ESECMaSE

Enhanced Safety and Efficient Construction of Masonry Structures in Europe

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Enhanced Safety and Efficient Construction of Masonry Structures in Europe

Horizontal Research Activities Involving SMEs

Collective Research

Work Package N°: 3

D 3.1 Theoretical Investigation on Stress States of Masonry Structures Subjected to Static and Dynamic Shear Loads (Lateral Loads)

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[draft 1]

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Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Contents:

1. Introduction

For the investigation of stress states in typical masonry buildings subjected to horizontal loads, calculations using the finite-element-method had to be performed. Originally, the intention was to use the finite-element-program DIANA, since it offers material models especially suited for masonry. However, after several tests, it turned out that this software is practically inapplicable for the intended work. The main reason is, that the use of masonry material models is not available for 3D- structural models. Also, it became evident that models with great degree of complexity and a large number of degrees of freedom could not be realized within the available time.

Hence, it was decided to use the finite-element-program Sofistik. For this software package, specific masonry material models are not available. However, basic nonlinearities, such as tension softening due to adhesion failure in the horizontal joints, can be treated using a smeared masonry model. So the influence of different varieties of masonry like different unit sizes or the influence of perforated bricks could not be determined.

Within this deliverable, the stress states of the shear walls in a terraced house as shown in figure 1 and figure 2 are calculated. A parametric study is performed in order to investigate the influence of the length of the main shear walls near the staircase. The stress states are determined for different levels of the lateral load.

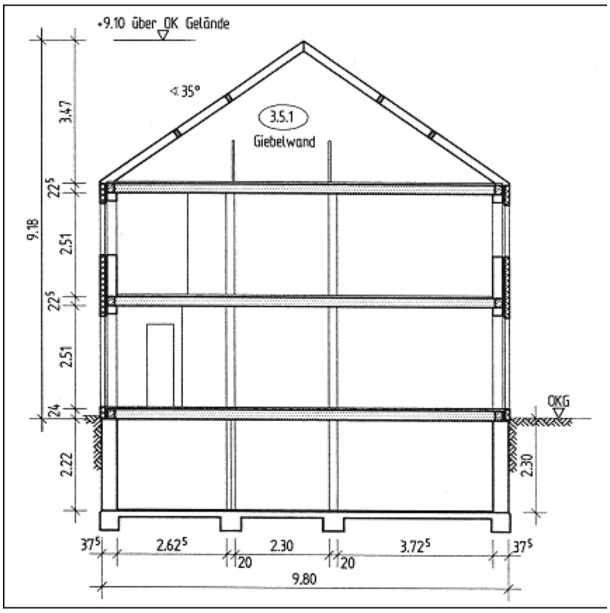


figure 1: front view of a terraced house

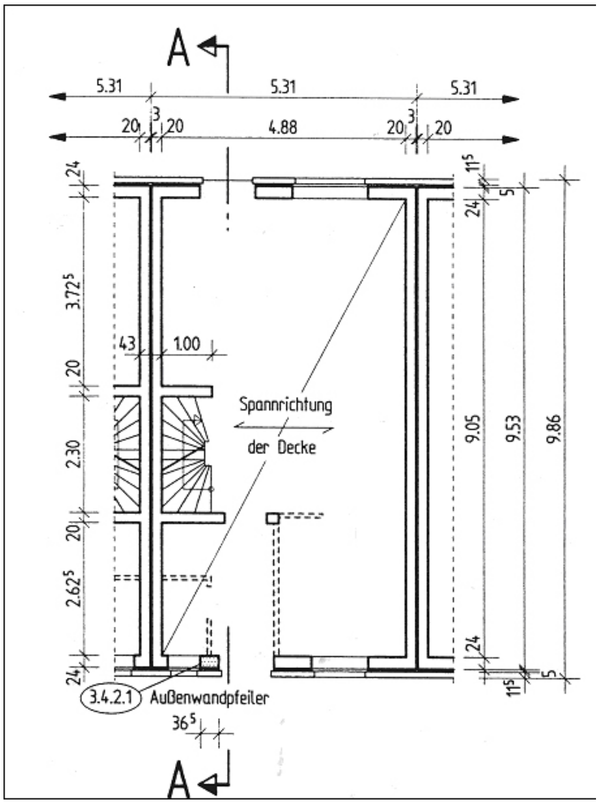


figure 2: ground-plan of a terraced house

2. Constitutive models for masonry

The investigations use shell elements in order to simulate the behaviour of masonry walls as well as of reinforced concrete slabs. For the masonry, a smeared modelling approach is being used. So the properties of brick and joint are combined in the constitutive model. In order to allow a gaping joint, the tension strength is assumed to be very low. This coincides with the usual approach to neglect tension strength of masonry in the joints for design checks. The stress-strain-relation of the material model in use under compression is shown in figure 3 and under tension in figure 4.

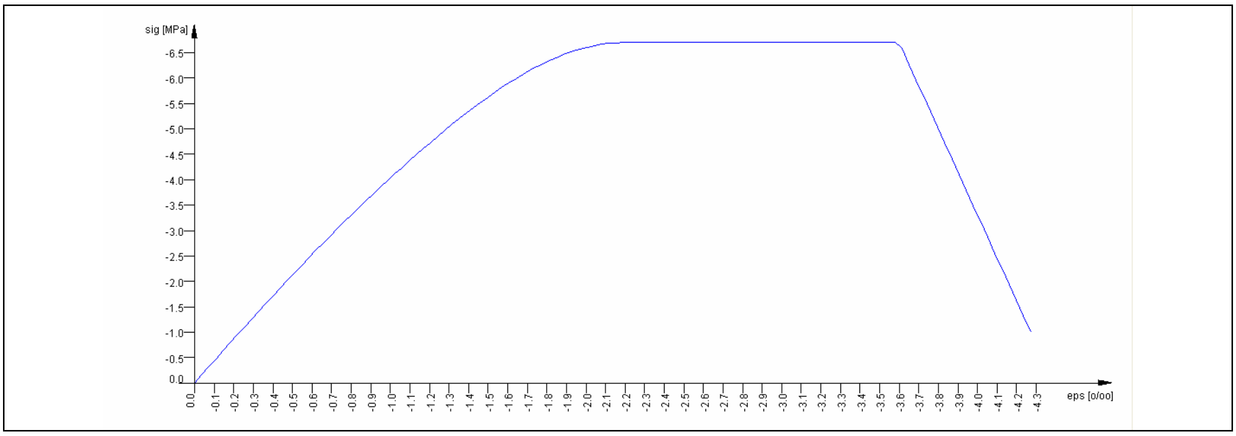


figure 3: stress-strain-relationship under compression

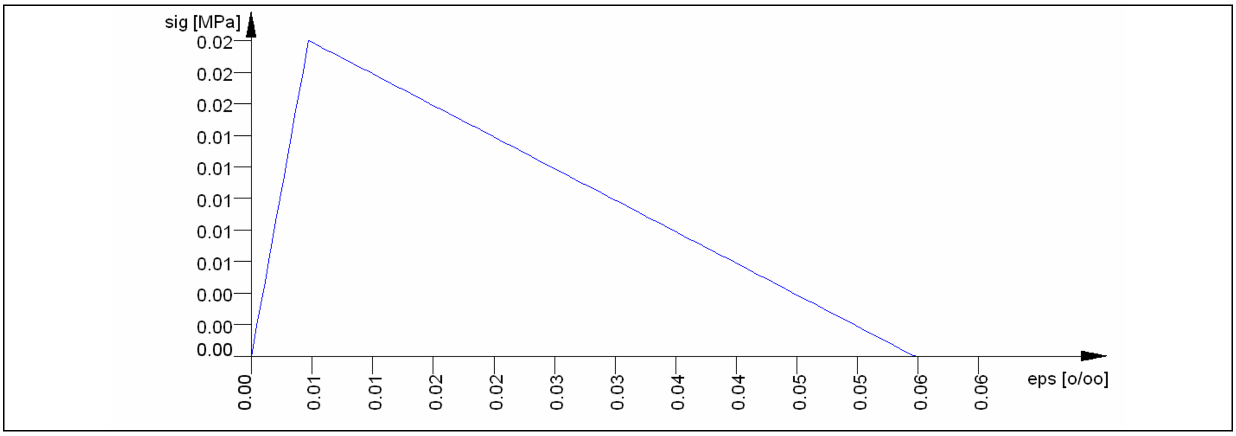


figure 4: stress-strain-relationship under tension

For testing the behaviour of the implementation of the material law in the finite-element-program, a cantilever masonry wall is modelled and investigated under different loading states. In figure 5 a cantilever wall, with a masonry compression strength of 8.5 N/mm^2 and a tension strength of 0.18 N/mm^2 is depicted. The wall (length = 1.0 m, thickness = 0.24 m and height = 2.75 m) is loaded with a vertical load of 33.0 kN and a horizontal concentrated load of 4.0 kN at the cap of the wall. To distribute the horizontal concentrated load, a concrete beam is modelled on the top of the masonry plate.

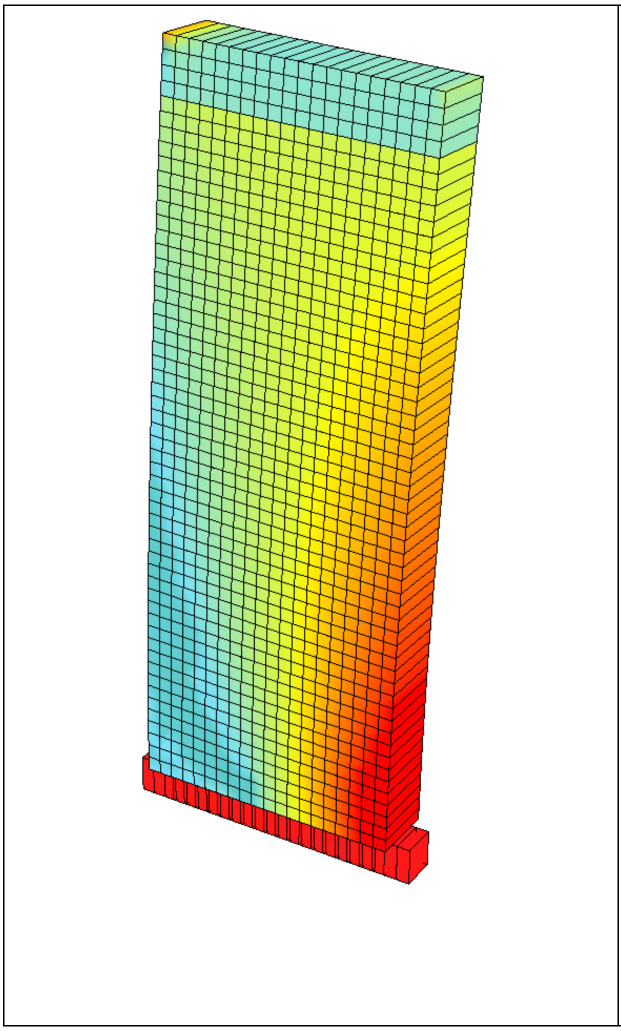


figure 5: model of the cantilever wall

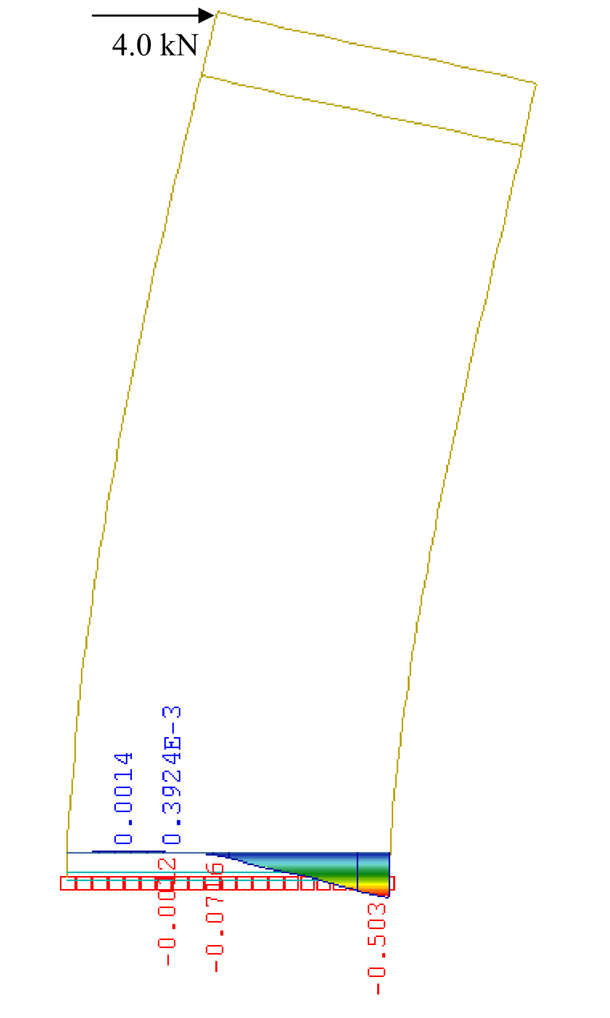


figure 6: stress [N/mm2] at the bottom of the wall

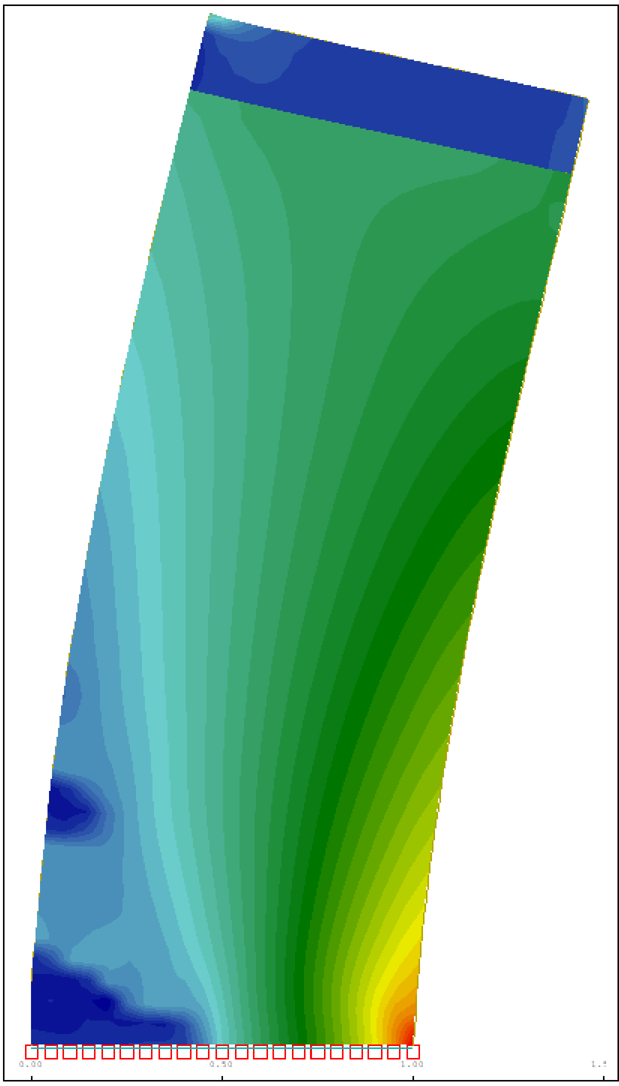


figure 6: strain at a horizontal load of 4.0 kN

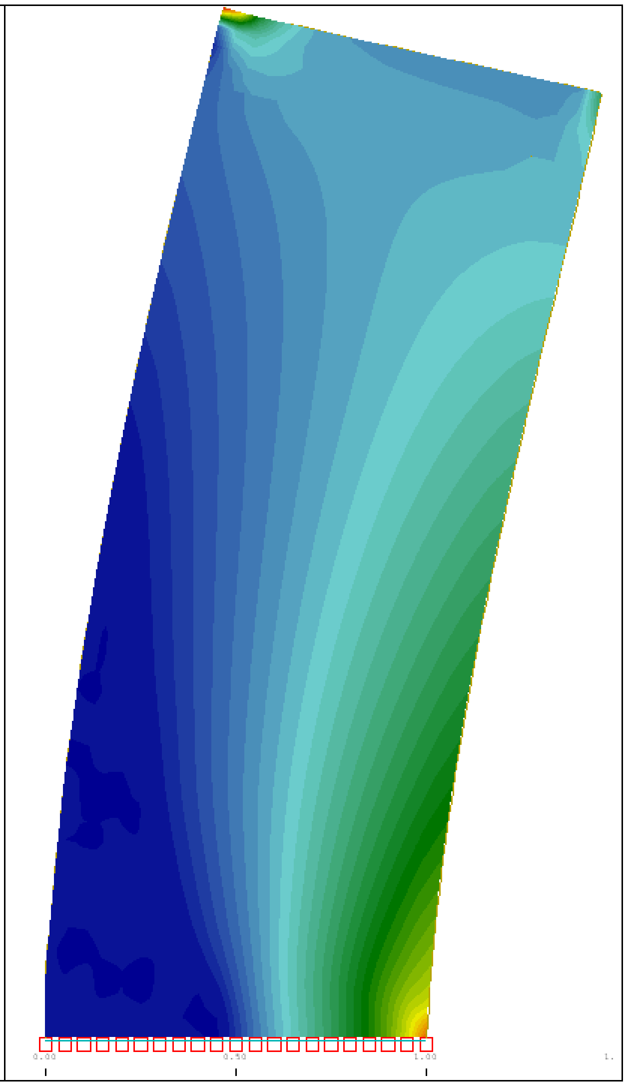


figure 7: stress at a horizontal load of 4.0 kN

The horizontal load is increased up to the ultimate possible load. In order to identify the ultimate load and to be able to model a descending branch of the force-deformation relationship, loading is being performed under deformation control by applying a horizontal deformation at the top of the wall. The resultant load-deformation-relationship is shown in figure 9. From this, the ultimate load can be established to 6.1 kN for this wall. This value corresponds well with the value for the extreme case of overturning of a rigid body (wall rotates around one of its corners).

In this case, the eccentricity of the normal force amounts to half the horizontal wall length:

e = $\dfrac{2.75m \cdot 6.1kN}{33kN}$ = 0.5 m

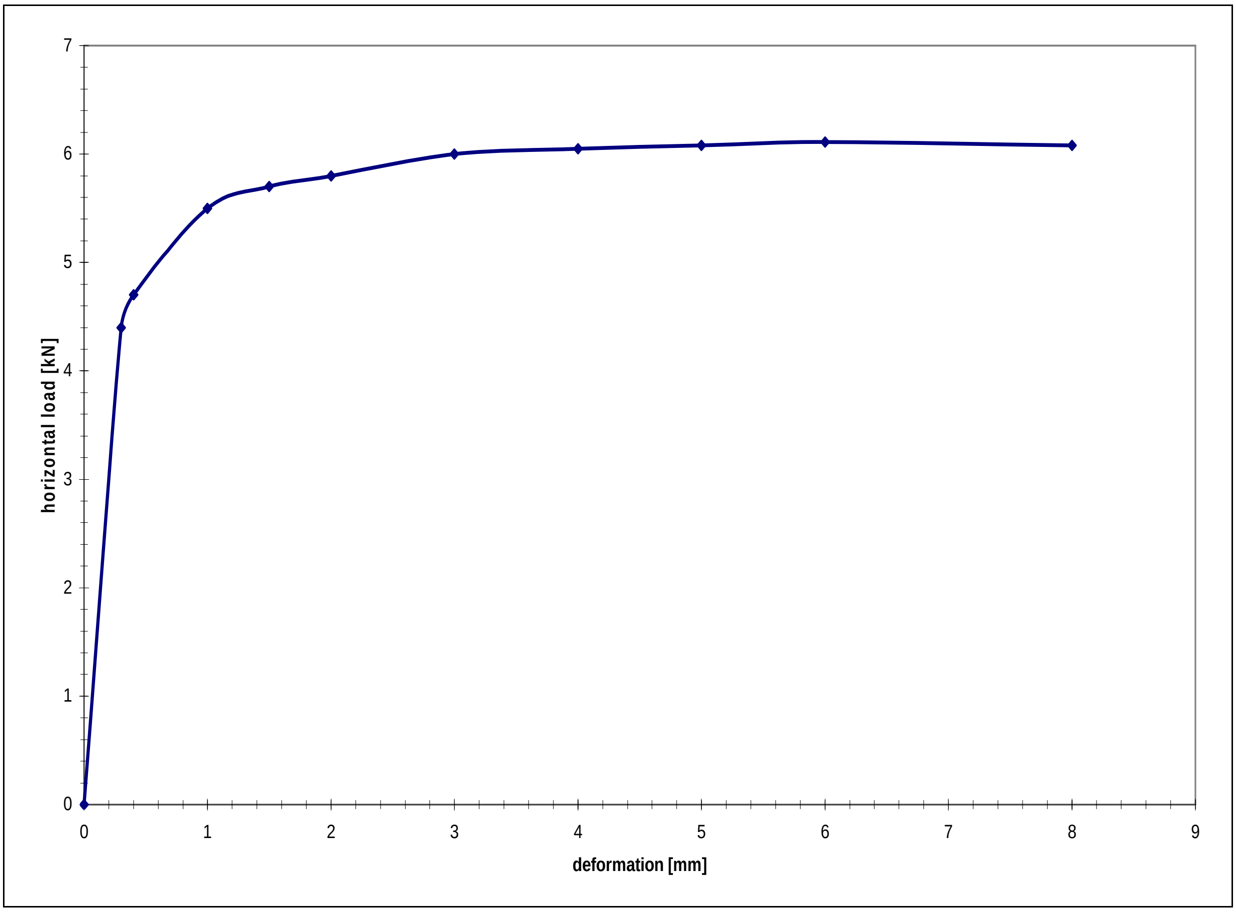


figure 9: load-deformation-relation of the cantilever wall

In figure 10 the stress values at the bottom of the wall for a horizontal deformation of 3.0 mm are given. Figure 11 shows the strain under the given combined action.

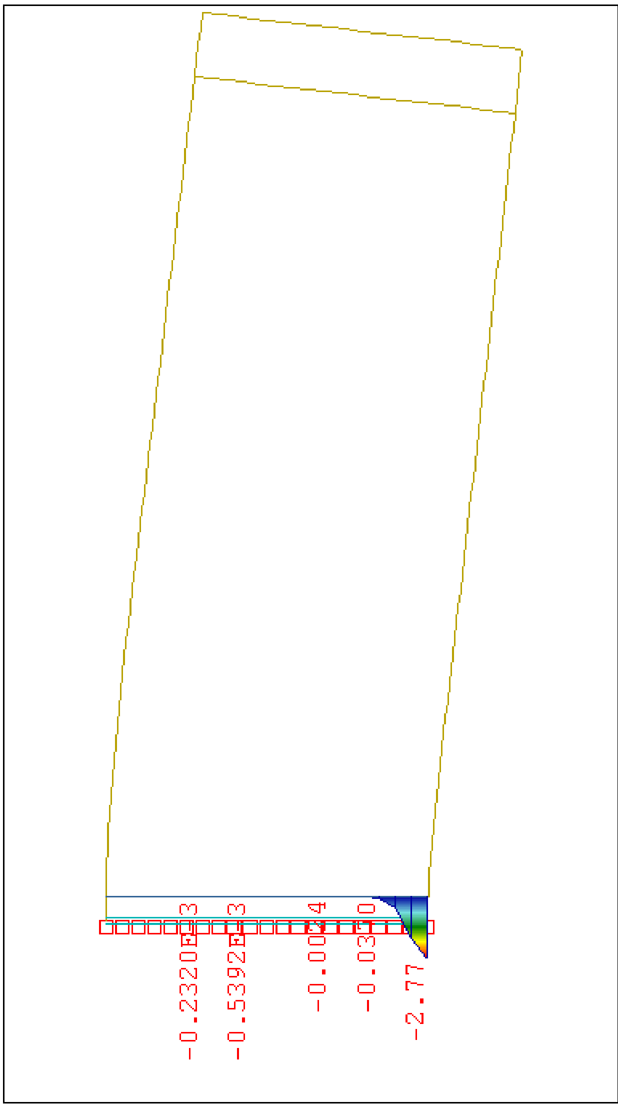


figure 10: stress [N/mm2] at the bottom of the wall

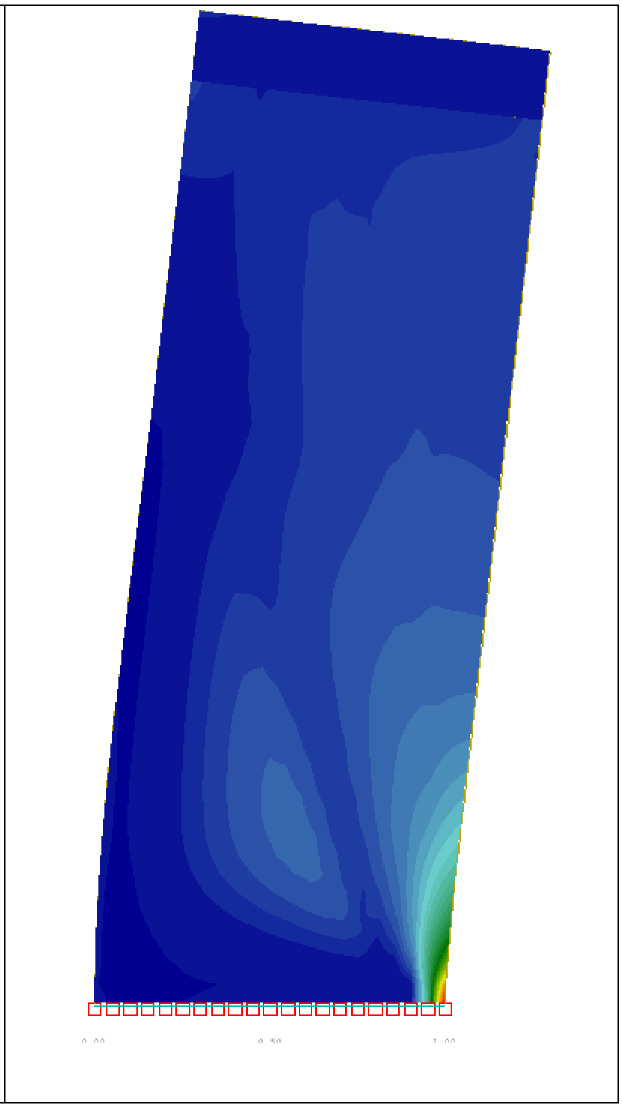


figure 11: stress [N/mm2] at the bottom of the wall

3. Investigation on Stress States of a Terraced House

3.1. Geometry of the simplified model

For the investigation of stress states in typical masonry buildings subjected to horizontal loads, calculations are performed using a simplified 3-dimensional model as shown in figure 12. Shell elements have been used for this model. The thickness of the exterior walls is given with 0.30 m, the thickness of the interior walls near the staircase with 0.175 m. The arrangement of the walls within the simplified model is displayed in figure 13.

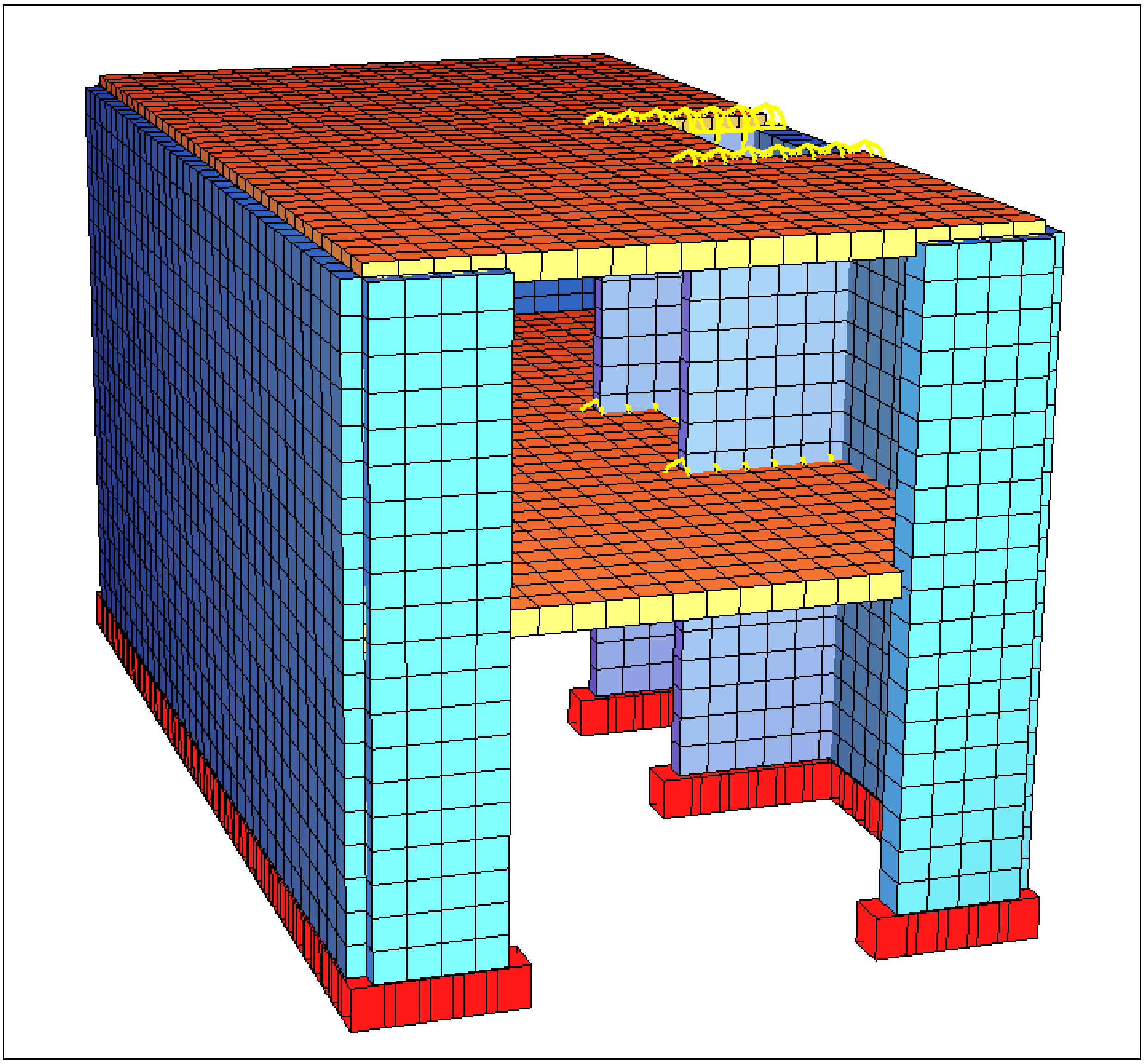


figure 12: finite-element- model of the terraced house (isometric view)

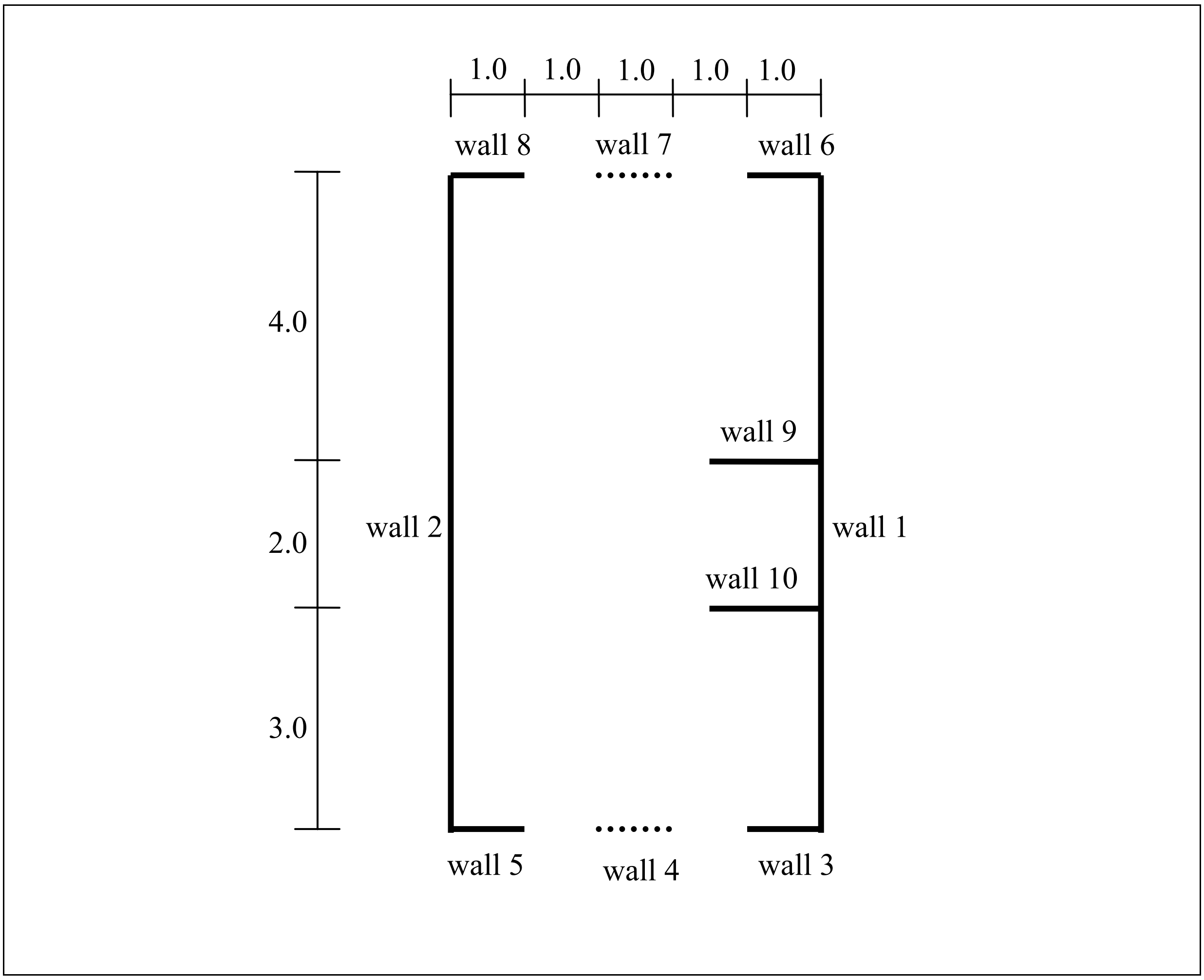


figure 13: arrangement of the walls (dimensions m)

3.2. Material model of the walls

The material used for the walls of the terraced house is the same as described in chapter 2, except the compression strength which is taken to 6.7 N/mm^2 (see deliverable D3.0.3).

3.3. Material model of the slabs

The concrete slabs of the house are modelled by the same type of shell elements as the masonry walls. However the material parameters are fit to the behaviour of concrete. At this the tension strength is taken to 20.0 N/mm^2 to assume an uncracked and consequently linear-elastic behaviour.

In order to study the influence of cracking of concrete in the slab on the moment transfer to the shear walls, a modified material model is being used. The documentation of the material model and the results is contained in the annex.

3.4. Structural system of the house

All exterior walls are coupled by moment stiff connections with each other. Also the concrete slabs are connected in this way. The interior walls are treated in a different way in order to simplify the interpretation of the results. Hence, they are coupled with the slabs without transfer of plate bending moments.

It is also important to note, that the two interior walls are not connected to the exterior walls, because in practice these walls are just connected by means of flat anchor strips in the bed joints. This type of connection intentionally does not allow transfer of significant membrane shear.

3.5. Load application

The vertical load is raised by modifying the mass (density) of the slabs and the masonry walls. Herewith the total load of the slabs and the permanently present live load can be covered within the slabs the total load of the walls and of the truss can be covered within the exterior walls. The interior walls do not bear the total load of the truss, so the mass of the interior walls is less than the mass of the exterior walls. So the overall vertical load of the terraced house with a interior wall length of 1.50 m is 1251.2 kN. Furthermore the horizontal load is set in the weak direction. The horizontal load is applied with positive and negative sign which is necessary since the interior walls are loaded eccentrically, even in the case of zero lateral loading. The positive direction of loading is orientated form the left to the right side according to figure 13. The lateral loads are distributed to the slabs as pictured in figure 14.

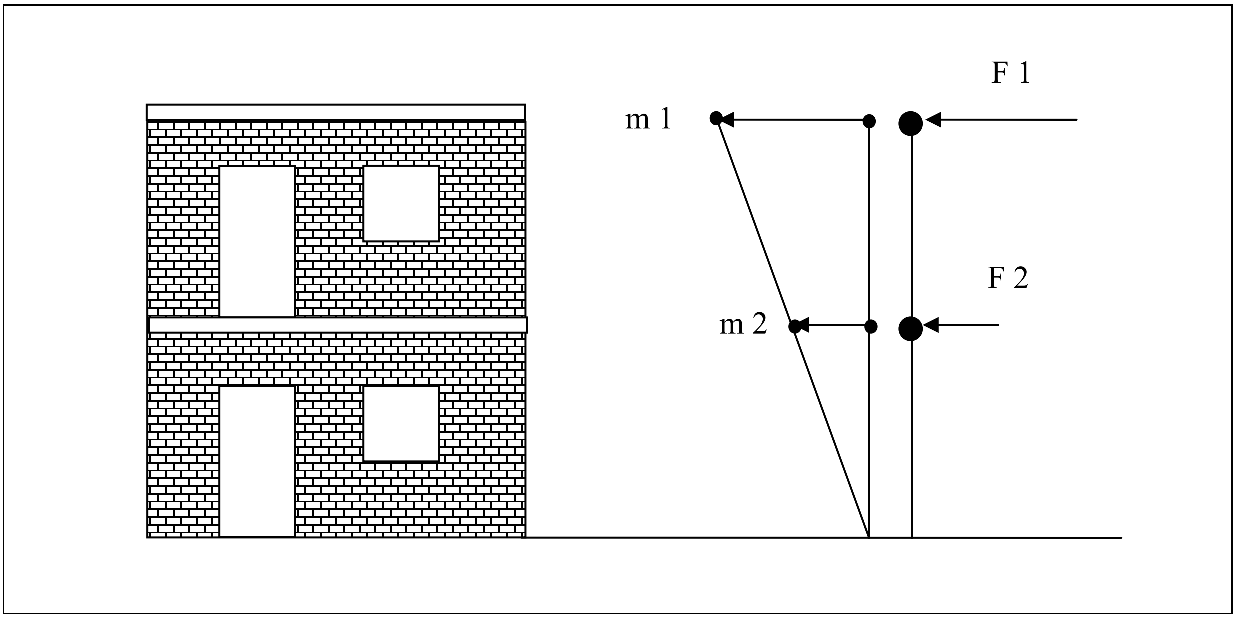
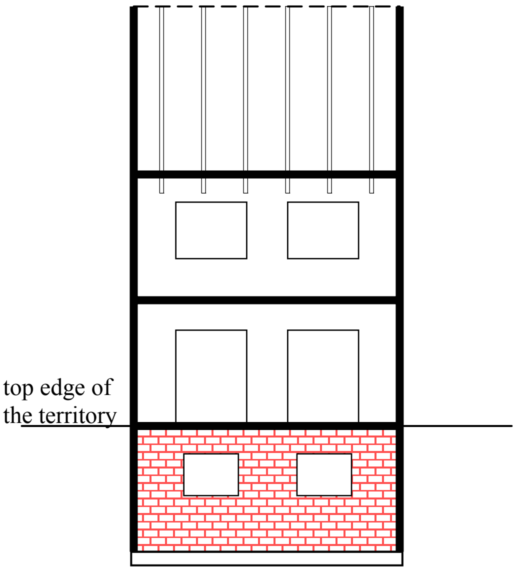


figure 14: Allocation of the horizontal load

The value of the horizontal load is applied in several ways. On the on hand the calculation is carried out by the ultimate possible load level (see chapter 4) and on the other hand the stress states are shown for an exemplary earthquake as estimated consecutively.



Geometrical data:

hight between floors: 2.50 m
floor space: 5 m · 9 m = 45.0 m²
mass of the house: 125 to

Data according to DIN 4149:

earthquake zone: 2 — a_g= 0.60 m/s²
subsoil combination: B-T

T_B= 0.05 s ; T_C = 0.30 s; S = 1.0
$ß_0$ = 2.5
γ_I = 1.0 (residential building)
q = 2.0

Calculation:

(according to the simplified response spectrum method, DIN 4149, chapter 6.2.2)

$S_d(T_1) = a_g \cdot \gamma_I \cdot S \cdot ß_0 / q$
(for $T_B \leq T_1 \leq T_C$, in the „plateau" of the response spectrum)

$= 0{,}60\ m/s^2 \cdot 1.0 \cdot 1.0 \cdot 2.5 / 2.0 = 0.75\ m/s^2$

horizontal earthquake load:

$F_b = S_d(T_1) \cdot M \cdot \lambda = 0.75\ m/s^2 \cdot 125\ to \cdot 0.85 = 80.0\ kN$

This level of lateral loading coincides well with the order of magnitude of forces to be expected from wind loading W(for the Ultimate Limit State ULS). Considering a free standing terraced house (most unfavourable case, to be considered according to regulations set out by building authorities), we have:

- wind exposure area 60 m²,
- average characteristic wind pressure: q_k= 0.7 kN/m²
- force coefficient (pressure + suction) c_f = 1,3
- partial safety coefficient for wind load γ_Q = 1,50

Hence:

$W_{Ed} = 60 \cdot 0{,}7 \cdot 1{,}3 \cdot 1{,}5 = 81{,}9\ kN$

Considering only pressure loading with c_f = 0.8 , as is accepted by some regional / local building authorities, a lower level of loading would result.

4. Ultimate Lateral Load

In the following the horizontal load is continuously increased up to the collapse load. This analysis is done only for the terraced house with the interior wall length of 1.5 m. In figure 15 the load-deformation-relationship is given. Furthermore, in figure 16 up to figure 19 the stress and strain states of this type of terraced house is depicted for a horizontal load of about 440 kN, which is the ultimate load as obtained for the Finite-Element-model. For higher load levels than this, convergence of the iteration has not been reached any more.

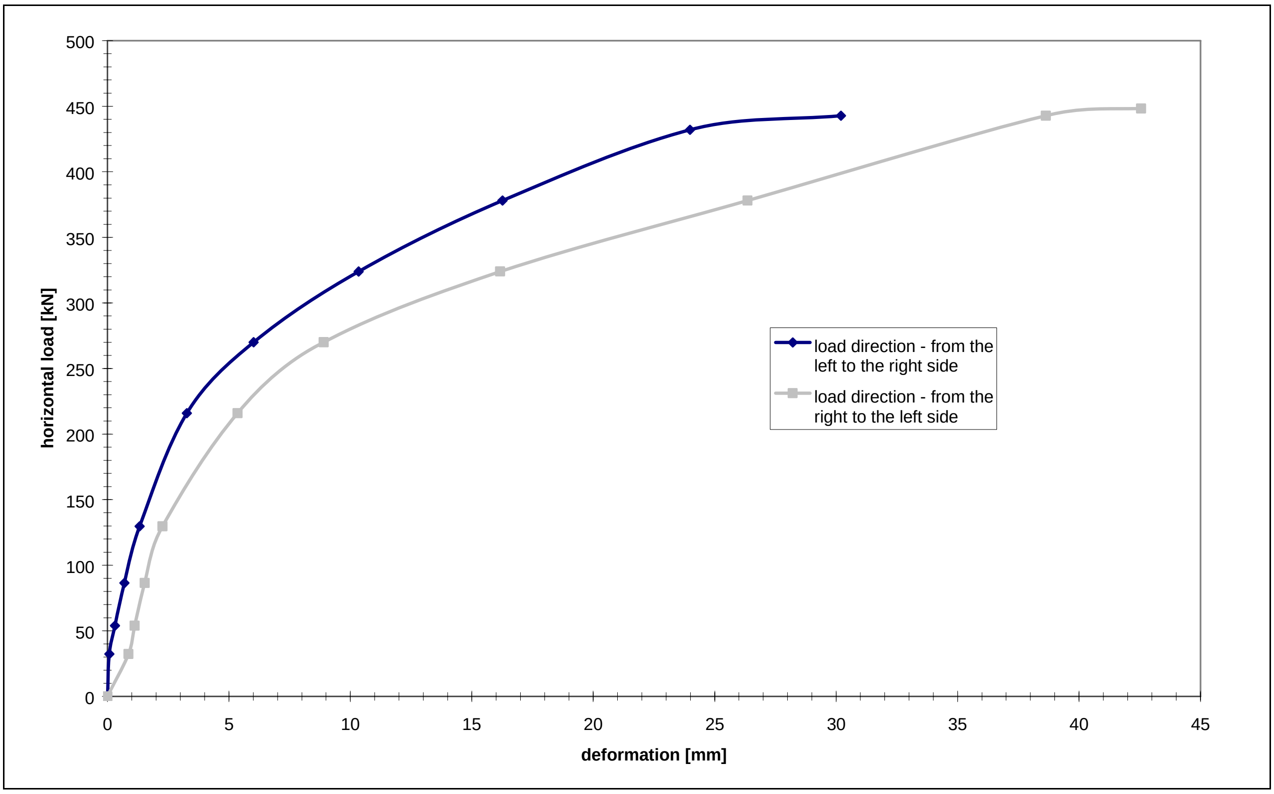
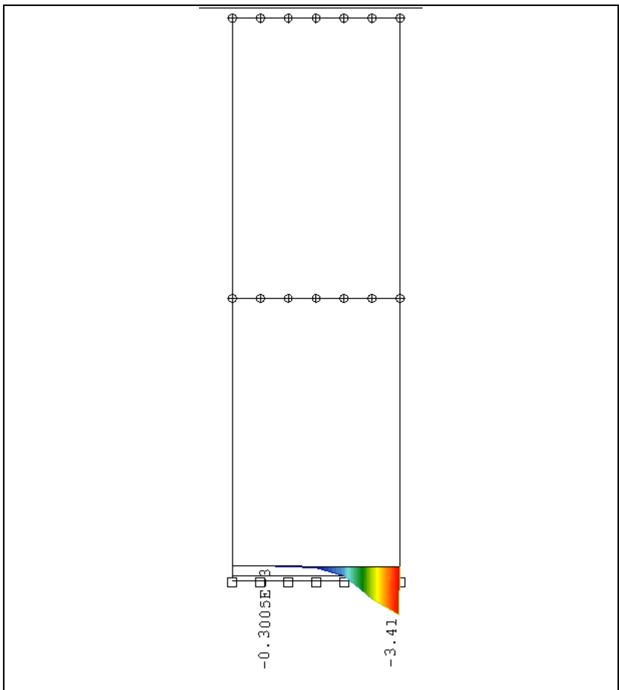


figure 15: load-deformation-relationship for a terraced house with interior wall length of 1.5 m



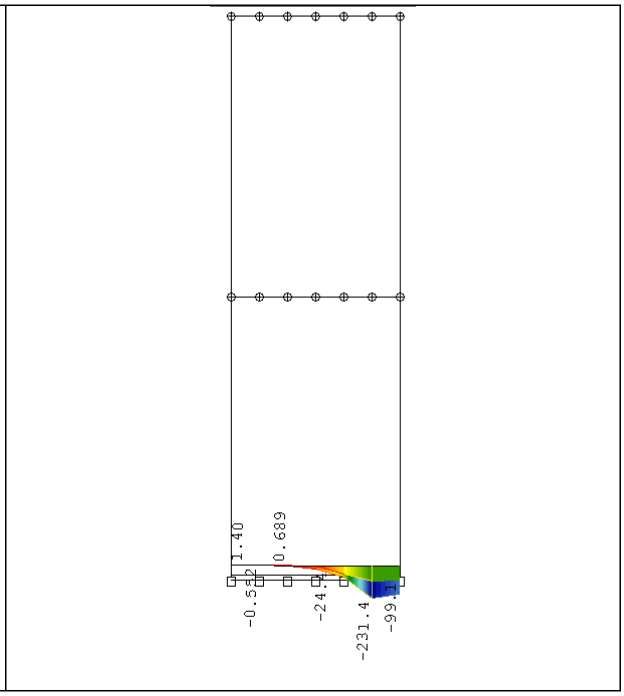


Figure 16: stress [N/mm^2] at the bottom of wall 9

figure 17: shear load [kN/m] of wall 9

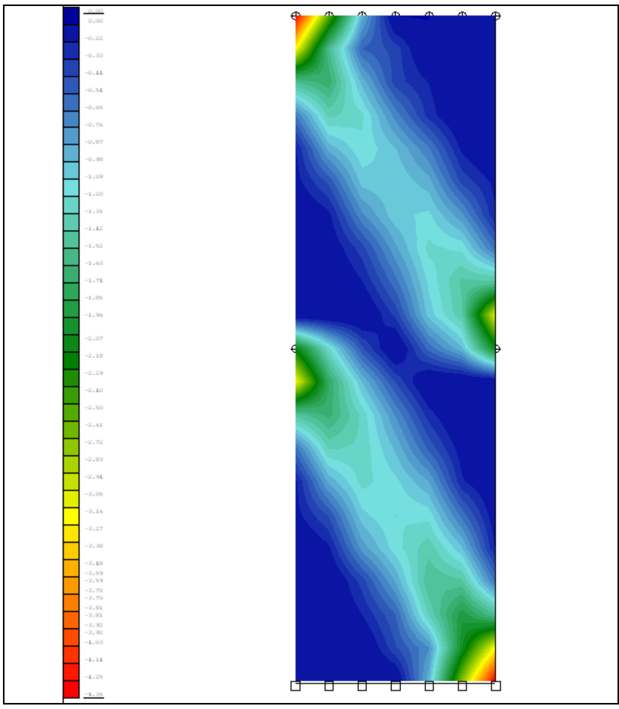


Figure 18: normal stress of wall 9

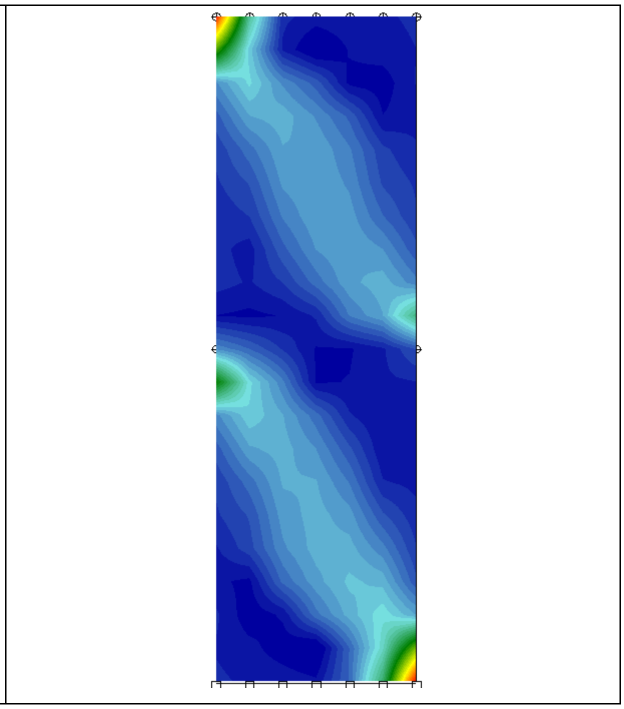


figure 19: strain of wall 9

Because the finite-element-model used can only represent basic nonlinearities, stress states with very high values of shear stress can be reached. However, due to the limitation of shear stresses according to the shear design models in EC 6, DIN 1053 and other codes, the acceptable shear stresses can be much lower. Hence, a shear stress verification is performed for different lateral load levels according to DIN 1053-100. For this, the calculated stresses (normal stress and shear stress) at the bottom of the main walls are evaluated. The results of the design checks are shown for the different wall lengths and a load direction from the left side to the right side in figure 20 to figure 24.

It becomes evident, that the maximum horizontal load to be exploited is significantly lower than the ultimate lateral load level as computed by use of the nonlinear finite-element-model. The maximum load levels compatible with design code provisions can be read from figure 20 up to 24 for the different interior wall lengths.

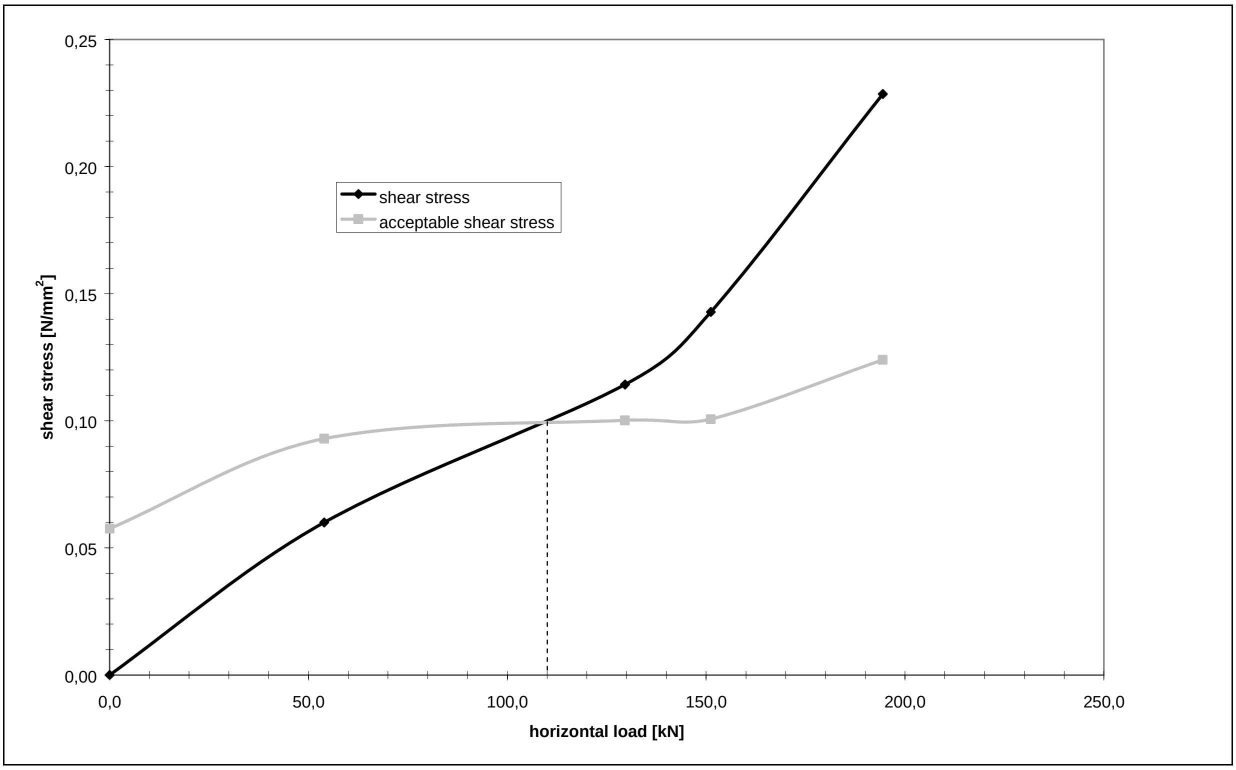


figure 20: horizontal load-shear stress-relationship for a terraced house with interior wall length of 1.0 m

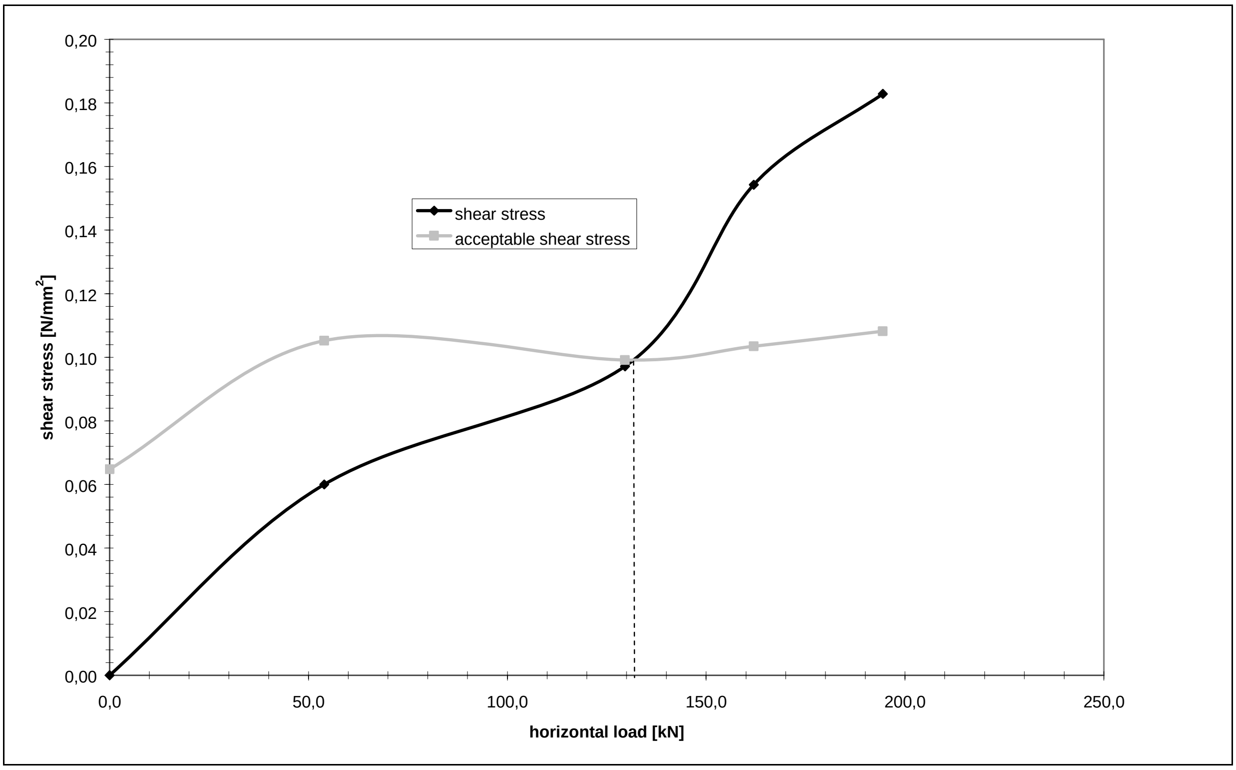


figure 21: horizontal load-shear stress-relationship for a terraced house with interior wall length of 1.5 m

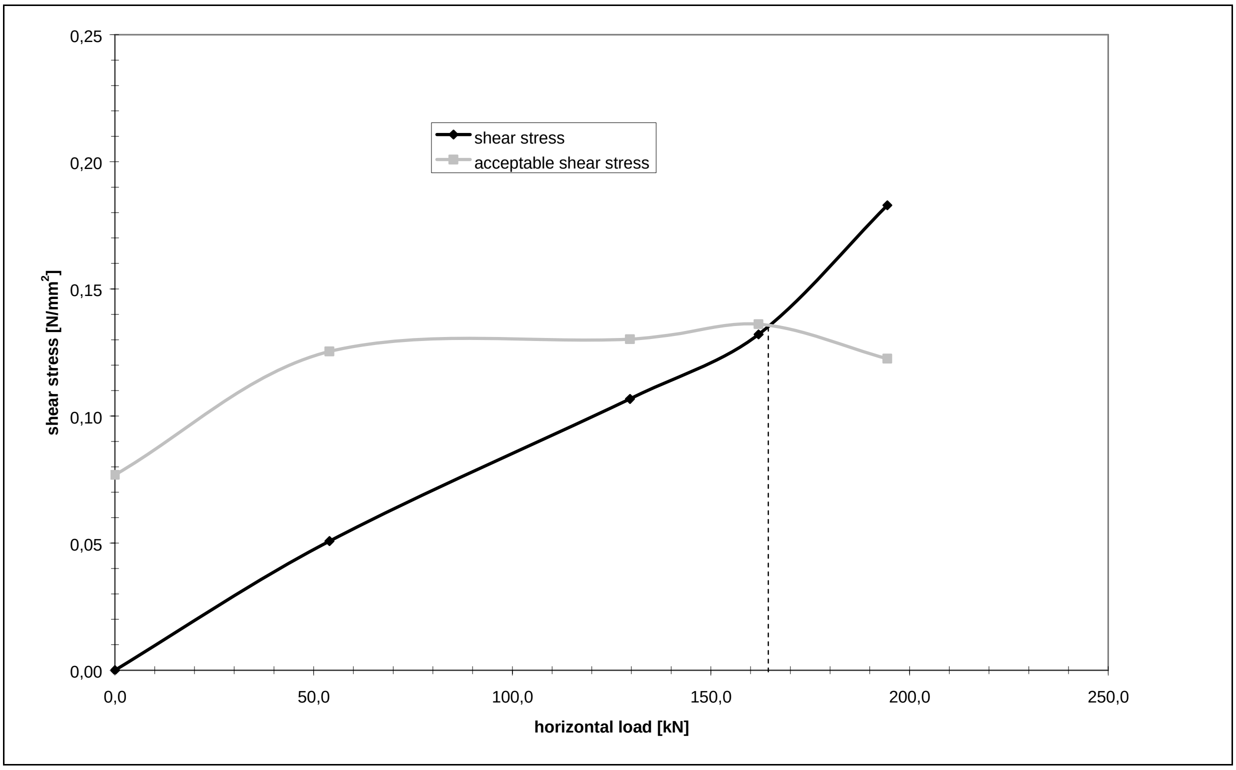


figure 22: horizontal load-shear stress-relationship for a terraced house with interior wall length of 2.0 m

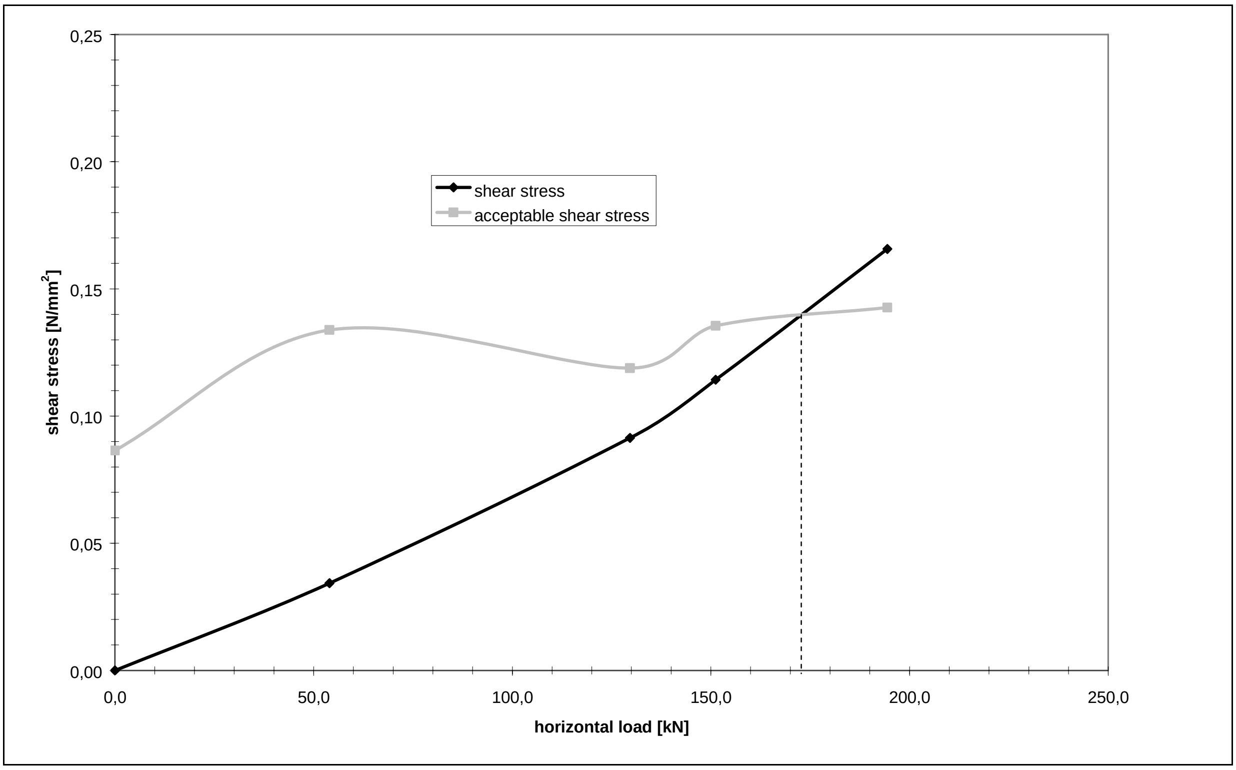


figure 23: horizontal load-shear stress-relationship for a terraced house with interior wall length of 2.5 m

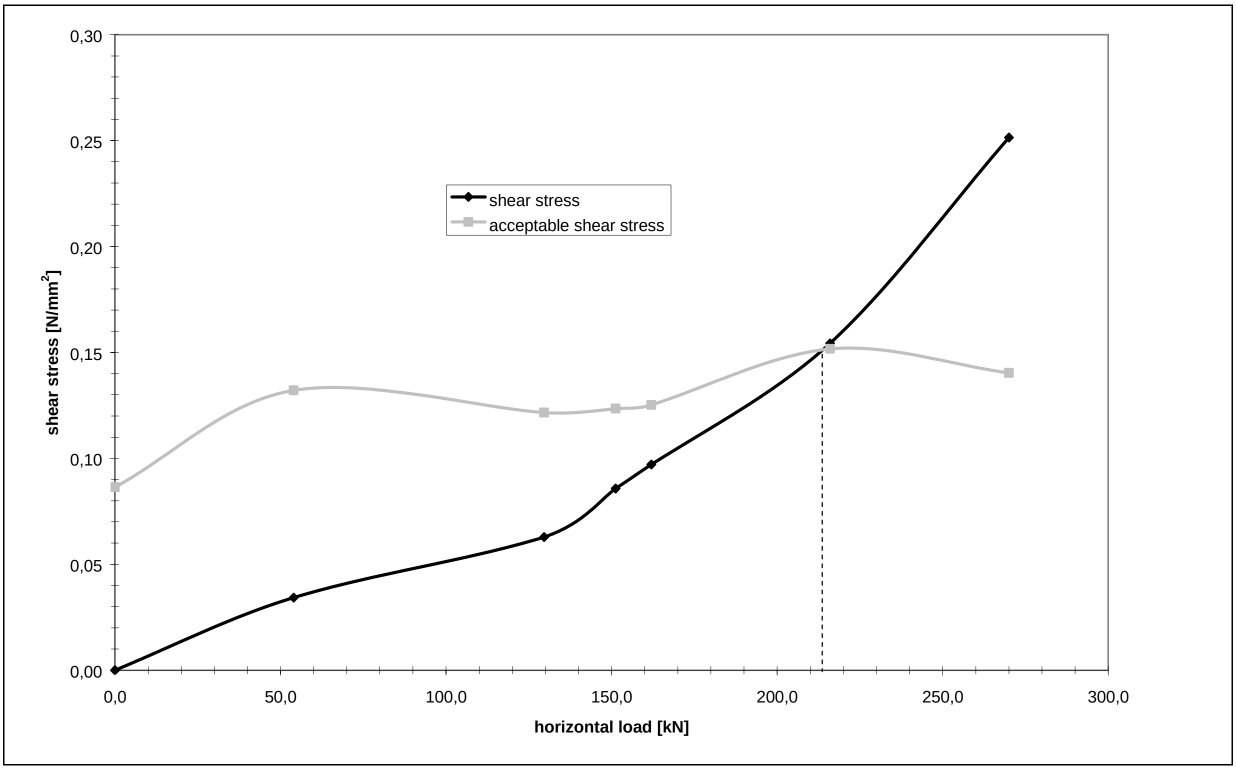


figure 24: horizontal load-shear stress-relationship for a terraced house with interior wall length of 3.0 m

5. Parametric study for different lengths of the interior walls

5.1. Stress states for the maximum possible lateral load according to design resistance

In the following, the stress states for the interior walls 9 and 10 are shown according to maximum lateral load level as obtained from the previous figures for the different cases.

5.1.1. Stress according to a length of the wall of 1.0 m (horizontal load of 110 kN)

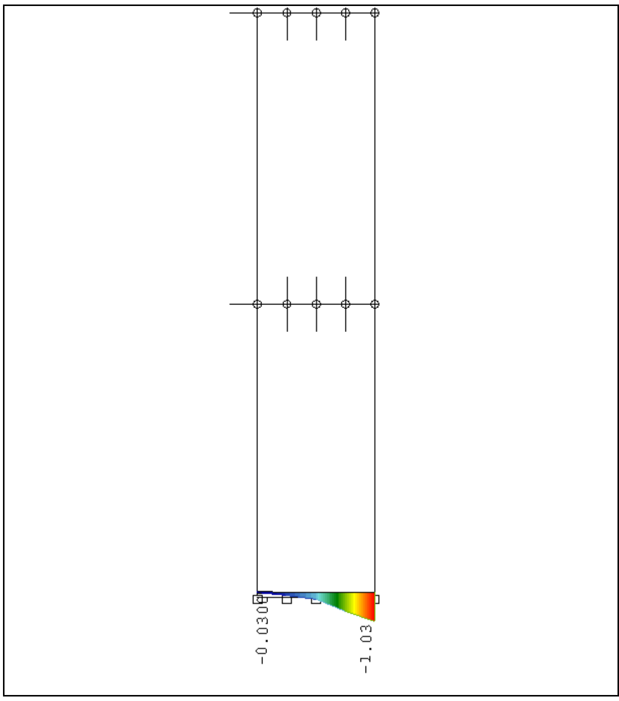


Figure 25: stress [N/mm^2] at the bottom of wall 9

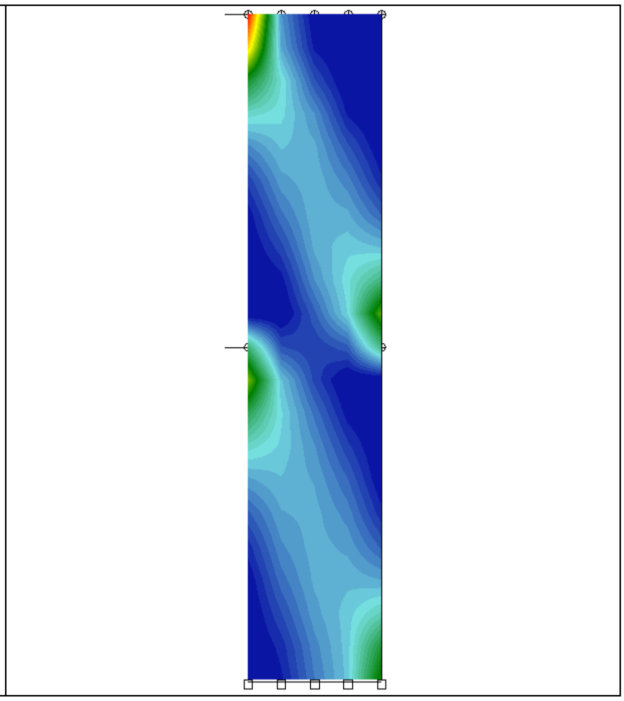


figure 26: normal stress of wall 9

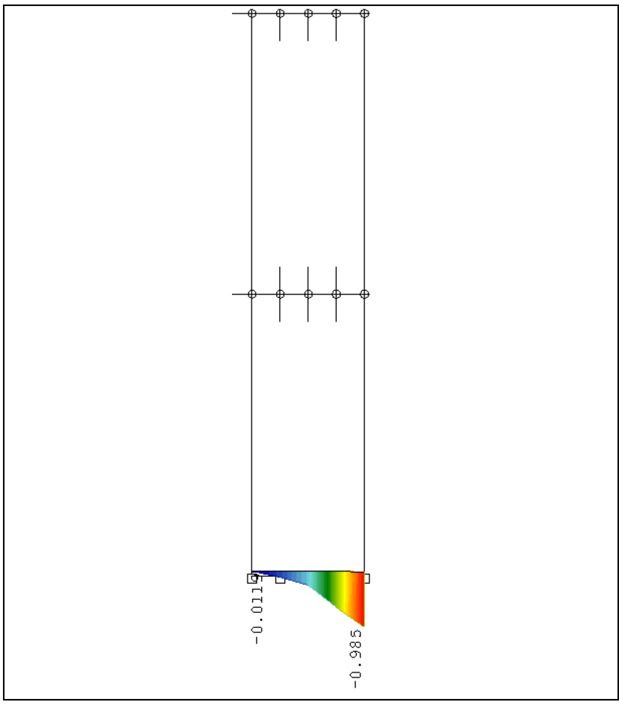


Figure 27: stress [N/mm^2] at the bottom of wall 10

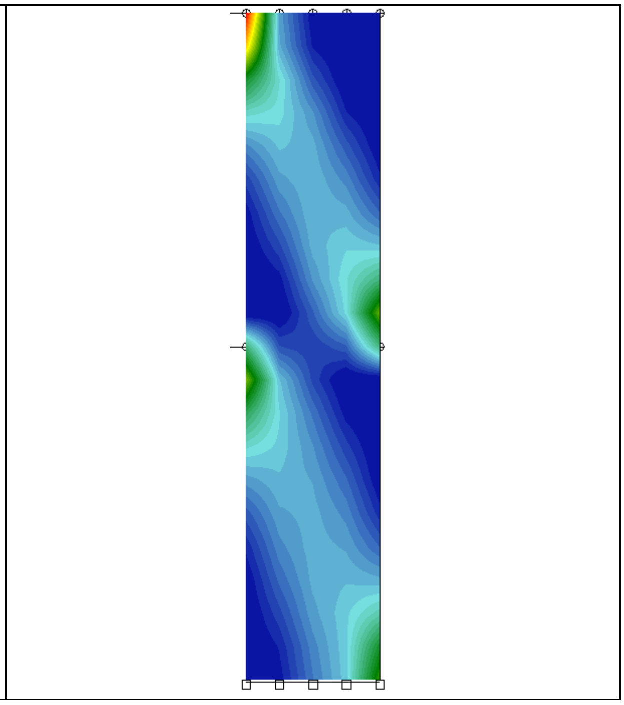


figure 28: normal stress of wall 10

5.1.2. Stress according to a length of the wall of 1.5 m (horizontal load of 130 kN)

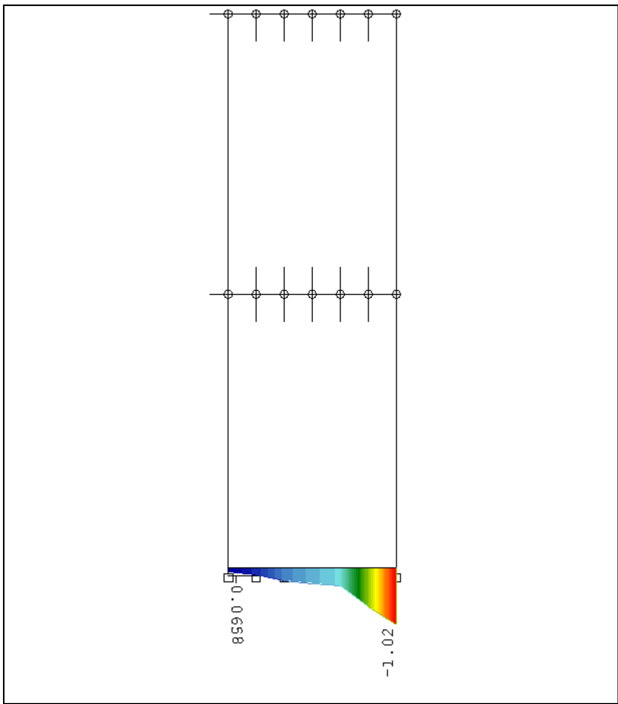


Figure 29: stress [N/mm²] at the bottom of wall 9

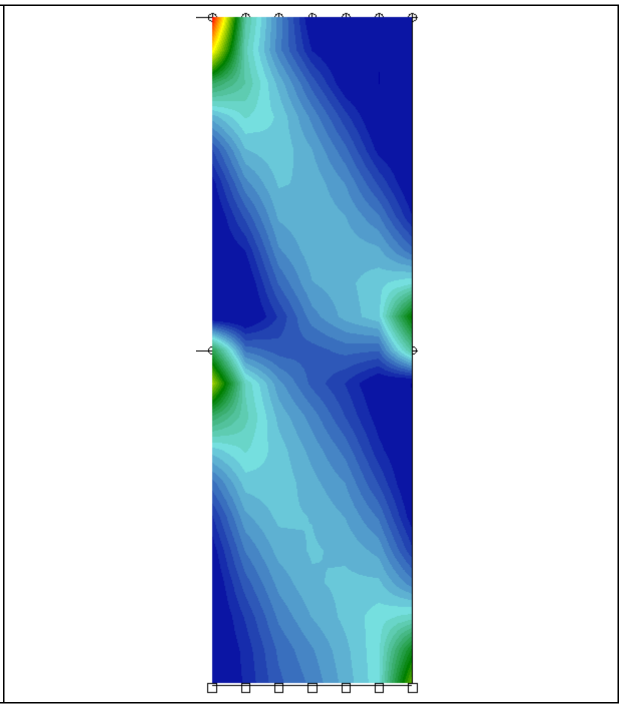


figure 30: normal stress of wall 9

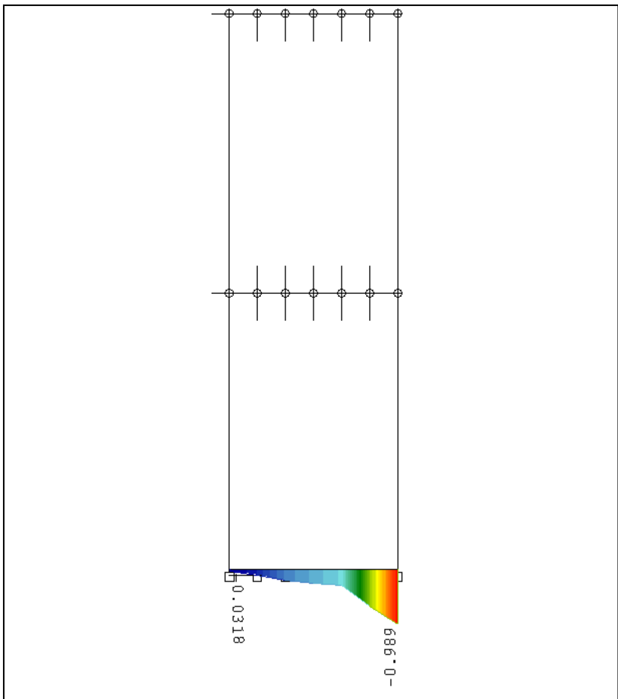


Figure 31: stress [N/mm²] at the bottom of wall 10

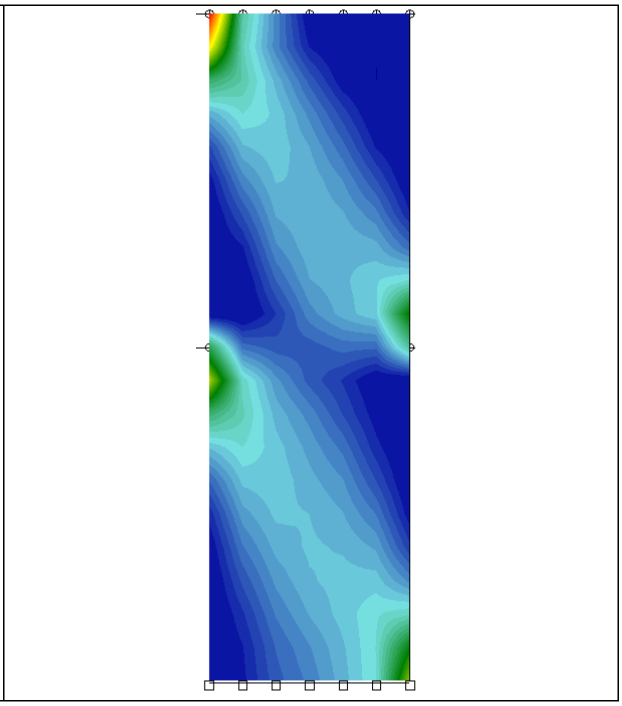


figure 32: normal stress of wall 10

5.1.3. Stress according to a length of the wall of 2.0 m (horizontal load of 165 kN)

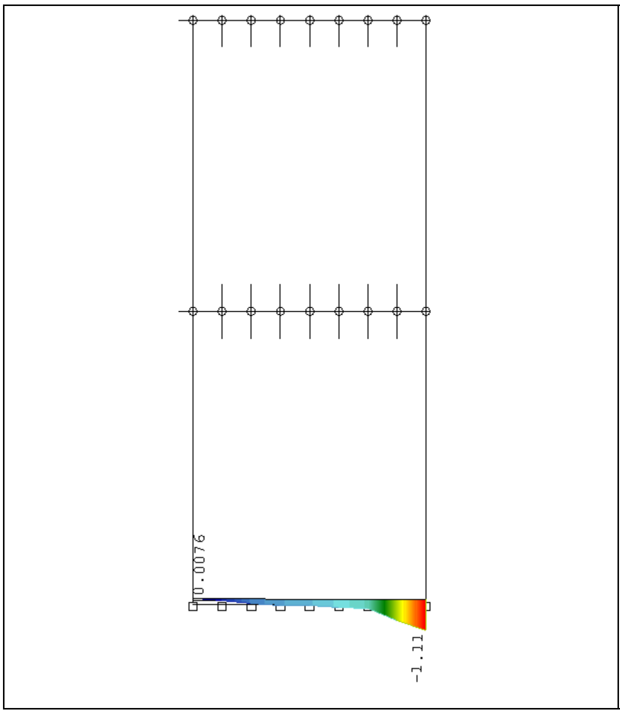


Figure 33: stress [N/mm²] at the bottom of wall 9

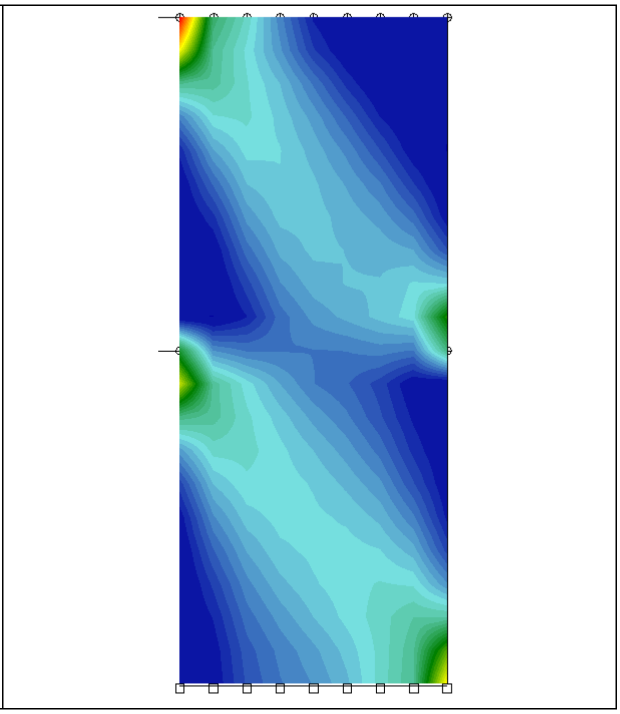


figure 34: normal stress of wall 9

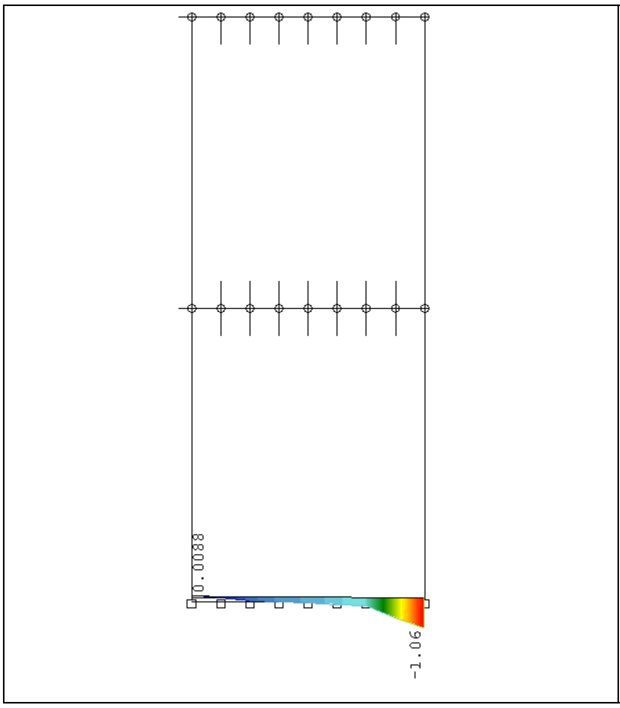


Figure 35: stress [N/mm²] at the bottom of wall 10

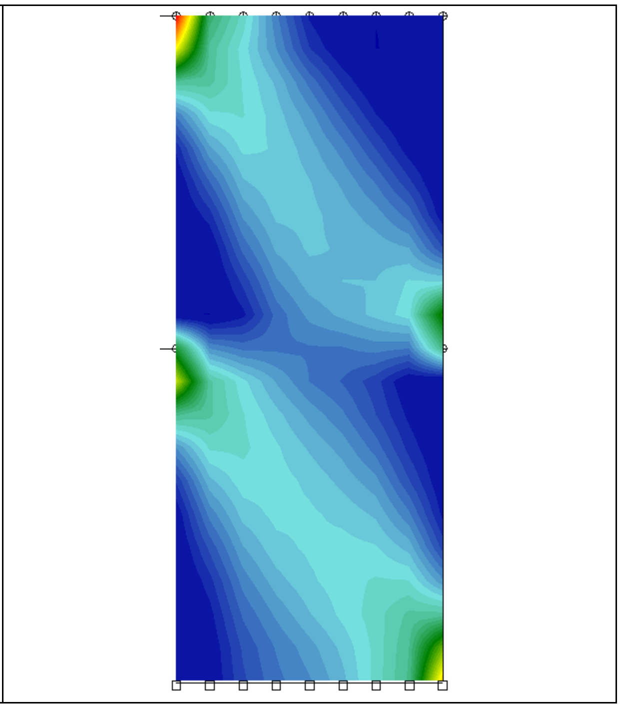


figure 36: normal stress of wall 10

5.1.4. Stress according to a length of the wall of 2.5 m (horizontal load of 175 kN)

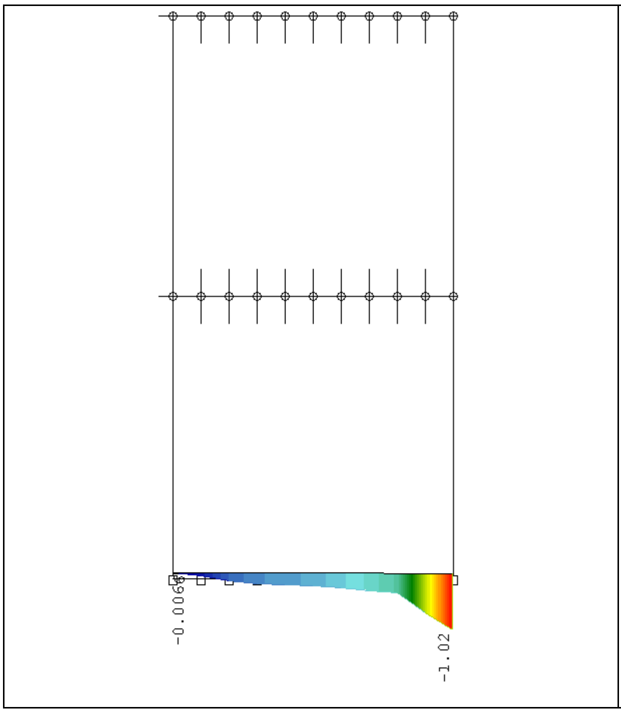


Figure 37: stress [N/mm²] at the bottom of wall 9

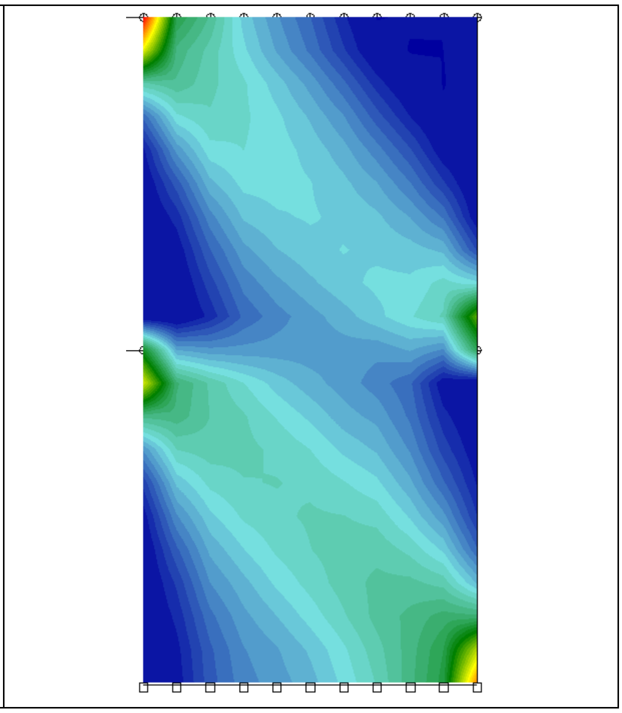


figure 38: normal stress of wall 9

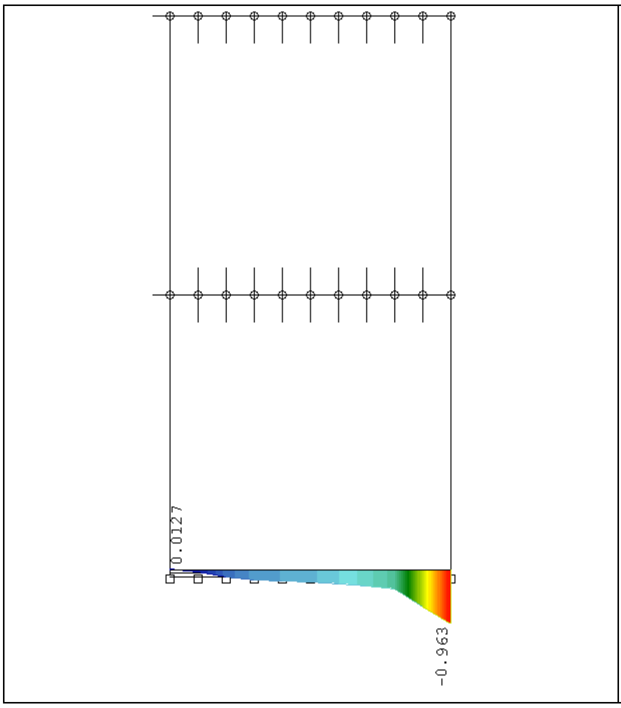


Figure 39: stress [N/mm²] at the bottom of wall 10

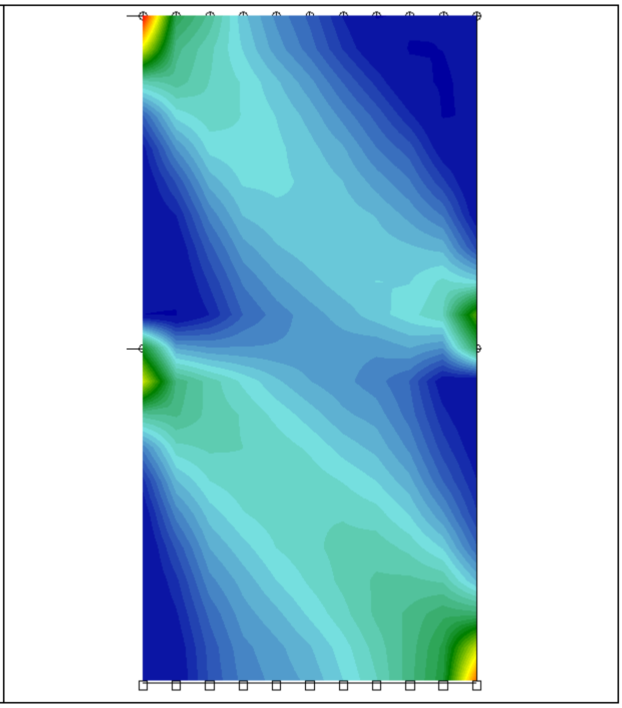


figure 40: normal stress of wall 10

5.1.5. Stress according to a length of the wall of 3.0 m (horizontal load of 210 kN)

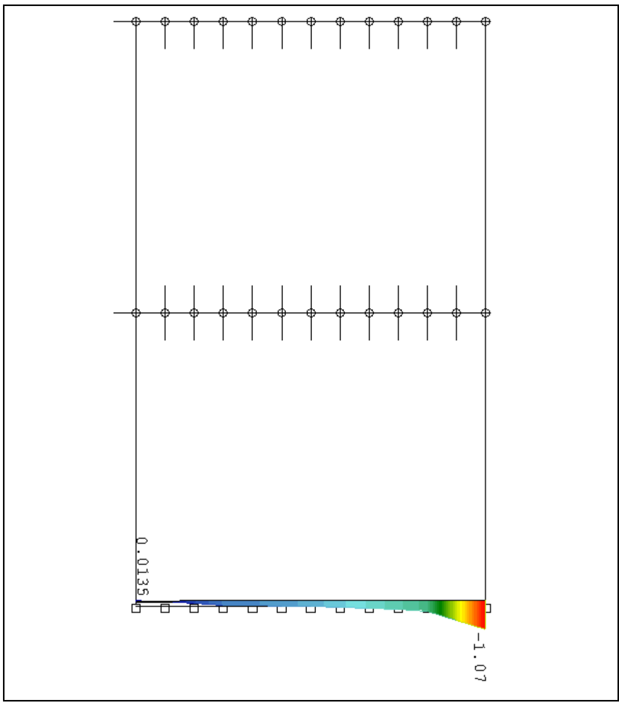


Figure 41: stress [N/mm²] at the bottom of wall 9

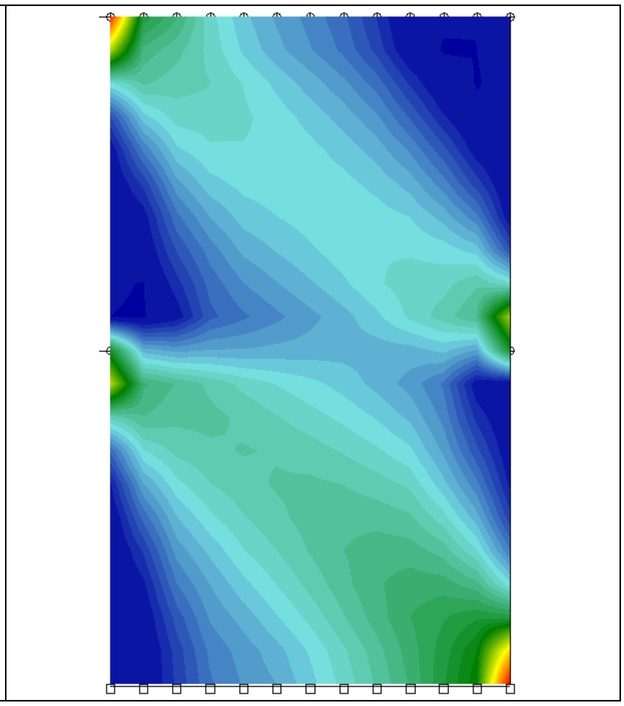


figure 42: normal stress of wall 9

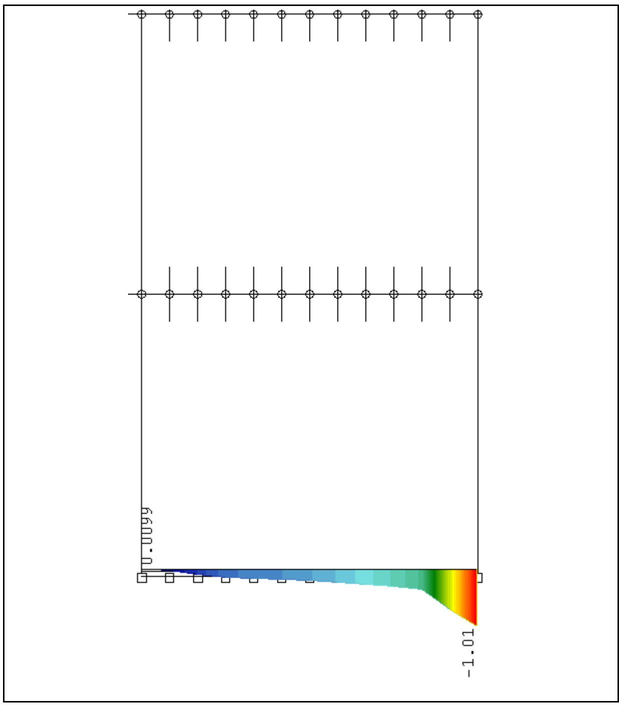


Figure 43: stress [N/mm²] at the bottom of wall 10

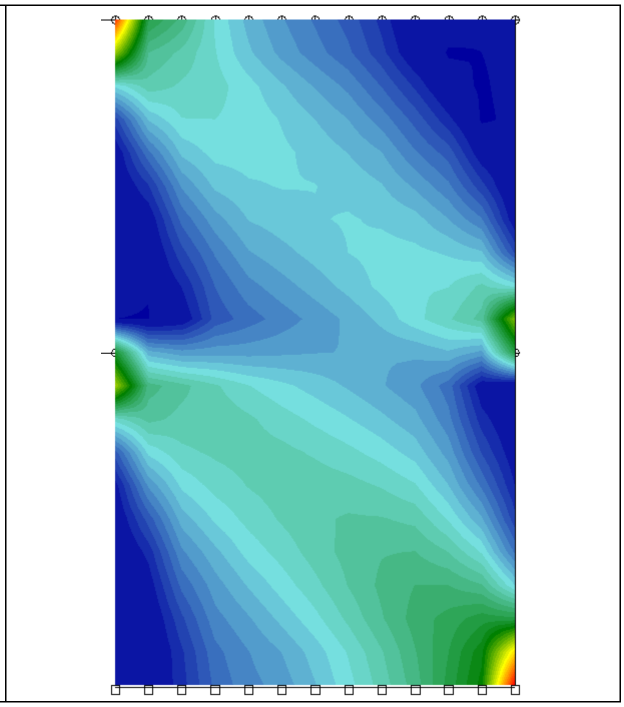


figure 44: normal stress of wall 10

5.1.6. Evaluation of the fracture behaviour

The interior walls of the terraced houses calculated with variable wall lengths and different horizontal loads show nearly the same ultimate stress. This shows, that the fracture behaviour of the different types of houses (different interior wall lengths) applies at almost the same stress level. So it can be verified, that the length of this walls enhances the acceptable horizontal load. By the way all these stress states show a break of the contour line at 0.5 m from the outside margin.

5.2. Stress states for design load level

In the following, the results of the parametric study for the investigation of the influence of different lengths of the interior walls are displayed. All the results are calculated for the loadlevel described in chapter 3.5. In figure 45 the deformation of the entire house can be seen. In figure 46 the stress next to the foundation is depicted for two exterior walls and the two interior walls.

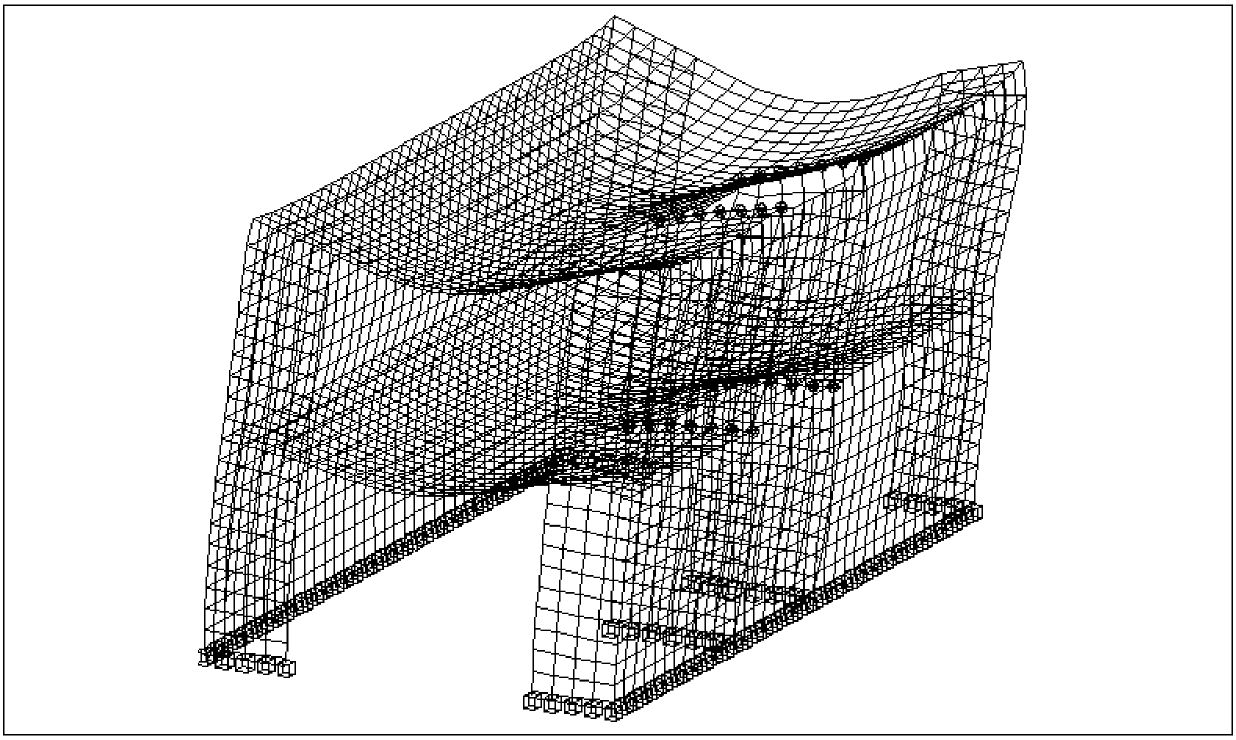


figure 45: deformation of the 3-dimensional model (interior wall length of 1.5 m, horizontal load of 80 kN)

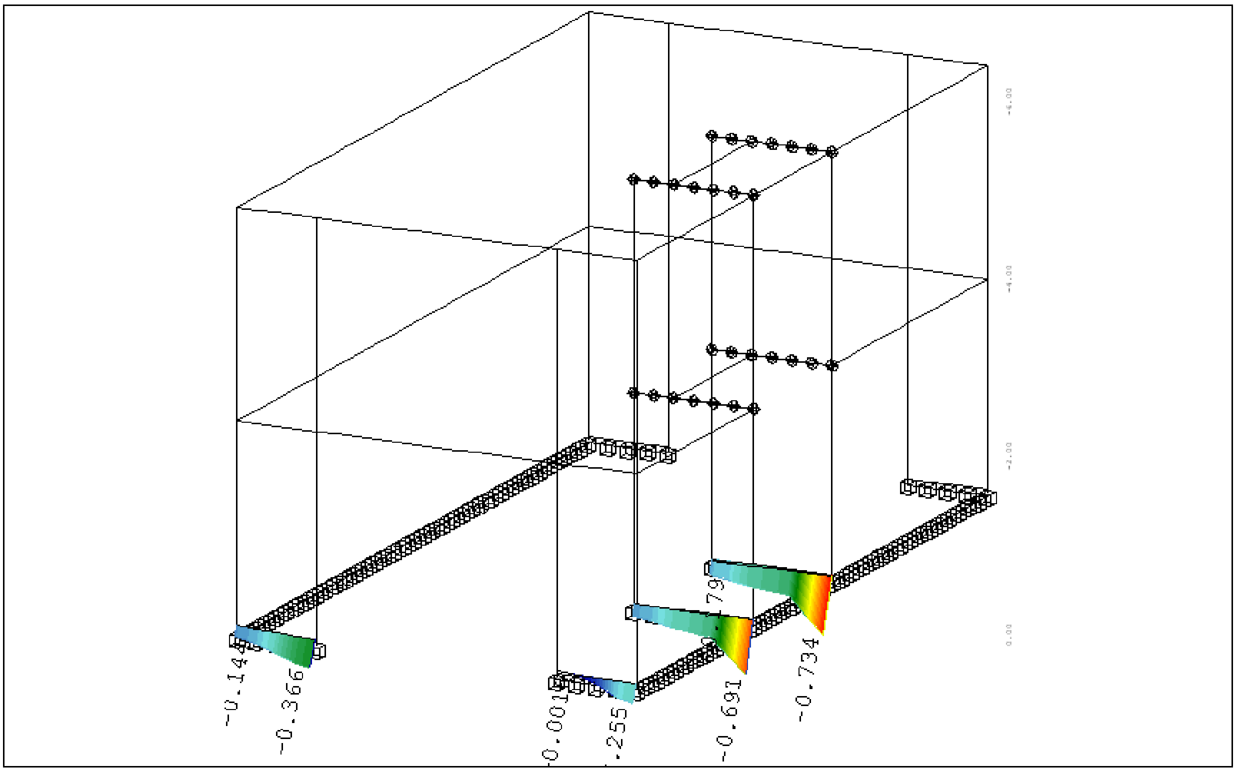


figure 46: normal stress [N/mm^2] next to the foundation of the 3-dimensional model
(interior wall length of 1.5 m, horizontal load of 80 kN)

5.2.1. Length of the wall of 1.0 m

5.2.1.1. Horizontal load from the left side

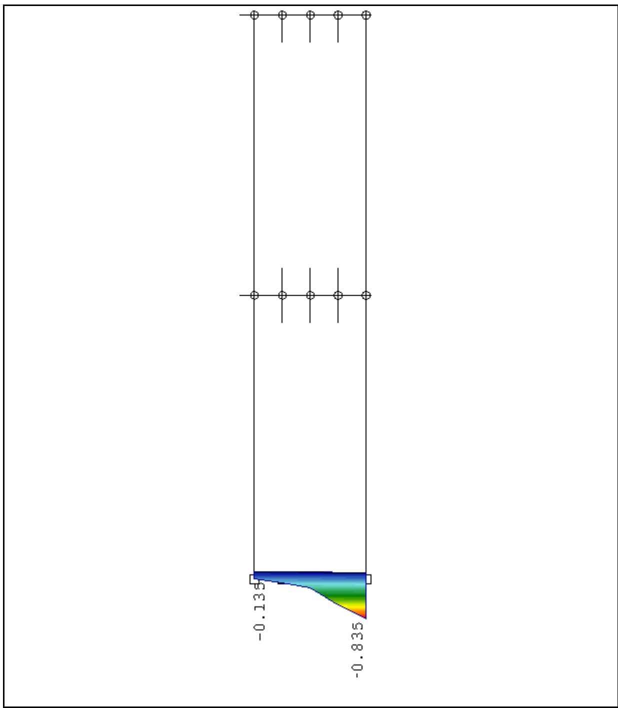


Figure 47: stress [N/mm^2] at the bottom of wall 9

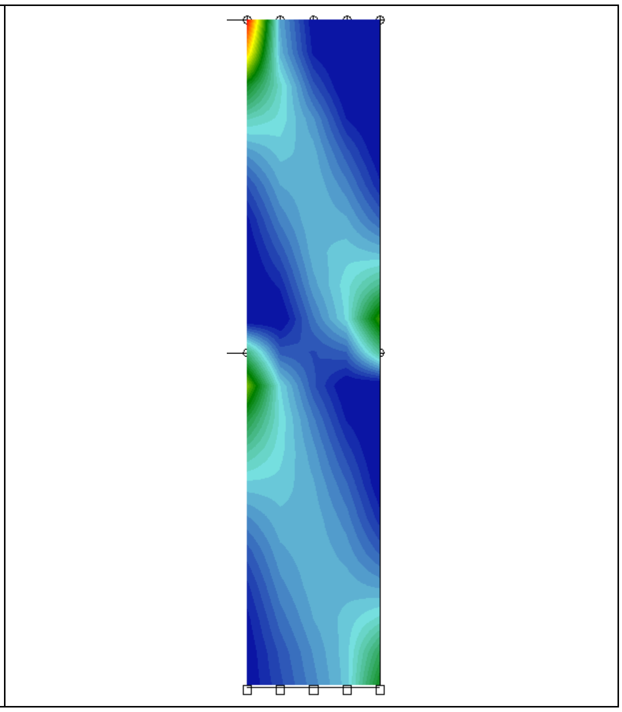


figure 48: normal stress of wall 9

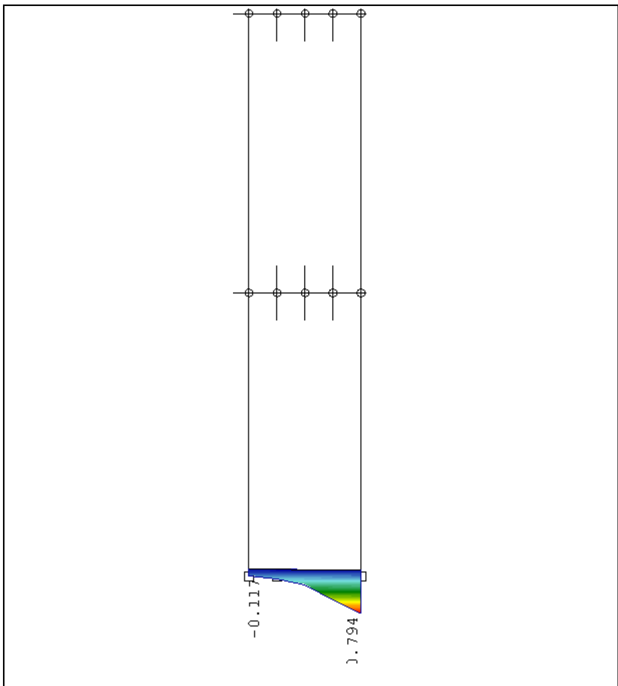


Figure 49: stress [N/mm^2] at the bottom the wall 10

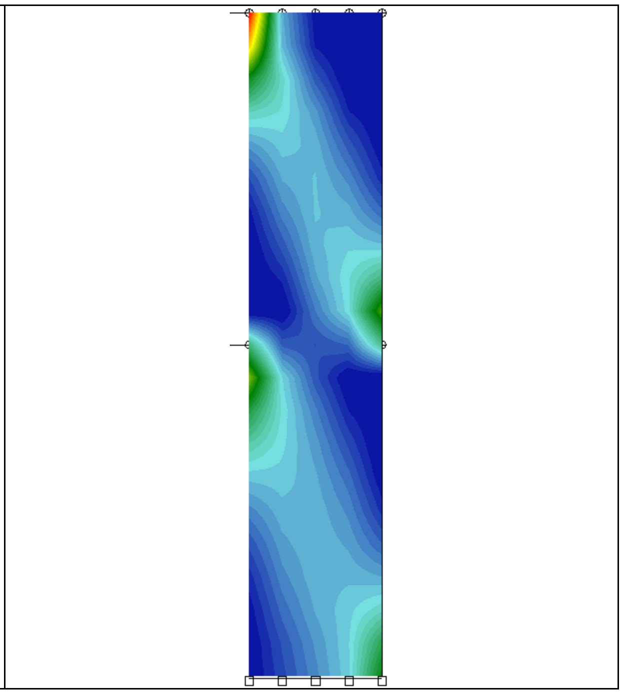


figure 50: normal stress of wall 10

5.2.1.2. Horizontal load from the right side

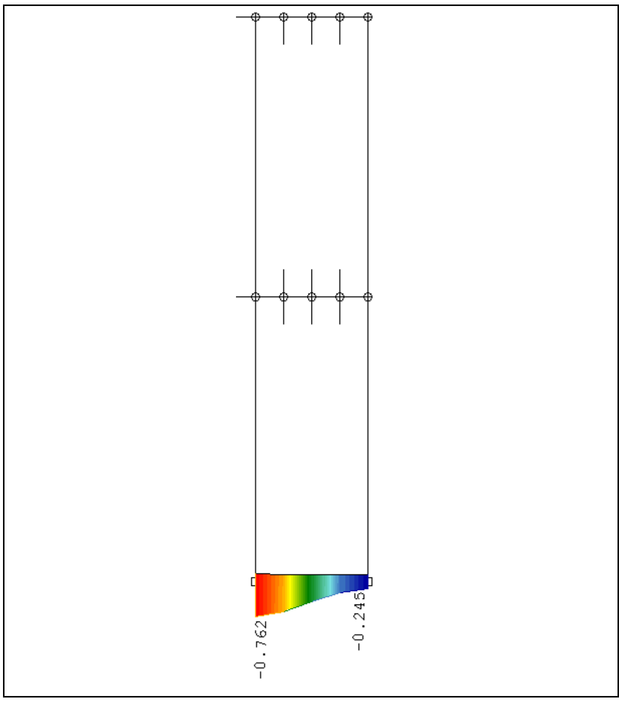


Figure 51: stress [N/mm^2] at the bottom of wall 9

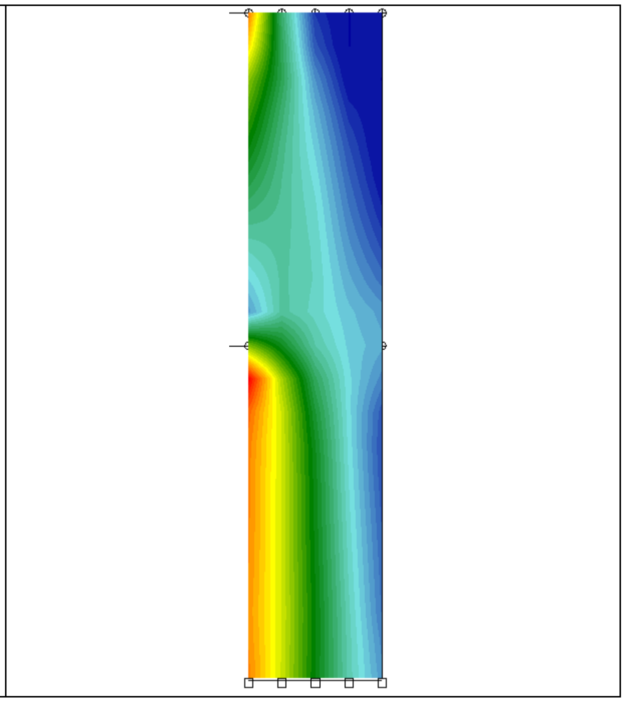


figure 52: normal stress of wall 9

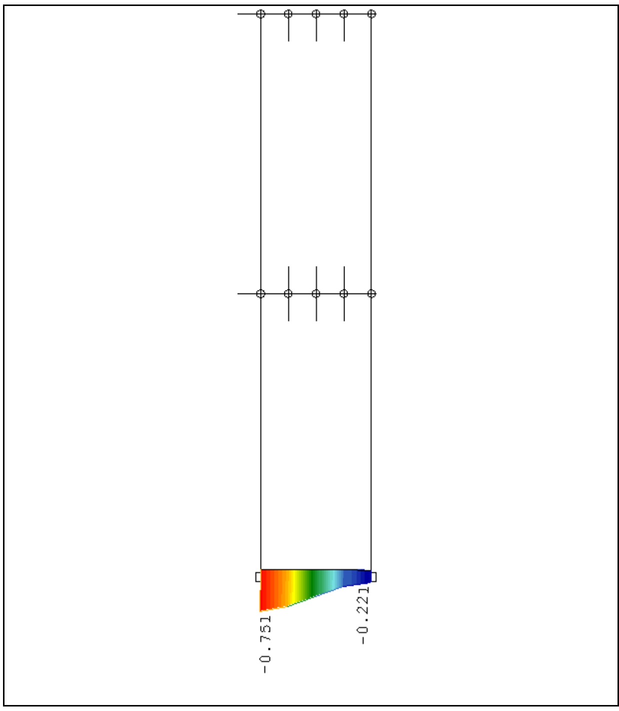


Figure 53: stress [N/mm^2] at the bottom the wall 10

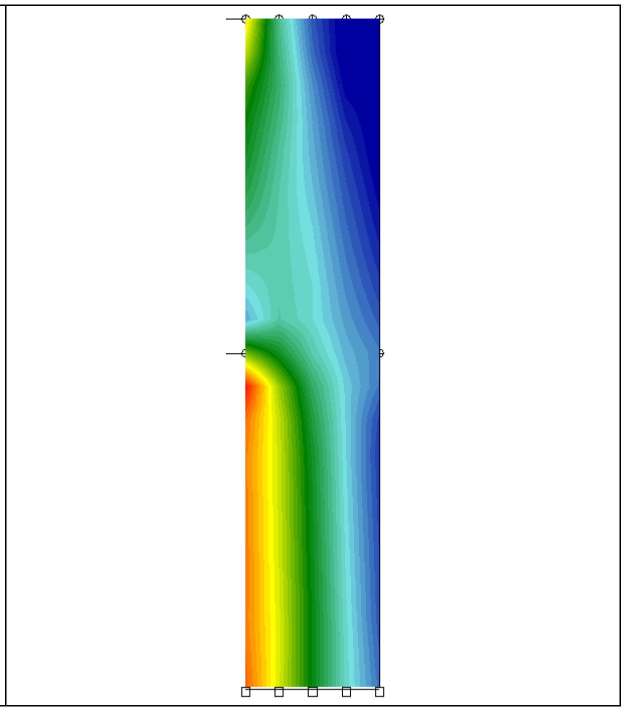


figure 54: normal stress the wall 10

5.2.2. Length of the wall of 1.5 m

5.2.2.1. Horizontal load from the left side

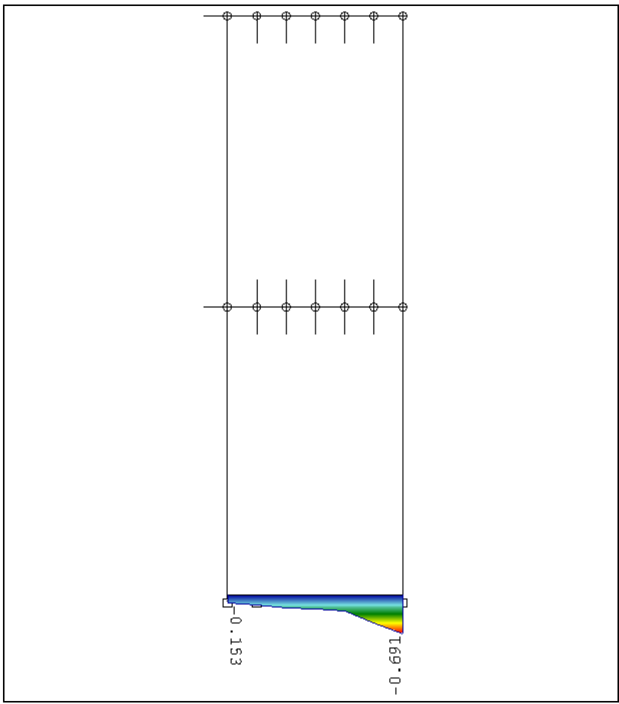


figure 55: stress [N/mm^2] at the bottom of t wall 9

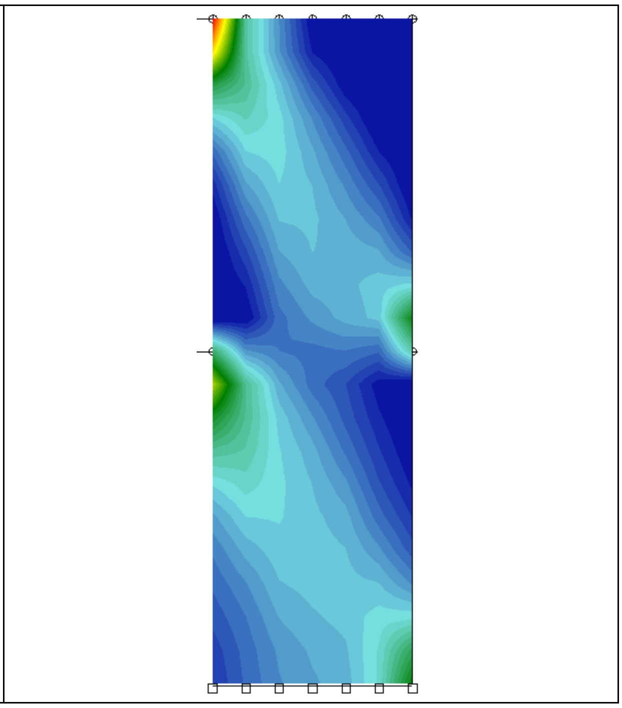


figure 56: normal stress of wall 9

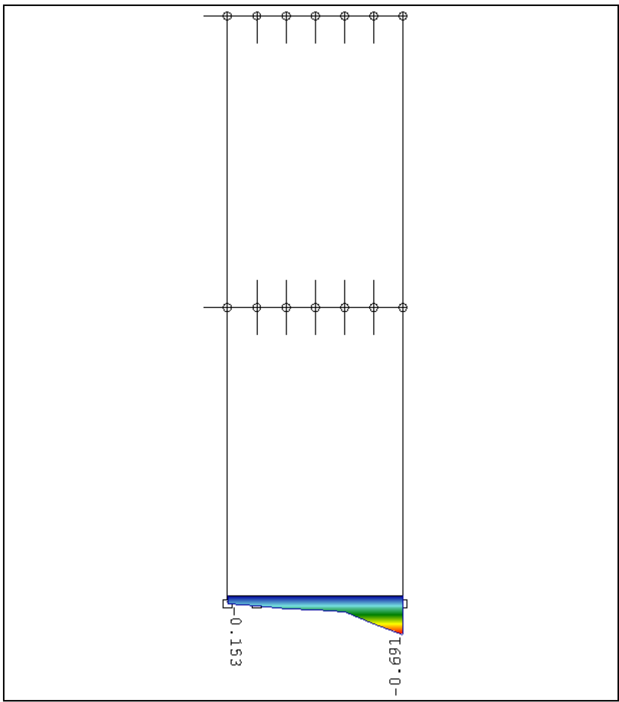


figure 57: stress [N/mm2] at the bottom of wall 10

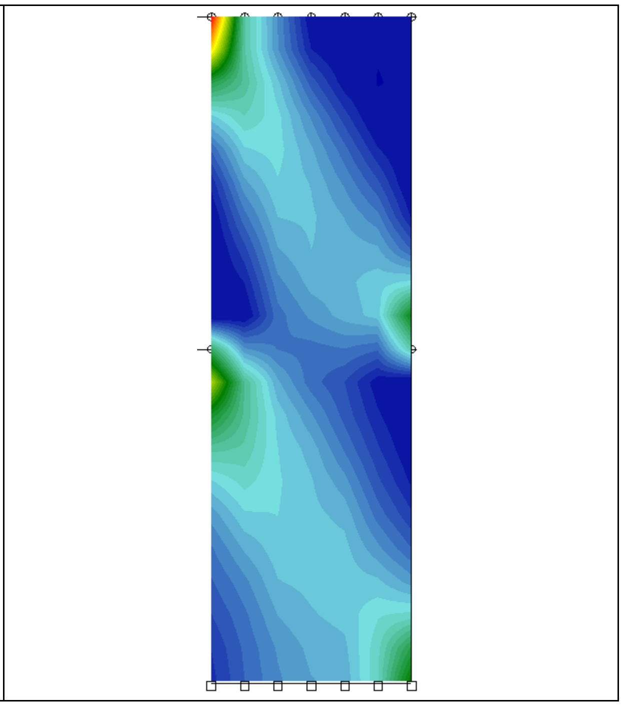


figure 58: normal stress of wall 10

5.2.2.2. Horizontal load from the right side

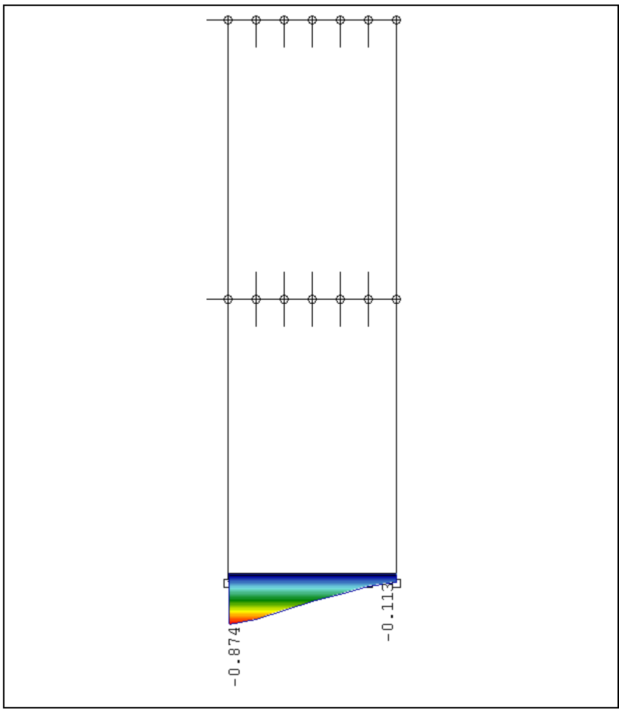


figure 59: stress [N/mm^2] at the bottom of wall 9

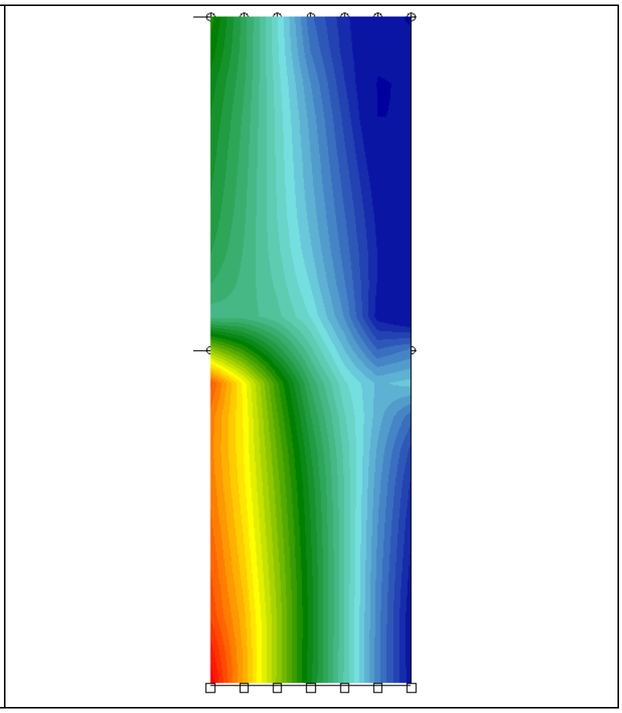


figure 60: normal stress of wall 9

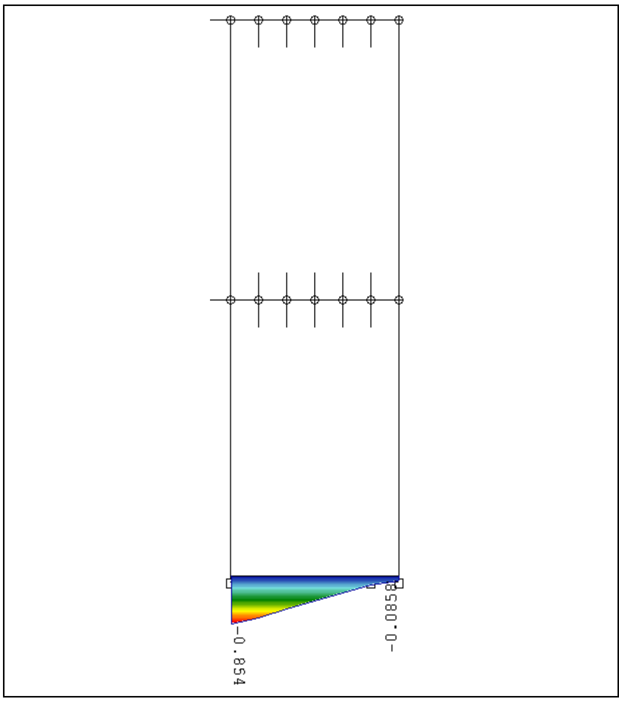


figure 61: stress [N/mm2] at the bottom of wall 10

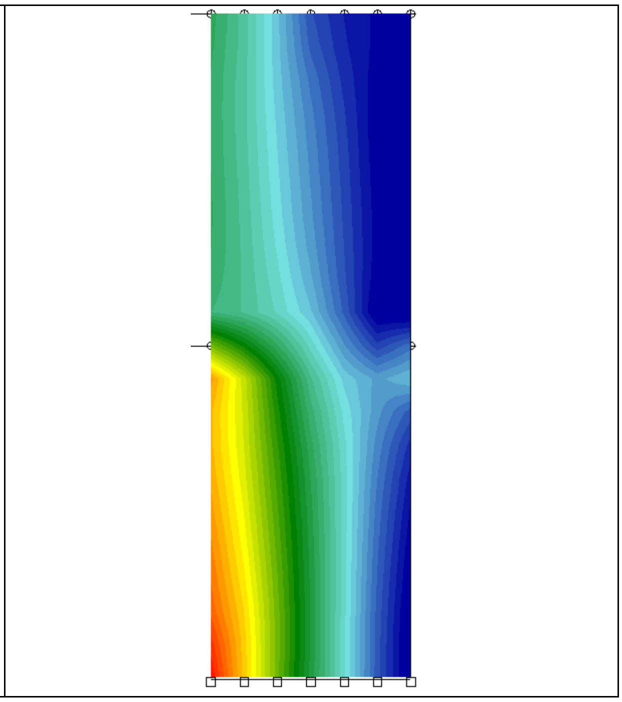
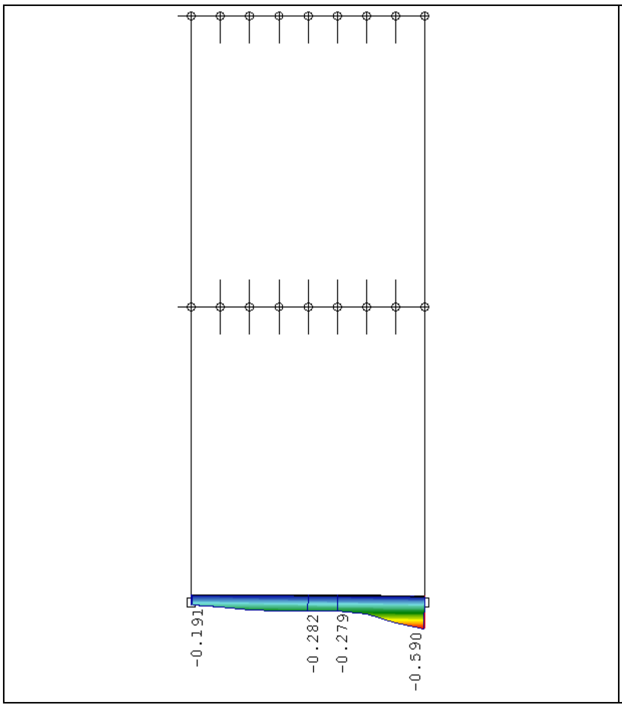


figure 62: normal stress of wall 10

5.2.3. Length of the wall of 2.0 m

5.2.3.1. Horizontal load from the left side



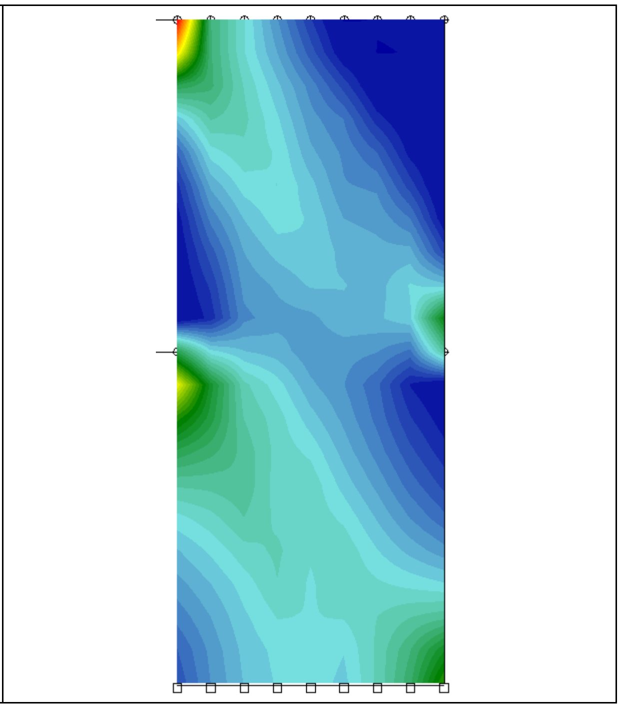
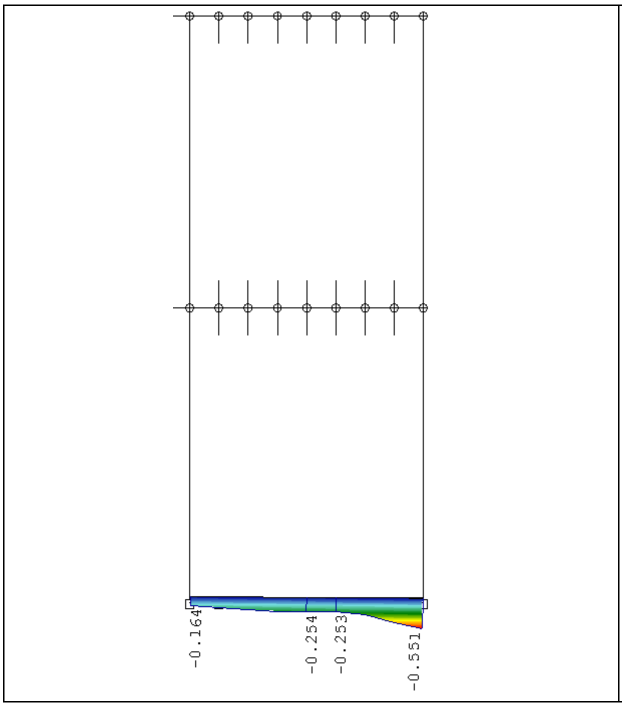


Figure 63: stress [N/mm^2] at the bottom of wall 9

figure 64: normal stress of wall 9



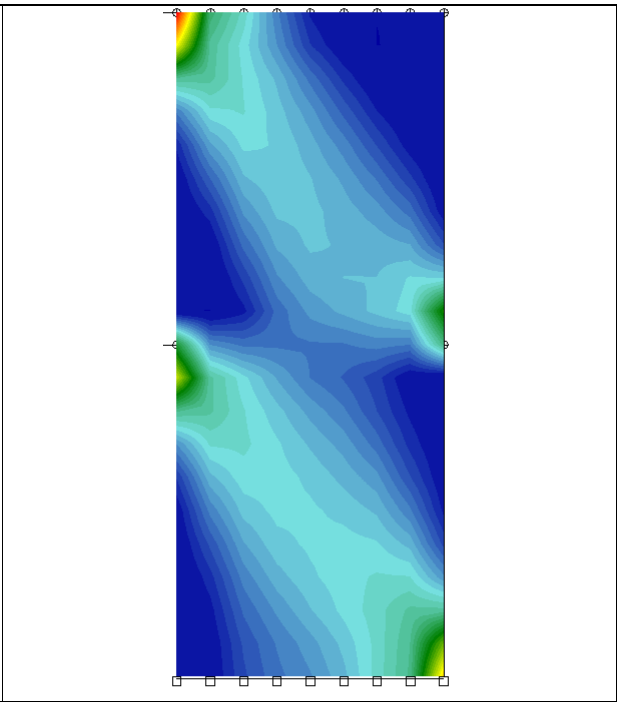


Figure 65: stress [N/mm^2] at the bottom of wall 10

figure 66: normal stress of wall 10

5.2.3.2. Horizontal load from the right side

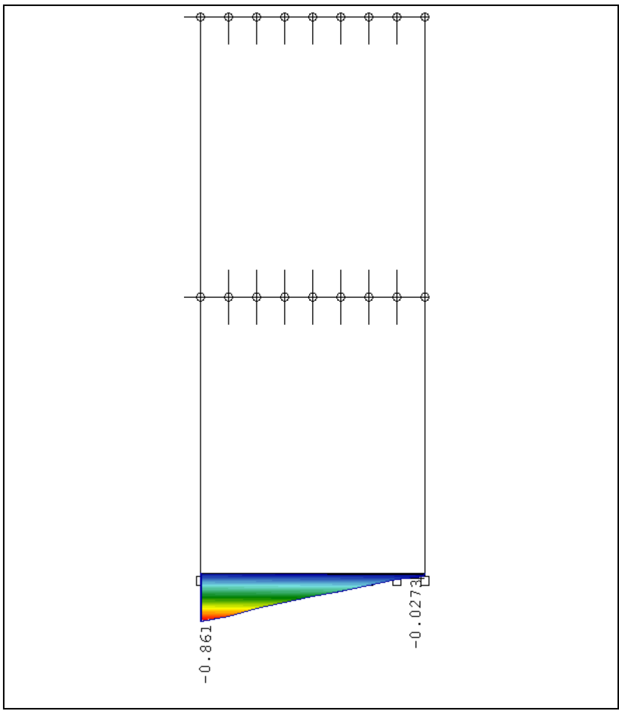


Figure 67: stress [N/mm^2] at the bottom of wall 9

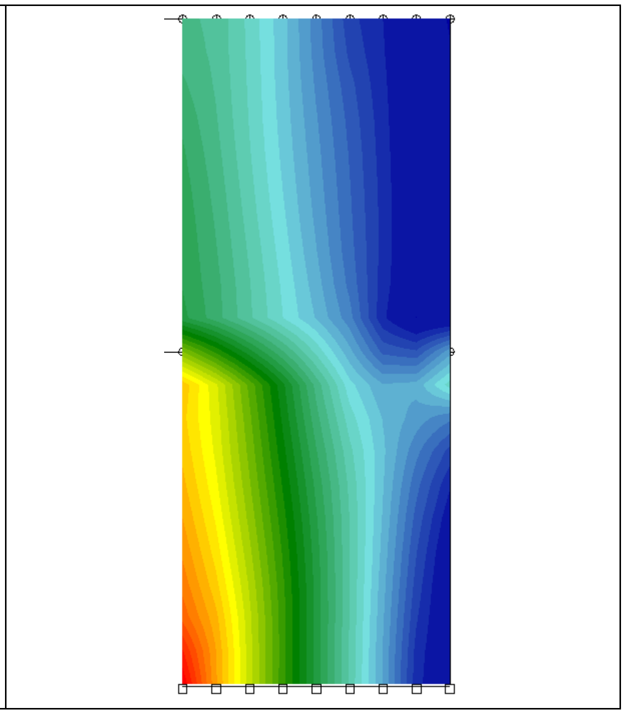


figure 68: normal stress of wall 9

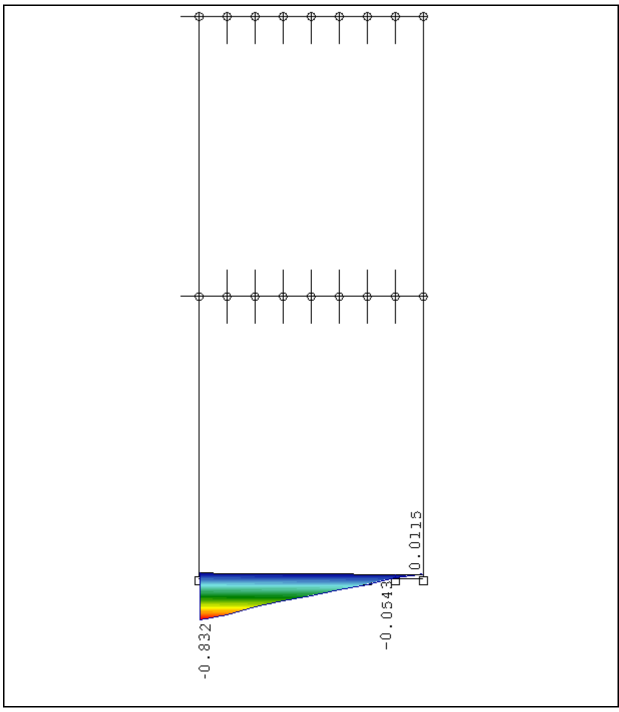


Figure 69: stress [N/mm^2] at the bottom of wall 10

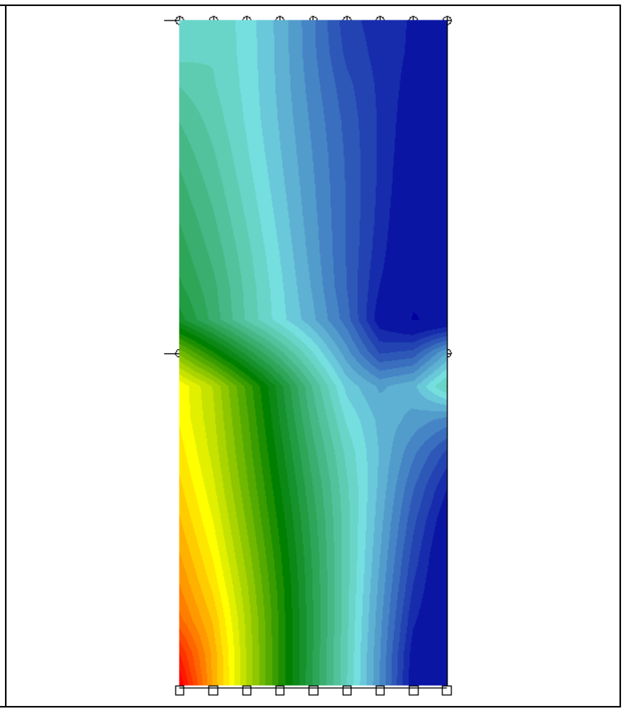


figure 70: normal stress of wall 10

5.2.4. Length of the wall of 2.5 m

5.2.4.1. Horizontal load from the left side

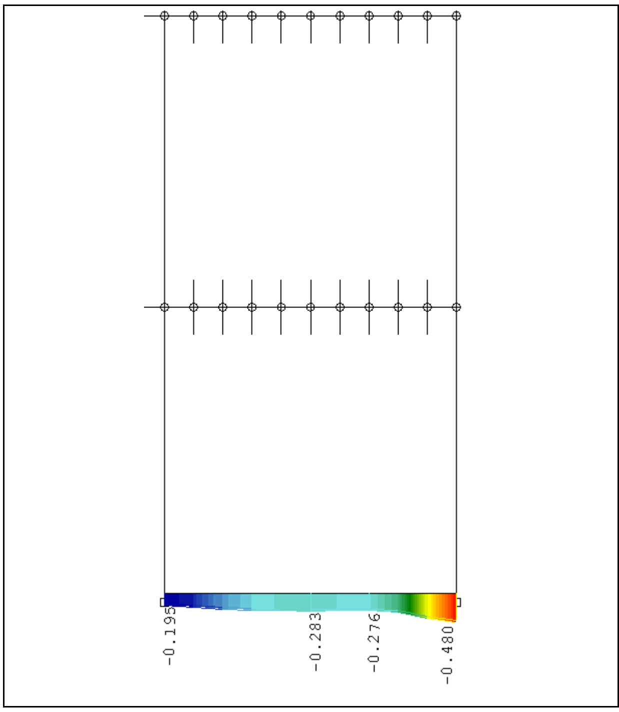


Figure 71: stress [N/mm²] at the bottom of wall 9

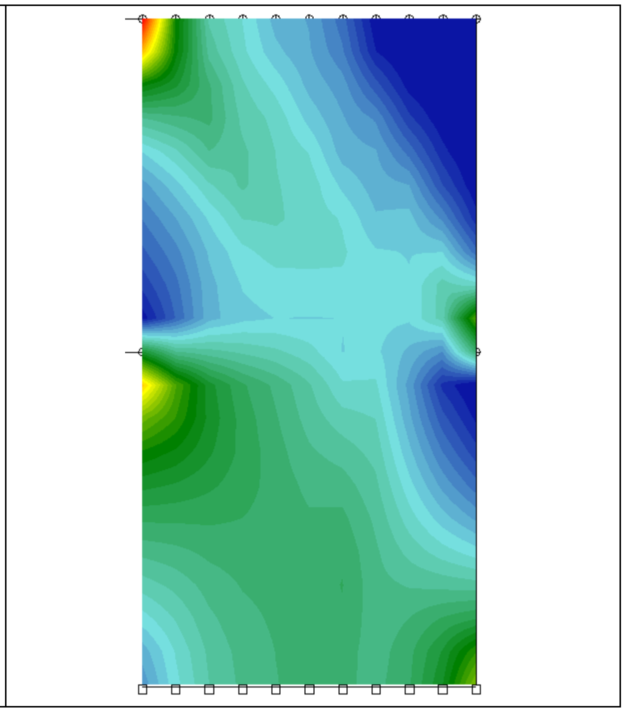


figure 72: normal stress of wall 9

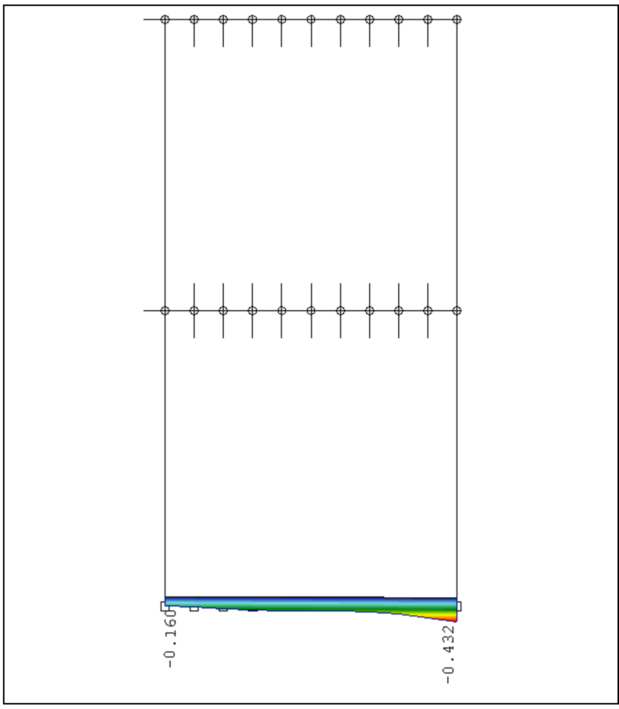


Figure 73: stress [N/mm²] at the bottom of wall 10

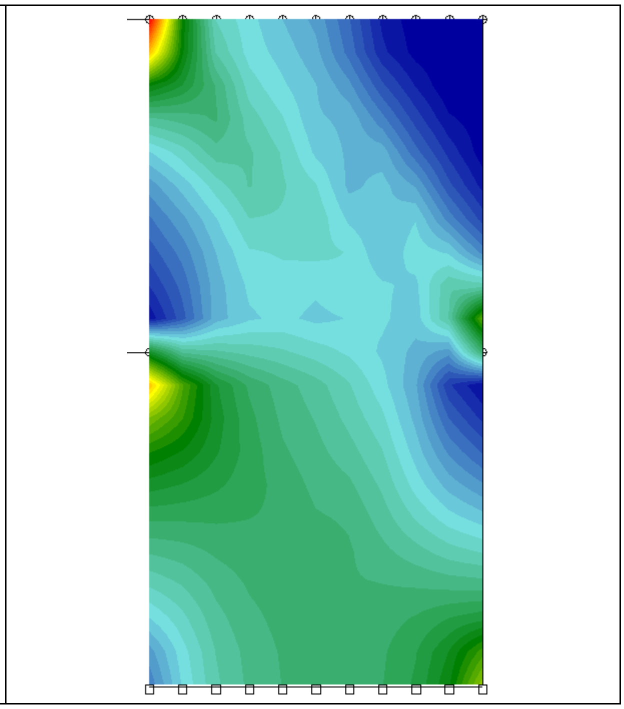


figure 74: normal stress of wall 10

5.2.4.2. Horizontal load from the right side

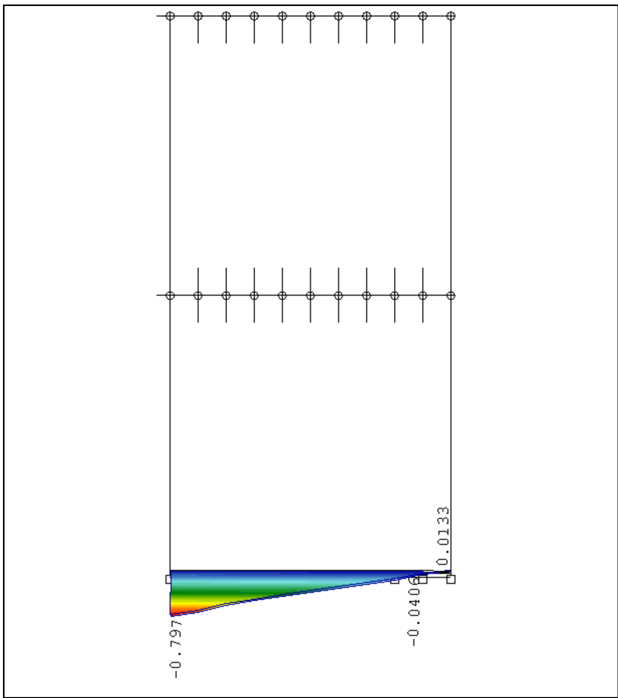


Figure 75: stress [N/mm²] at the bottom of wall 9

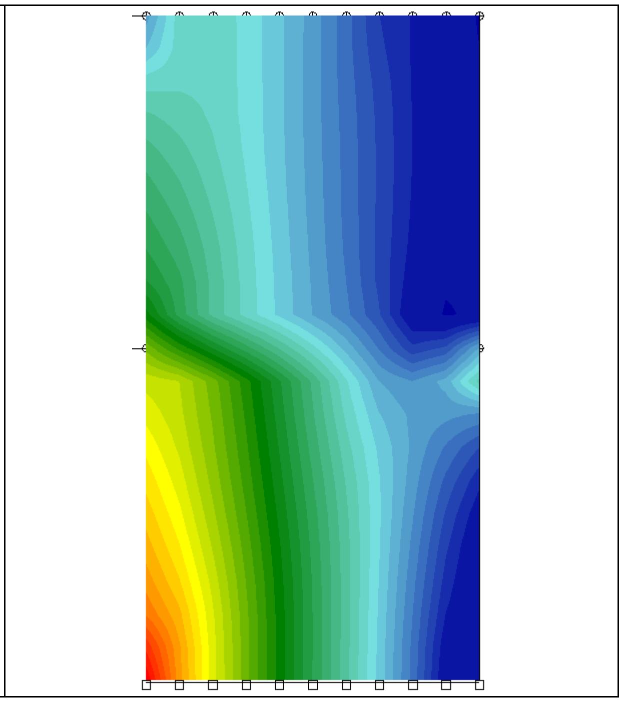


figure 76: normal stress of wall 9

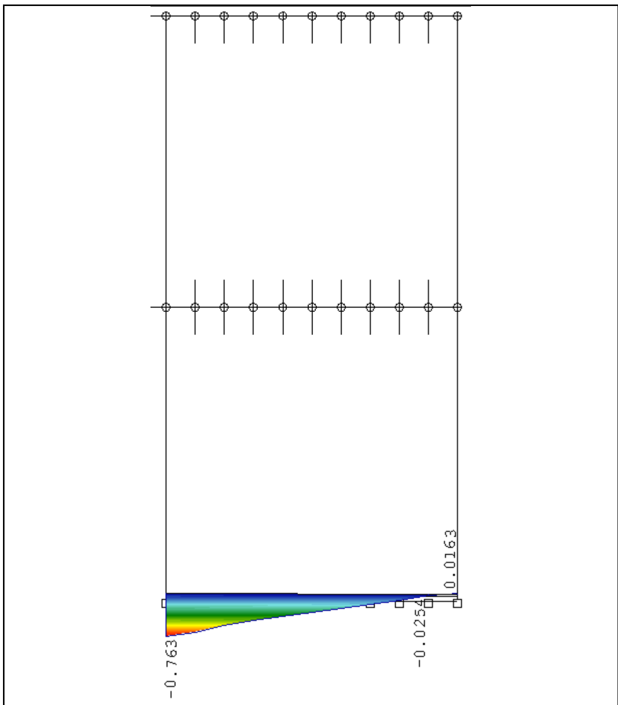


Figure 77: stress [N/mm²] at the bottom of wall 10

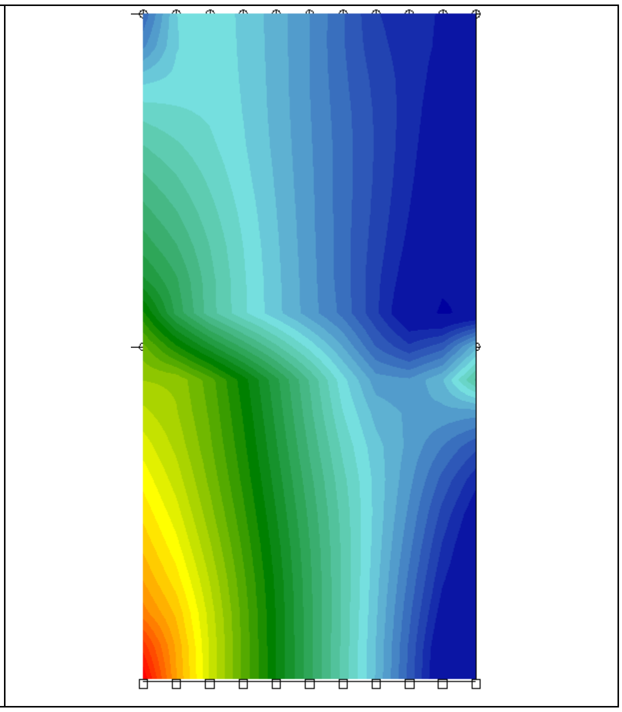


figure 78: normal stress of wall 10

5.2.5. Length of the wall of 3.0 m

5.2.5.1. Horizontal load from the left side

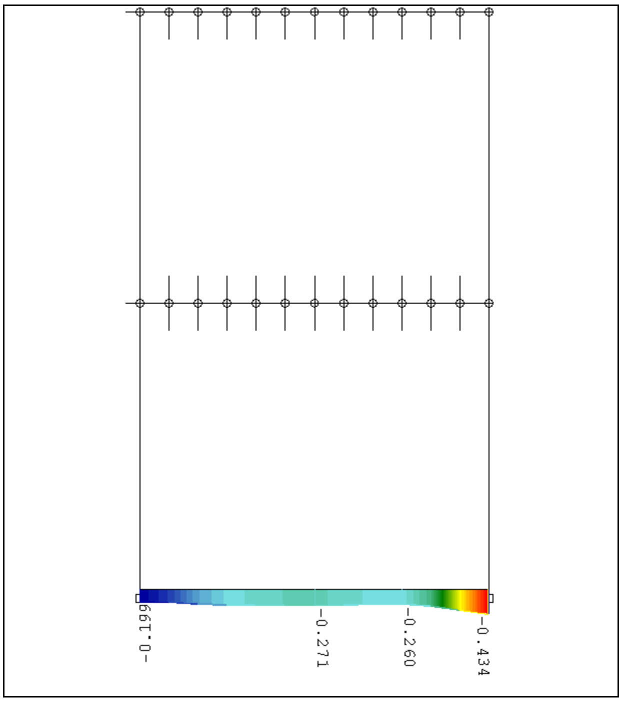


Figure 79: stress [N/mm^2] at the bottom of wall 9

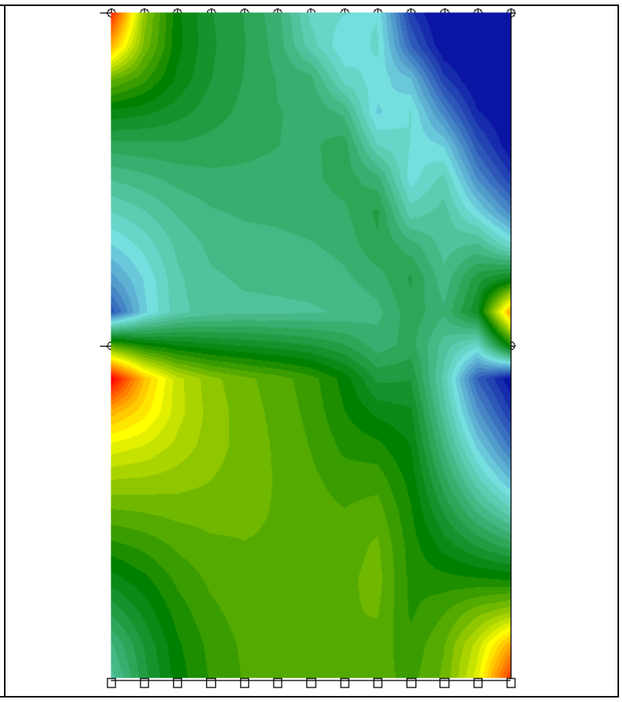


figure 80: normal stress of wall 9

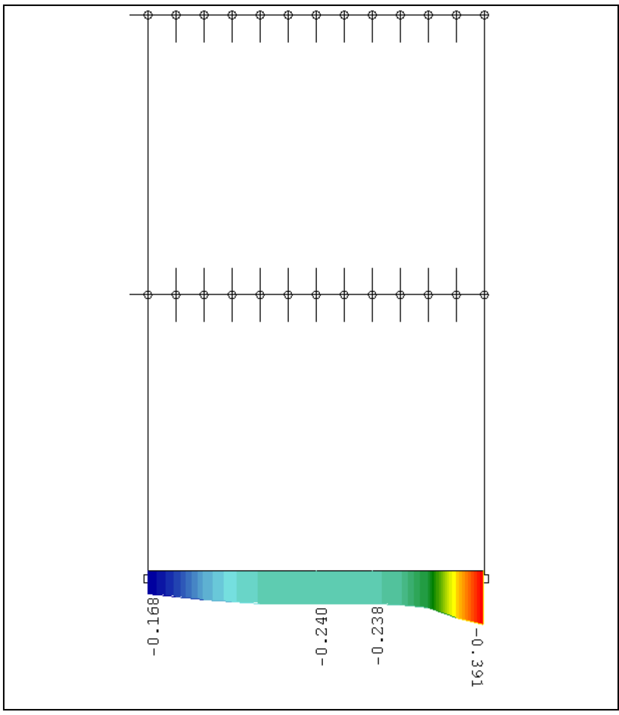


Figure 81: stress [N/mm^2] at the bottom of wall 10

figure 82: normal stress of wall 10

5.2.5.2. Horizontal load from the right side

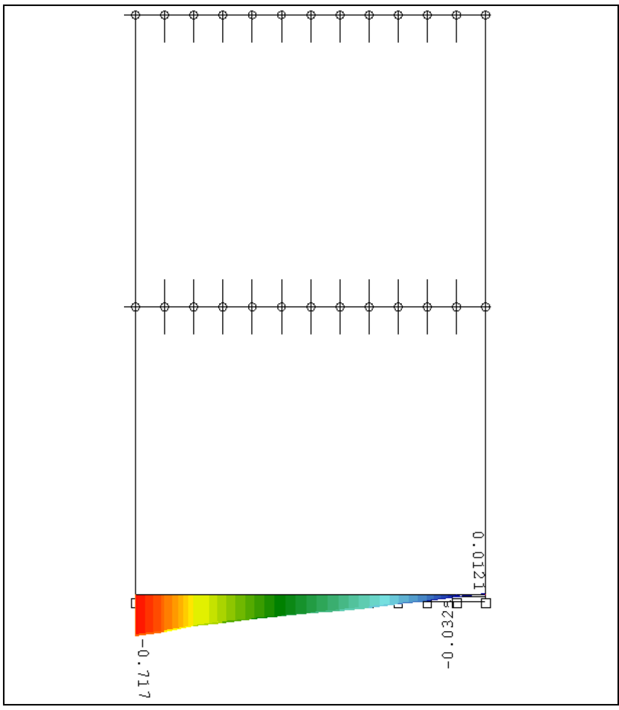


Figure 83: stress [N/mm²] at the bottom of wall 9

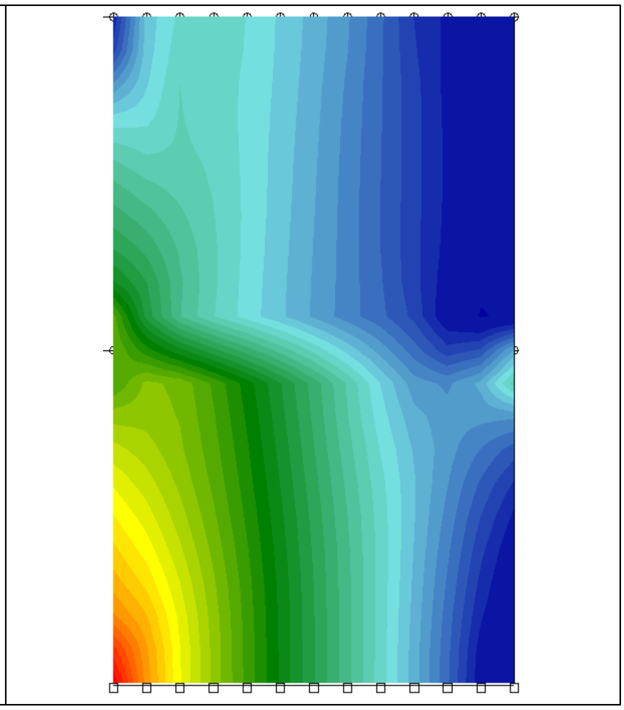


figure 84: normal stress of wall 9

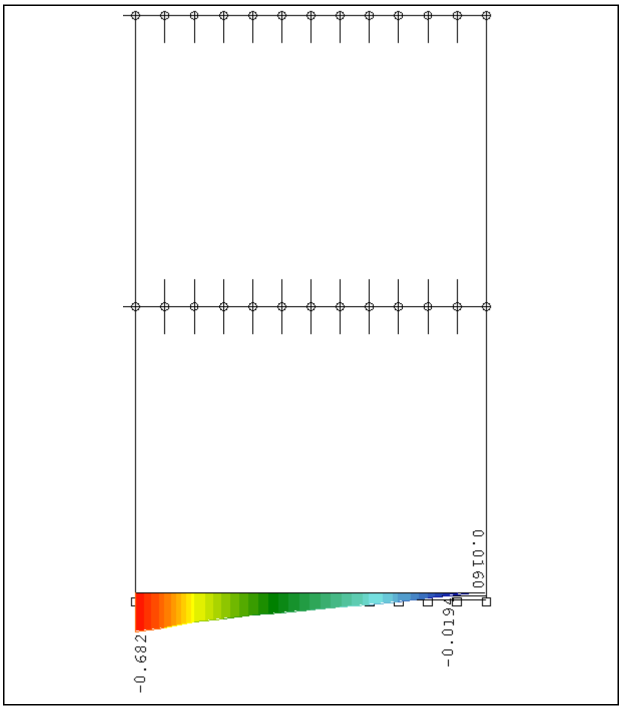


Figure 85: stress [N/mm²] at the bottom of wall 10

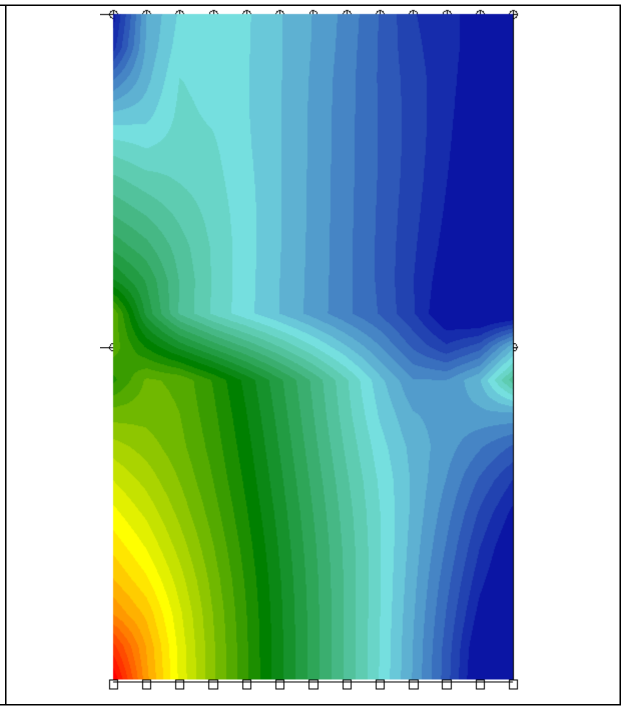


figure 86: normal stress of wall 10

5.3. Comparison of stress levels for different wall lengths

In figure 87 the maximum stress at the bottom of wall 9 is shown for the different wall lengths. These are all calculated for a horizontal load level of 80 kN, as estimated in chapter 3.5. From this figure, it becomes evident, that the maximum stress for the load case - horizontal load from the left side - is dependent in a nearly linear way on the length of the wall. For the other load case – horizontal load from the right side – the graph shows upper stresses, because the stress distribution of the horizontal loads counteracts the stress distribution of the vertical loads. Hence for this load case the stress peaks are on the same side of the wall, the maximum stress has to be higher. On the other hand the 1.0 m long wall according to the load from the right side shows lower stresses than from the other side, which contradicts this explanation. So this deviation can only be interpreted by a displacement of the horizontal load to the exterior walls for the house with the short interior walls, because the stress would be to high without this rearrangement.

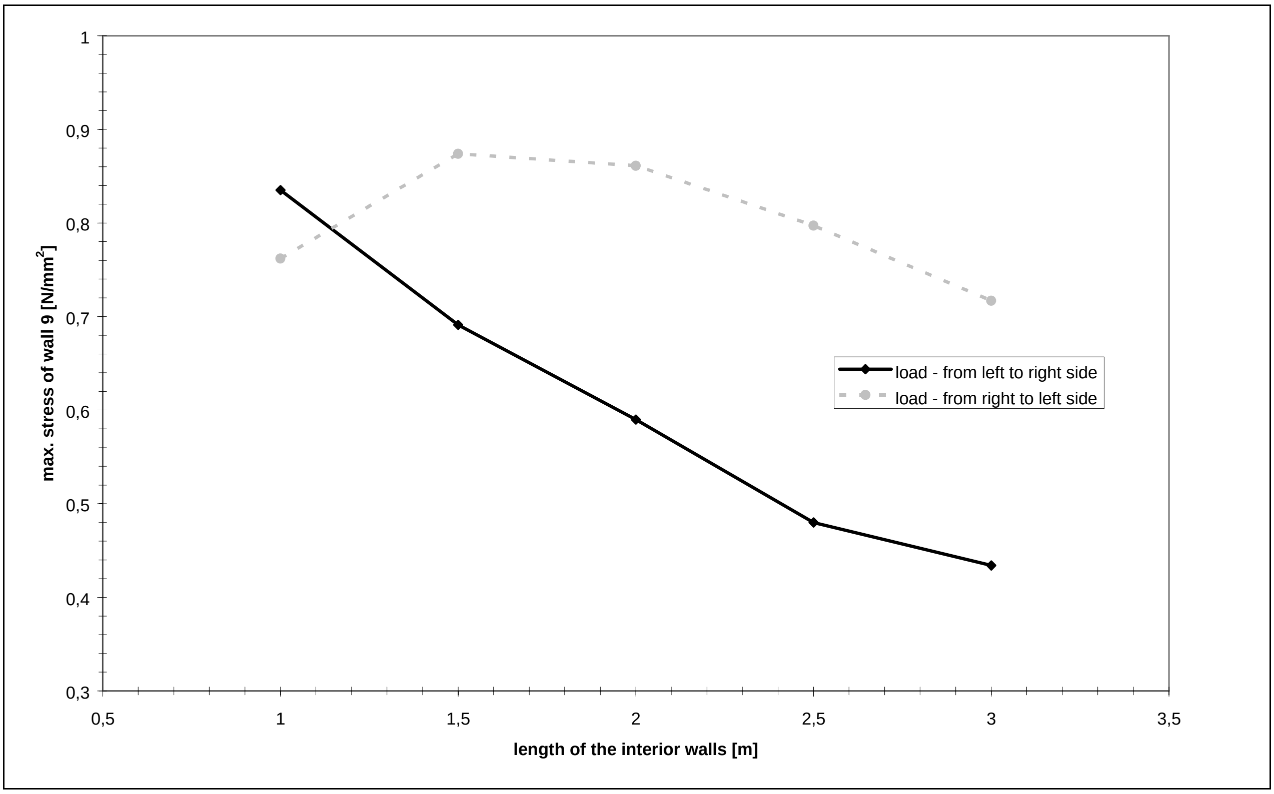


figure 87: relationship between length of the wall and maximum stress

6. Abstract

A three-dimensional finite-element-model of a terraced house has been established by using a smeared masonry model including basic nonlinearities. This model is able to present a tension failure in the horizontal joints. Since the shear failure cannot be modelled realistically, the verification for shear stress is calculated according to DIN 1053-100 separately from the finite-element-computation. It could be shown, that a shear failure accurse at lower load levels in comparison to the ultimate load according to the finite-element-model.

Stress states for the ultimate horizontal load and a horizontal load of 80 kN according to an earthquake example load (zone 2) were shown. The parametric study for different lengths of the interior walls showed, that there is a nearly linear behaviour between the stress at the bottom of the wall and the length of the wall, when the stress peak of the vertical load is at the same end of the wall as the stress peak of the horizontal load.

7. Annex

In figure A1 the stress-strain-behaviour of a modified material model for the slabs is shown. This study of the influence of cracking of the concrete slabs shows an increase of about 20% of the stress at the bottom of wall 9, when the slabs are modelled in this way.

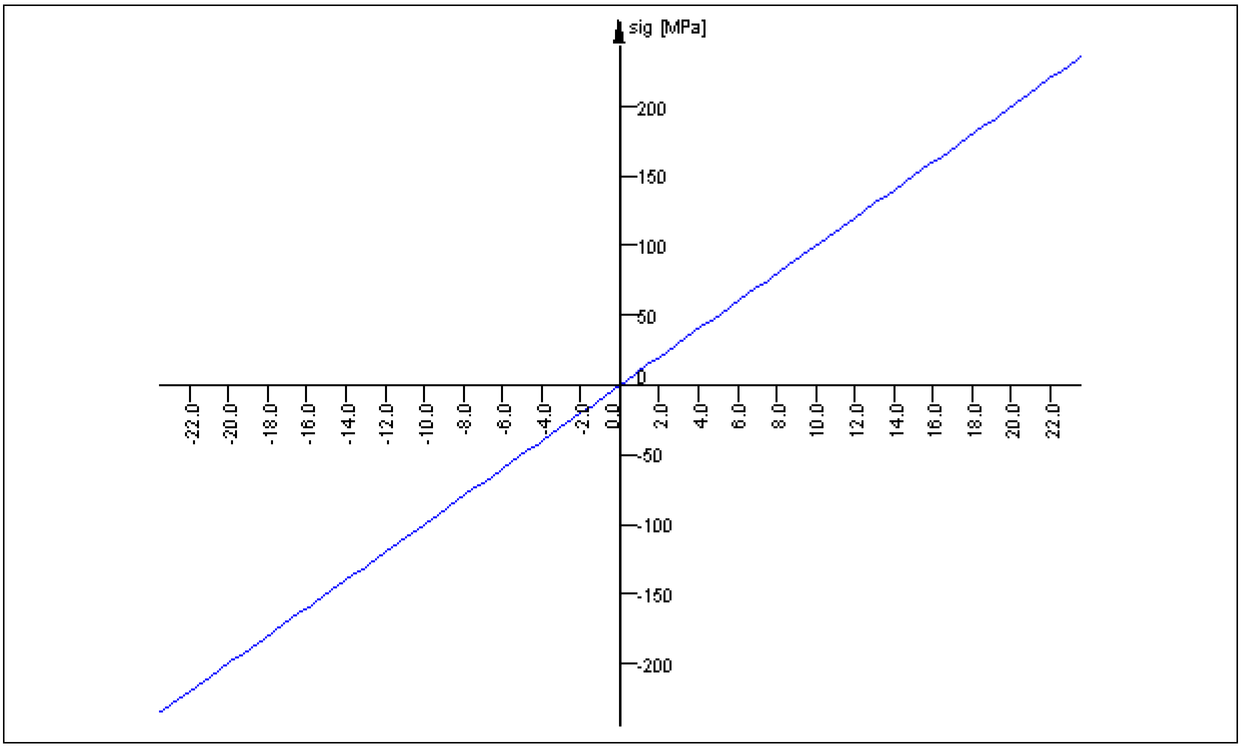
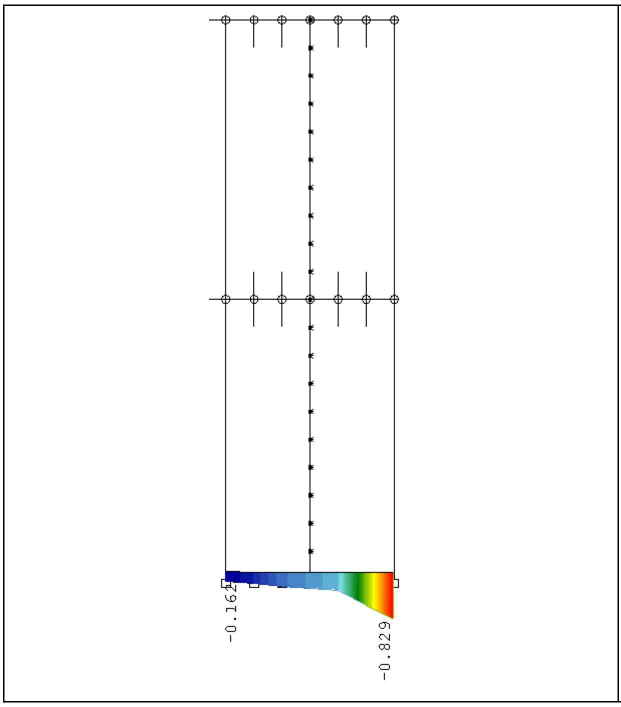


Figure A1: stress-strain-relationship of the slab (E = 10.000 N/mm^2)

Figure A2 and figure A3 display the stress states of a 1.5 m long interior wall according to a horizontal load of 80 kN.



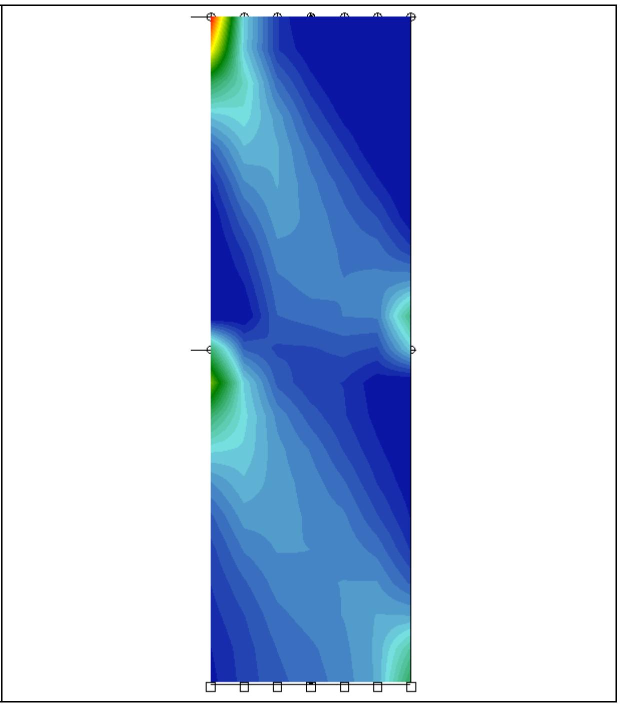


Figure A2: stress [N/mm^2] at the bottom of wall 9

figure A3: normal stress of wall 9