the volume experiments. It gives a relative comparison, in terms of model, when you go from walls to volume.

To calculate a "3D factor", the stiffness of the volume, up to 5 mm offset, was compared with the model with the two walls. At ratio 1 the walls that can buckle are used and at ratio 2 they cannot buckle. This was tested so that the buckling is not taken into account in manual calculations. The result of the contact stiffness from individual walls was used for the walls of the volume. A summary of models can be seen in Table 9.

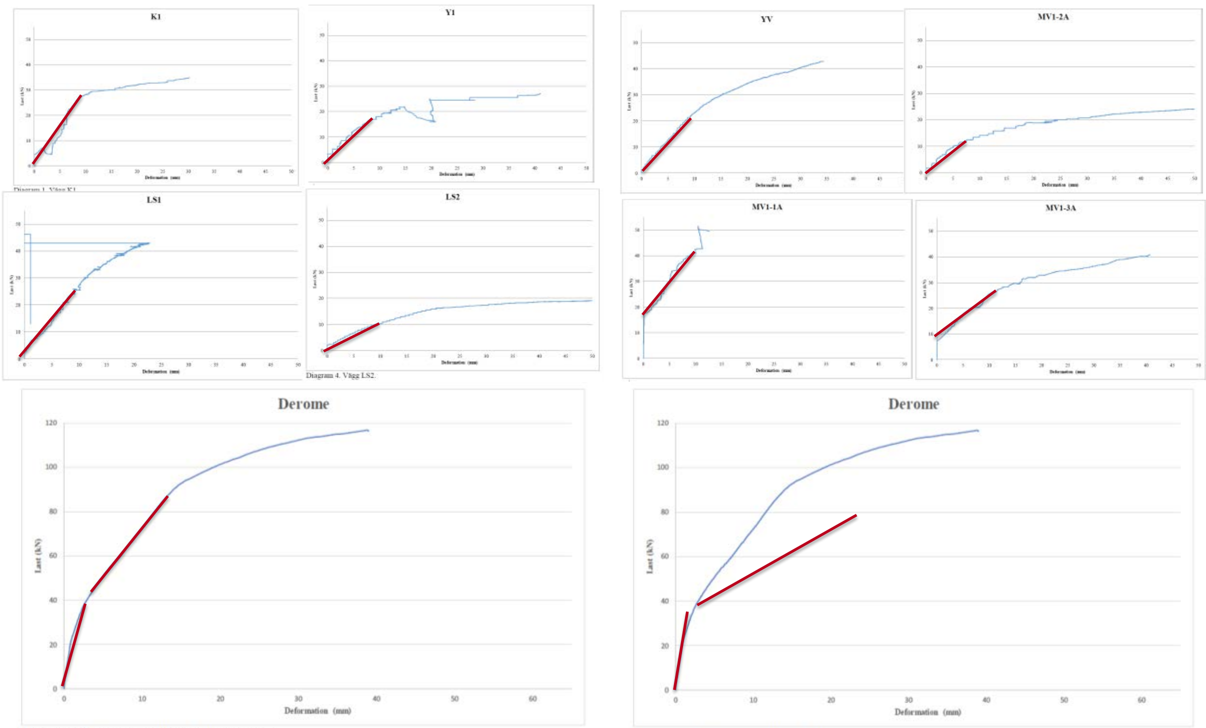

Figure 13 shows the basic calibration stiffness of the models, for both walls and volumes.

Table 9. Calibrated models, walls, two walls, volumes

Name	Description	Name	Description	Name	Description
LS1 (6m)	entire wall	LS-1/2	2 walls with buckling	Volume LB_1	1:a stiffness
LS2 (6m)	opening	LS-1/2	2 walls without buckling	Volume LB_2	2:a stiffness
MV-1-1A (6m)	entire wall	MV-11A/13A	2 walls with buckling	Volume LB_3	Calib. With wall stiffness
MV-1-3A (6m)	opening	MV-11A/13A	2 walls without buckling		
K1 (3m)	door			Volume D_1	1:a stiffness
Y1 (3m)	window			Volume D_2	2:a stiffness
MV-1-2A (3m)	door			Volume D_3	Calib. With wall stiffness
YV (3m)	window				

5.2.2 Results and conclusions from FE calculations

In Tables 10 and 11, the results of the models can be seen in the form of the stiffnesses of the walls and volumes and the calibrated contact stiffnesses.

Table 10. Results from the wall tests

Name	**Stiffness (N/mm)**	**Contact stiffness (N/m)(kx, ky, kz)**
LS1 (6m)	2 600	2.5E8, 5E7, 5E7
LS2 (6m)	700	9E7, 1.8E7, 1.8E7
MV-1-1A (6m)	2 600	3E8, 6E7, 6E7
MV-1-3A (6m)	1 900	2E8, 4E7, 4E7
K1 (3m)	2459	2.5E9, 5E8, 5E8
Y1 (3m)	1421	8E7, 1.6E7, 1.6E7
MV-1-2A (3m)	1 494	6E8, 1.2E7, 1.2E7
YV (3m)	2 265	2.2E8, 4.4E7, 4.4E7
2 walls		
LS-1/2	2613	Buckling
LS-1/2	4235	No buckling
MV-11A/13A	4687	Buckling
MV-11A/13A	8039	No buckling

The results from the volume tests with the different ratios can be seen in Table 11.

Table 11. Volume stiffness and ratio

Volume	Stiffness (N/mm)	Contact stiffness (N/m)	Ratio1	Ratio2
Volume LB_1	12 100	5E10, 1E10, 1E10	4.63	2.86
Volume LB_2	2 200	4E7, 8E6, 8E6	0.84	0.52
Volume LB_3	**5780**		**2.21**	***1.36***
Volume D_1	15 000	5E8, 1E8, 1E8	3.20	1.87
Volume D_2	4 100	6E7, 1.2E7, 1.2E7	0.87	0.51
Volume D_3	**11016**		**2.35**	***1.37***

In Table 10, it can be seen that the stiffnesses when introducing buckling-free walls increase by 60% for LB walls and 70% for D-walls. Table 11 shows the three stiffnesses for the volumes. The difference in stiffness for LB's volumes is large, they were assumed that the stiffnesses for LB1 and LB2 were unreasonably high and low and that LB3 was the most reasonable to compare with the stiffnesses for the two walls. There you can see that ratio 1 = 2.21 and ratio 2 = 1.36. The same was done for Derome's volumes, where ratio 1 = 2.35 and ratio 2 = 1.37. The values of ratios 1 and 2 are similar for the two volumes. It is most fair to look at ratio 2 and one should compare with the hand counts that are made. Then both volumes get a 3D factor of about 1.36.

However, no rigidities for the attachment between the walls, floors and ceilings have been calibrated. These are estimated to be able to make the 3D value vary by at least ± 20%. A quick test of different stiffnesses for the walls, floors and ceilings gave a span for the 3D factor from 1.36-1.70 and 1.08-1.43 for LB and Derome, respectively.

6. Conclusions from tests and results from tests

In an analytical evaluation of test results, a 3D factor of 0.98 to 2.28 for deformations below 20 mm is obtained for the entire volumes. The 3D factor decreases with increasing deformation, see diagram below.

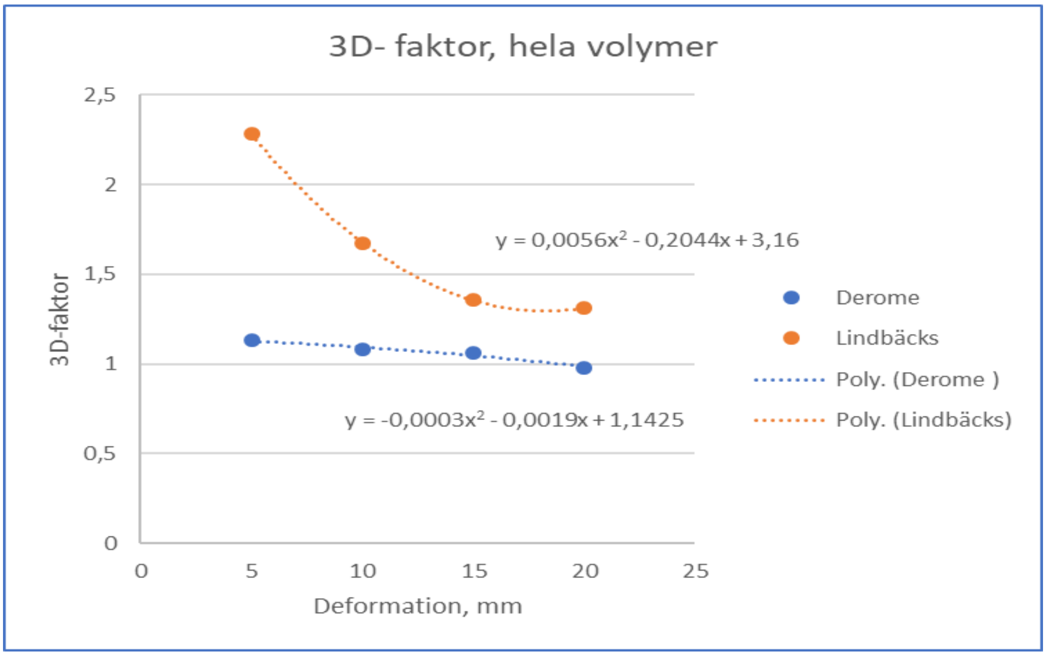

Diagram 1 Change in 3D factor due to deformation during measurements of the entire volume

The same is also available for individual walls, as shown in

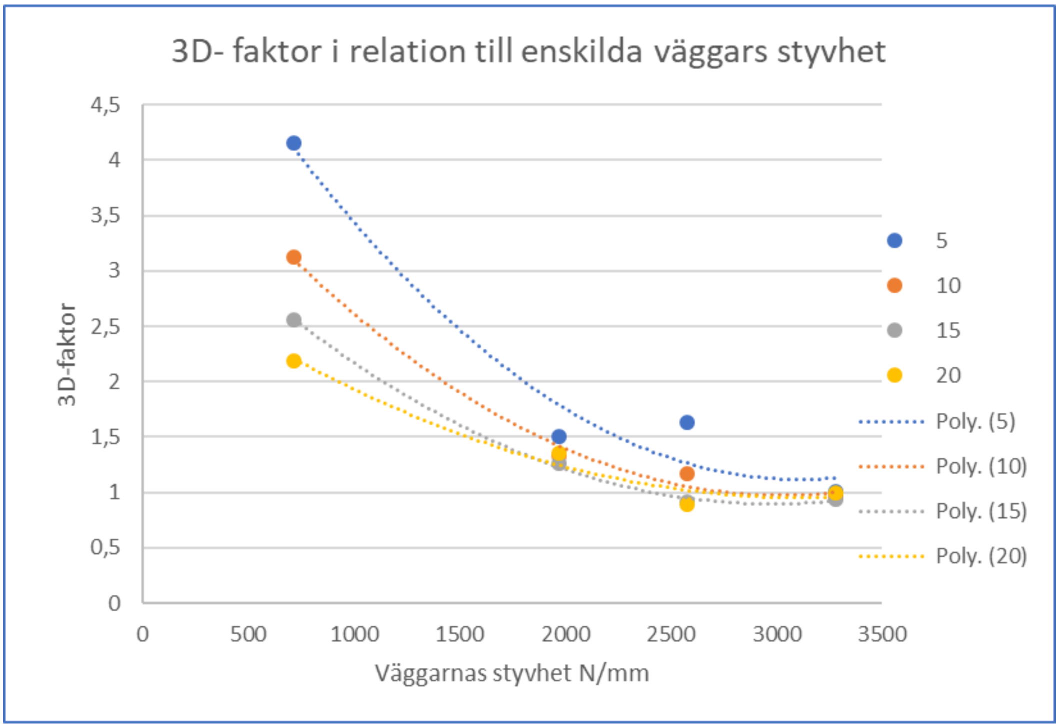

Diagram 2 Change of 3D factor in relation to the individual stiffness values of the walls

The results from tests are not unambiguous but several observations can be made:

- The stiffness of the volumes in relation to the sum of the stiffness of individual walls.

- The difference is relatively small for deformations larger than 15-20 mm.

- How big the 3D factor will depend on the individual stiffnesses of the walls.

- A "weak" wall will have a significantly higher 3D factor.

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About TräCentrum Norr

TräCentrum Norr is funded by the participating parties together with funds from the European Regional Development Fund and the Västerbotten Region.

Participating parties in TräCentrum Norr are: Lindbäcks Bygg AB, Luleå University of Technology, Martinsons Trä, SCA Forest Products, Norra Skogsägarna, Sågverken Mellansverige, SÅGAB, Sveaskog, Setra, Luleå University of Technology, Skellefteå municipality and Piteå municipality.

More information about TräCentrum Norr can be found at: www.ltu.se/ske/tcn

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