DEVELOPMENT OF WOODEN FLOOR ELEMENTS – PART 2

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TallWood

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SUMMARY

This project was a continuation of previously conducted work. The overarching objective is to study the acoustic properties of a floor structure developed by Masonite Beams that uses springs at its supports and in the ceiling hangers. The previous work covered the acoustic properties of the floor with just the beams, floorboards and the springs at the supports. This project aimed to study the effect on the acoustic properties by adding noggins and the suspended ceiling to the floor structure. A FEM-model was developed by modelling the noggins and the suspended ceiling on to an already created model of the floor without these components. The results were received through simulations which consisted of the first five natural frequencies of the floor. Different combinations of springs stiffness in both the supports and the ceiling hangers, and with and without noggins, were tested. It was concluded that the noggins only show a significant effect on the natural frequencies higher up in the frequency spectrum, at around 30 Hz and above. The ceiling reduced the natural frequencies overall due to its weight and depending on the spring stiffness in the ceiling hangers the subsequent frequencies would vary, were higher spring stiffness resulted in higher frequencies.

Contents

1. INTRODUCTION

The background to the project, previously completed work, and what was done in this project, is presented here.

1.1. Background

Masonite Beams has developed a new solution for apartment-separating floors for dwellings. The floor uses springs at the supports consisting of hangers which are hung on the walls. Springs are also used to mechanically suspend the ceiling. The floor is built with noggins to increase stiffness of the structure. Tests have been conducted on the floor in some six-story buildings with good results from sound measurements, but it is not fully clear why the floor gives good results. Research is necessary regarding the floor's stiffness, natural frequencies, how it functions for different spans, and the effect of noggins and change of the floorboard thickness on the acoustic and mechanical properties. Ultimately, all work should culminate in a calculation tool that takes all these parameters into account and can be used in the design process.

1.2. Previous work

In a previously conducted project regarding this floor, "*Development of wooden floor elements*", some groundwork was made. The natural frequencies of the floor was studied by implementing simulations on a FEM-model that was designed and replicated according to drawings that was provided by Masonite Beams. The previous project studied the "basic structure" of the floor, consisting of the beams, floorboards, and the hangers, see figure 1. The effect on the acoustic properties of the suspended ceiling and the cross-lying noggins where disregarded.

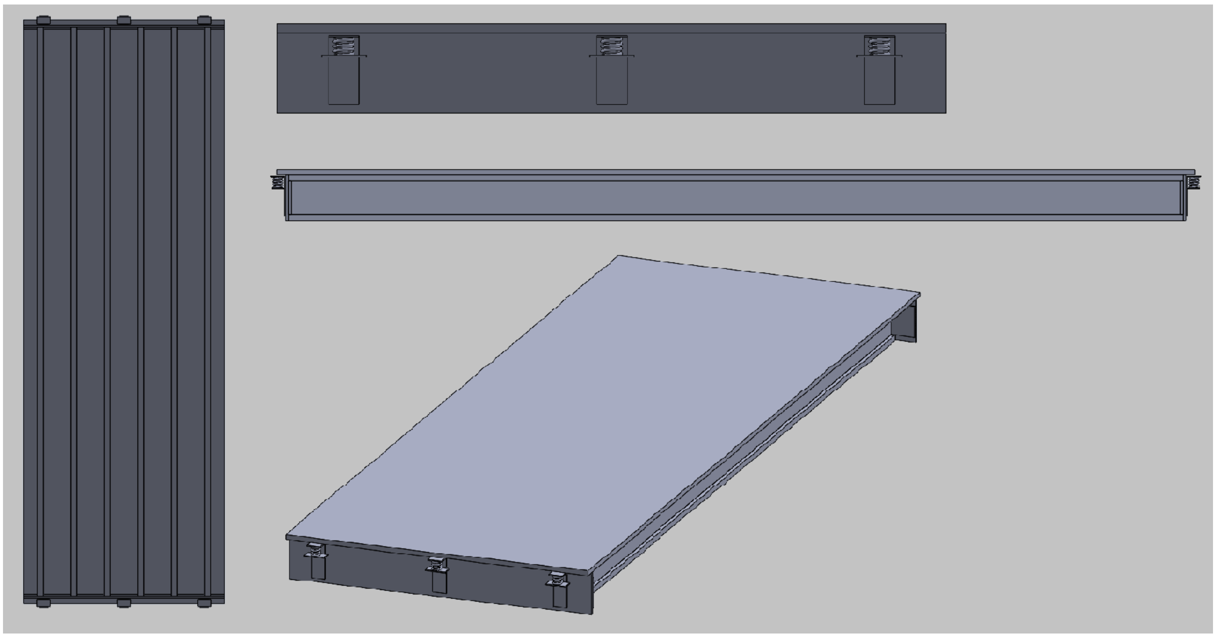


Figure 1. A FEM-model of the floor structure that was studied in the previous project. The model was made in Solidworks.

Two cases were studied in the project; the floor with rigid springs and flexible springs at the supports. The results showed that the rigidly supported floor had higher natural frequencies due to increased stiffness of the structure. Table 1 presents the first five natural frequencies of the floor with rigid springs.

Table 1. The first five natural frequencies of the rigidly supported floor.

Mode No.	Frequency (Rad/sec)	Frequency (Hertz)	Period (Milliseconds)
1	104,8	16,7	60,0
2	113,3	18,0	55,5
3	189,0	30,1	33,2
4	211,2	33,6	29,8
5	214,0	34,1	29,4

The first five natural frequencies for the floor with flexible springs are presented in table 2.

Table 2. The first five natural frequencies of the flexibly supported floor.

Mode No.	Frequency (Rad/sec)	Frequency (Hertz)	Period (Milliseconds)
1	54,3	8,6	115,7
2	60,1	9,6	104,6
3	97,8	15,6	64,2
4	120,9	19,2	52,0
5	186,2	29,6	33,7

1.3. Purpose and Objectives

The purpose of this project was to give a deeper understanding of the acoustic performance of Masonite Beams' developed floor and to further push the research of this floor project.

For this project, two objectives were identified. The first objective was to find the natural frequencies of the floor with the added influence of noggins and the suspended ceiling. For this objective, the natural frequencies of the floor were studied in its current intended composition regarding dimensions and part positions. The second objective was to tune the floor by changing stiffness of the springs, or by making changes in the floor composition, like changing numbers, or position of noggins. This was done to receive optimal natural frequencies with regard to excitation from footsteps. These objectives were met by continuing to develop the FEM-model of the floor, seen in figure 1, by adding the noggins and ceiling, and to perform simulations on the developed FEM-model to determine its natural frequencies.

1.4. Limitations

The limitations for the project are listed below. The points specifically state what has been omitted from the work and what was treated.

- The project will not treat the mechanical aspects of the floor, only the acoustic aspects.
- The effect of different spans on the floor's acoustic performance will not be accounted.
- Only the acoustic effect of noggins and the suspended ceiling will be studied in this project. These components will be added to the already established floor structure from the previous project.
- Any calculation aids or tools will not be developed. That will be left for future research.

- The amplitude of the mode shapes received from simulations, as well as damping of the different floor compositions studied, are not investigated. Only the locations of the natural frequencies are focused in this project.

- Fasteners such as screws or nails that join different floor components were not modelled in the FEM-model.

2. THEORY

This chapter describes acoustics in general and acoustic behaviour in structures.

2.1. Acoustics in wooden buildings

Wooden buildings fall into the category as light-weight buildings, and when comparing wooden constructions with heavy-weight constructions like concrete, the acoustic- and vibration properties differ. The most common acoustic problem for light-weight buildings is sound and vibration in low frequencies. This problem is most prominent with impact induced excitation like footsteps (Forssén et al., 2008).

Flanking transmission of sound and vibration is another challenge for wooden constructions. An example of when this phenomenon is induced is when vibrations of a floor is transmitted to the load-bearing walls, resulting in sound radiation from the walls to adjacent spaces (Forssén et al., 2008).

Heavy constructions rarely experience the same problems regarding low frequencies as light constructions. The reason is that the weight (mass per unit area) is an important parameter for sound insulation properties, especially for lower frequencies, in general 20-200 Hz (Forssén et al., 2008).

2.2. Sound and vibration propagation

Sound and vibration can be described as oscillations in an elastic medium and is caused by disturbances in the equilibrium of the medium. It is required that the medium has a mass and is elastic for the oscillations to occur. The disturbance will cause the particles in the medium to oscillate around its equilibrium and the elastic forces will try to bring back the particles to its original position. The oscillating particles will affect the adjacent particles, spread the disturbance and cause a wave propagation. When the oscillations can be perceived with hearing, it is called sound (Nilsson et al., 2005). The term vibration is more commonly used when describing oscillations in mechanical systems (Vigran, T.E, 2008).

Sound and vibration consist of multiple different waves with varying wavelengths. Wavelength is denoted with λ and is the distance between two points with the same phase, see figure 2. The time for a wave to complete a full oscillation, a period, is called period time, T. Depending on how fast a wave oscillate, the wave will have a specific frequency f (number of periods per second), see equation 1.

$$f = \frac{1}{T} \text{ [Hz]} \tag{1}$$

Low frequencies have longer wavelengths than higher frequencies. The amplitude of the waves determines the power of the sound (Nilsson et al., 2005).

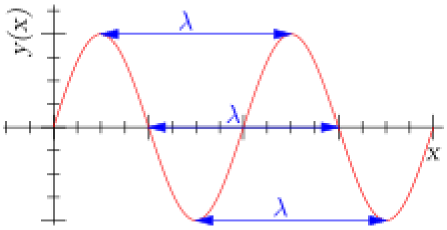


Figure 2. The wavelength of a soundwave (Wikipedia, n.d).

2.3. Excitation and response of structures

Sound and vibrations are dynamic phenomena that needs to be considered when designing buildings. When a construction is excited by an impact or soundwave, the construction will be set into motion and then radiate sound to adjacent space. The sound isolation and vibration properties of a construction are determined by that constructions ability to withstand the oscillations caused by excitation and not letting that motion transfer as sound (Nilsson et al., 2005).

An important term regarding oscillations is natural frequency. All mechanical systems have frequencies at which the system will oscillate with a higher amplitude than at other frequencies. These selected frequencies are the natural frequencies. If a construction is excited by a periodic dynamic load and the frequency of said load coincides with the natural frequency of the construction, resonance occurs, and the oscillations can be severely strengthened. Because of this it is necessary to design the building elements so that resonance can be avoided. The natural frequency of a construction is in principle decided by its mass and stiffness (Heyden et al., 2008).

The relationship between input and output is of great interest when studying the response of a system to dynamic load. An example could be when dynamic forces (input) cause excitation of a structure, which then radiates noise to the adjacent room (output). The relationship between the input and output variables is called transfer functions and is defined as the ratio of the output of a system to the input, see figure 3. If it is assumed that the physical system is linear (the principle of superposition is valid) and the physical parameters are constant (system properties are independent of time), the response of a system for any type of excitation can be calculated when the transfer function is known (Vigran, T.E, 2008).

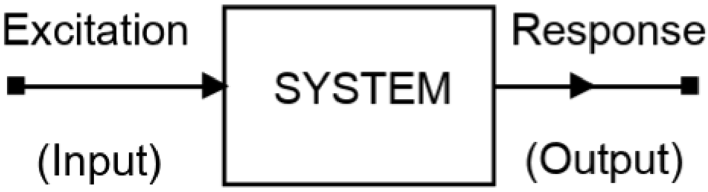


Figure 3. A system having one input and output (Vigran, T.E, 2008).

Some important transfer functions in acoustics and vibration are *mechanical impedance* and *mechanical mobility*. Mechanical impedance is a measure describing a structures resistance to motion when subjected to force. It measures the forces when velocities (motion) are imposed on a system. The transfer function for mechanical impedance is the ratio of force F, applied to the system, and the resulting velocity v, see equation 2 (Vigran, T.E, 2008).

$$Z_{mech} = \frac{F}{v} \left[\frac{\mathrm{N} \cdot \mathrm{s}}{\mathrm{m}}\right] \tag{2}$$

It is important to note that impedance is not the transfer function when the force is interpreted as the input (excitation), but when the displacement or motion is the input. When forces are the input to the system, the transfer function is mechanical mobility. Mechanical mobility is the inverse to mechanical impedance and measures the velocities of a system when subjected to forces. The quantity representing mechanical mobility is defined according to equation 3 (Vigran, T.E, 2008).

$$M_{mech} = \frac{v}{F} \left[\frac{m}{\mathrm{N} \cdot \mathrm{s}}\right] \quad (3)$$

Transfer functions can be illustrated by a theoretical model called the mass-spring-damper system, see figure 4. The vibrational response of structures can be derived by using this model. The model consists of masses, springs and dampers, and the system can be of single degree of freedom or multiple degrees of freedom (Vigran, T.E, 2008). The degree of freedom defines the structures movement. For a system with a single degree of freedom, the movement of the mass will only occur in one direction. In the case of a multiple degree of freedom systems, the motion of the structure is defined by two or more coordinates. A single degree of freedom model can often be used as an approximation when describing a construction. When more advanced analyzes are required, for example a structure that consists of several masses, a multiple degree of freedom model should be made (Heyden et al., 2008).

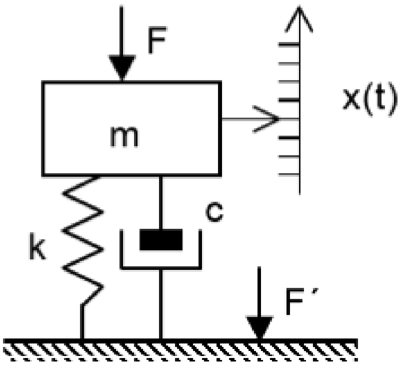


Figure 4. A simple mass-spring-damper system with a single degree of freedom. F is the outside force, x is the displacement, C is the damper. K is the spring and F' is the transmitted force (Vigran, T.E, 2008).

2.4. Vibrations in structures

Wave propagation in structures come in different types; longitudinal waves, shear waves and bending waves. Figure 5 illustrates the different wave types in structures. The solid lines in the figure represent the structure in rest and the dotted lines represent the deformation of the structure, both in the direction of wave propagation and laterally (Vigran, T.E, 2008).

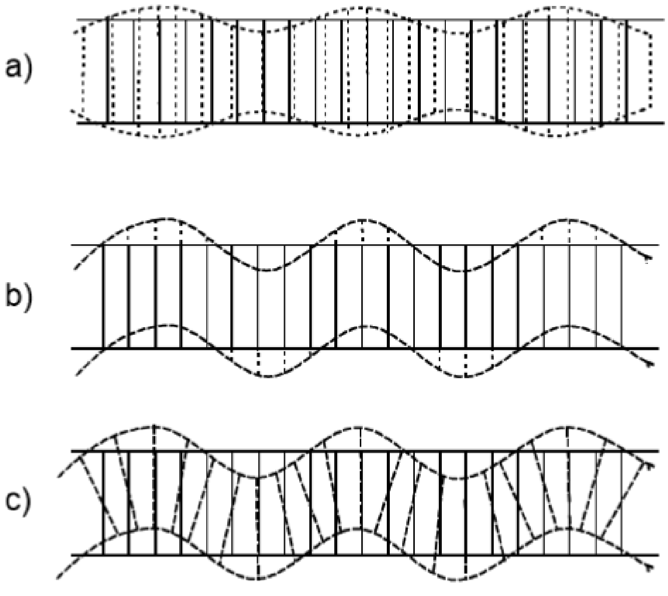


Figure 5. Wave types in structures. a) Longitudinal wave. b) Shear wave. c) Bending wave (Vigran, T.E, 2008).

Longitudinal waves cause displacements normal to the direction of wave propagation and the Poisson effect expands and contracts the element laterally. Shear waves makes the particles move in the direction normal to the wave propagation and causes shear deformations on the structure (Vigran, T.E, 2008). Bending waves are most severe when it comes to sound radiation from vibrating structures. Like shear waves, bending waves move the particles in the direction normal to the wave propagation, while deforming the element transversely. Bending waves also causes the structure to rotate about the neutral axis, making bending waves more complicated than the two aforementioned wave types. Because of bending waves impact on sound transmission, it is of greatest interest when implementing noise control of structures (Hambric, 2006).

2.5. Designing with regard to natural frequencies

The problem with natural frequencies is that if it coincides with the excitation frequency of an excitation source, the response of the structure will be amplified and noise and vibration will transmit very easily. The structure must therefore be designed so that coincidence between excitation and natural frequencies can be avoided, unless sufficient damping can be ensured to reduce the amplification of the response.

Footsteps, or impact sound, is the most problematic noise source for wooden floors as it occurs frequently and is perceived as annoying. How a floor will respond to excitation from footsteps depends on where in the frequency spectrum the floor has its first natural frequency. Floors with a first natural frequency below 8 hertz are more exposed to the low frequency parts of the footsteps which may cause a resonant response of the construction. Within a spectrum of about 8 to 40 hertz, the floor is more responsive to the impulsive parts of the footsteps which origin from impacts when the heel hits the floor. Something to also consider is the natural frequencies of the human body which is within the range of 4 to 8 hertz. Excitation of these frequencies can cause resonance with the human organs which can cause discomfort. It is therefore preferable to have the natural frequencies of the structure outside of that frequency range (Swedish wood, 2016).

In addition to the lowest natural frequency, the spacing between the initial natural frequencies can cause contribution to the discomfort of the occupants (Swedish wood, 2016). Clustering of the natural frequencies can cause increased amplitude of the structure’s vibration response. The spacing between a structure’s natural frequencies is primarily governed by the ratio of stiffnesses in two orthogonal directions, where a greater difference in stiffness leads to more clustered natural frequencies. For strongly orthotropic structures, like joisted timber floors, this is a normal phenomenon due to high stiffness along the joists, but lesser stiffness across the joists (Glisovic et al., 2010). Construction details like material properties and thickness of floorboards, fastening of floorboards, joist spacing, support condition and bridging, can increase stiffness in the direction perpendicular to the joists and therefor result in a larger separation between the structure’s natural frequencies (Swedish wood, 2016).

3. MATERIAL AND METHOD

All FEM-work including modelling and simulations were conducted in Solidworks. The model presented in figure 1 was used as base and additional components were added to said model. These components were the noggins and the suspended ceiling.

3.1. Development of FEM-model

The noggins and ceiling were built to the model according to instructions from Masonite beams. For the specific floor structure studied in this project, two rows of noggins are used. A plank of 22 x 70 mm is attached to the noggin rows. Figure 6 shows the structure of the noggins in the floor.

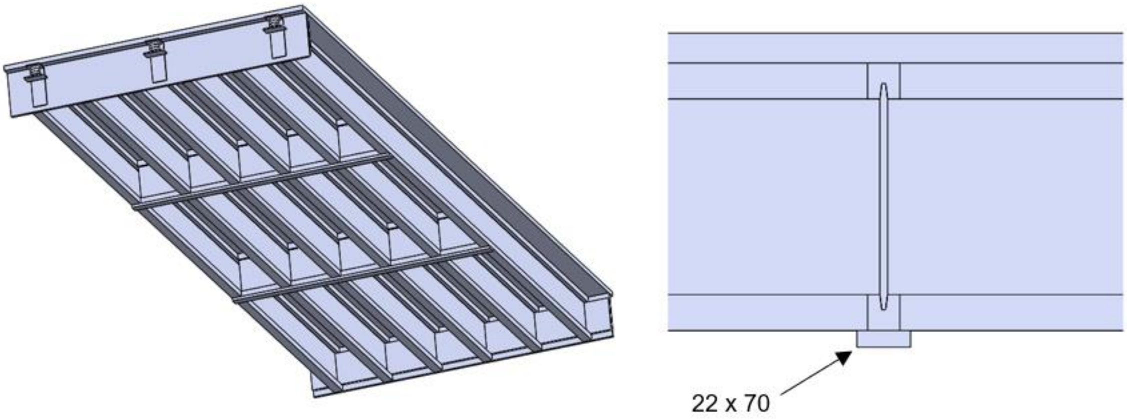


Figure 6. Structure of noggins in the floor.

The ceiling is suspended with hangers that uses springs. Two ceiling hangers are attached between every noggin row, and on four beams, making a total of 24 hangers. Planks with dimensions 45 x 70 mm are hung from the hangers, and on to these, planks of 34 x 70 mm are attached. The 34 x 70 mm planks are suspended 16 mm from the I-beams. The ceiling itself consists of two plasterboards, 12,5 + 15 mm. The structure of the suspended ceiling is shown in figure 7.

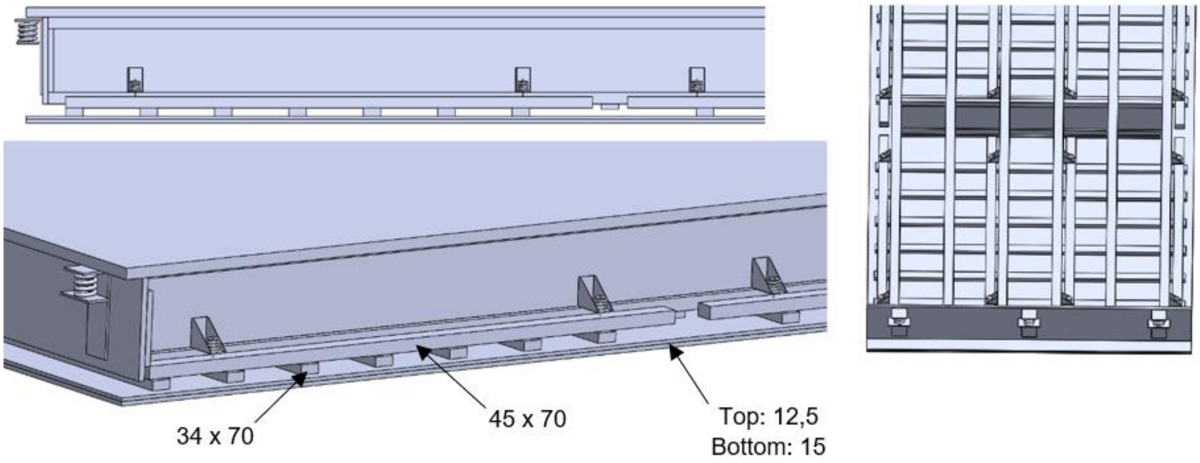


Figure 7. Structure of the suspended ceiling.

The final model is presented in figure 8.

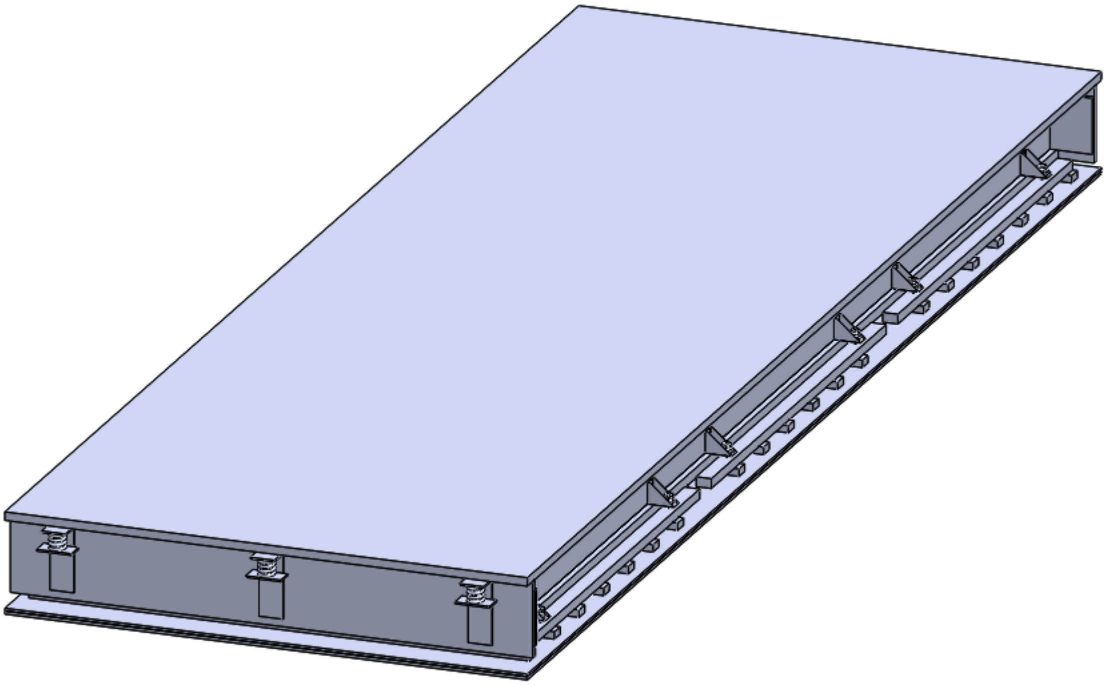


Figure 8. Final model of the floor with noggins and suspended ceiling.

3.2. Implementation of simulations

A frequency study was conducted on the model. The general simulations settings were set to calculate the frequencies for the first five modes. Multiple combinations of stiff and flexible springs, and different compositions, in the model were tested during the analysis. “Spring connectors” and “rigid connectors” were used to simulate the effect of flexible and stiff springs. These connectors were set between the parallel faces in the ceiling hangers where the springs are supposed to be located. When “spring connectors” were used, the ceiling hangers were fixed laterally to avoid excessive deformation. Figure 9 shows the placement of fixtures and connectors on the ceiling hangers.

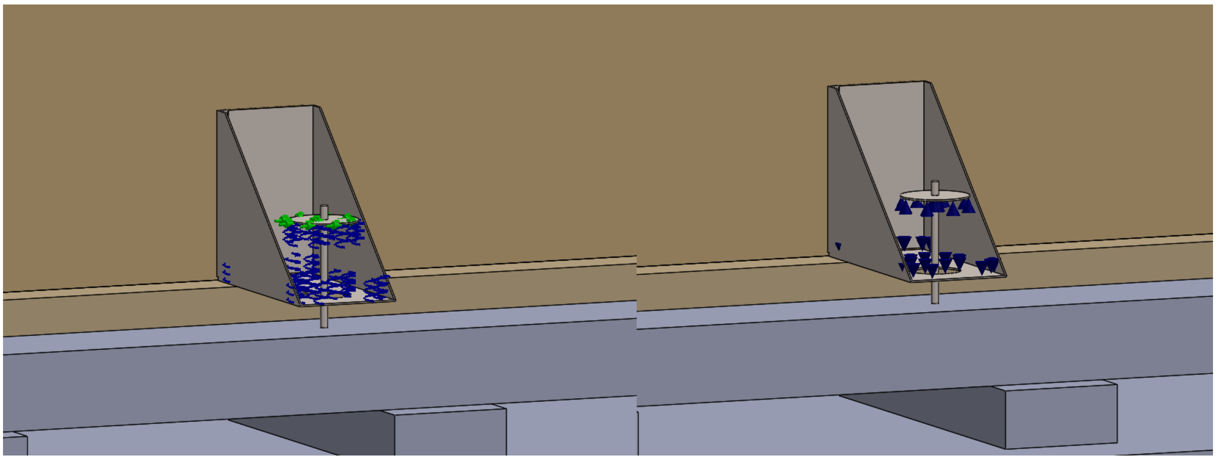


Figure 9. Fixtures and connectors on the ceiling hangers. Green color indicate fixtures and blue color indicate connector.

The material parameters that were applied to the noggins and the suspended ceiling are presented in table 3.

Table 3. Material parameters used for the noggins and the suspended ceiling in the FEM-model.

Part	Material data
12,5 GtA plasterboard	Elastic modulus = 2500 MPa Density = 720 kg/m^3 Poisson's ratio = 0,29
15 GtF plasterboard	Elastic modulus = 2500 MPa Density = 847 kg/m^3 Poisson's ratio = 0,29
34 x 70 planks 45 x 70 planks Noggin flange	Elastic modulus = 8000 MPa Density = 380 kg/m^3 Poisson's ratio = 0,29
Noggin web	Elastic modulus = 3500 MPa Density = 650 kg/m^3 Poisson's ratio = 0,29
Ceiling hangers	Elastic modulus = 210 000 MPa Density = 7700 kg/m^3 Poisson's ratio = 0,28
Springs (spring connectors)	Stiffness = 661357015 (N/m)/m^2

The settings used for the simulations of the floor with only the noggins included in the analysis, are shown in table 4. A standard mesh was used and with the level of detail set to max.

Table 4. Setting used for the simulations of the floor with only the noggins added.

Analysis type	Frequency
Mesh type	Solid Mesh
Number of modes	10
Solver Type	Direct sparse solver
Soft Spring	Off
Improve accuracy for contacting surfaces with incompatible mesh	On
Mesher Used	Standard mesh
Automatic Transition	Off
Include Mesh Auto Loops	On
Jacobian points for High quality mesh	16 points
Element size	93,916 mm
Tolerance	4,6958 mm
Mesh quality	High
Total nodes	123714
Total elements	60501
Maximum Aspect Ratio	46,148
Percentage of elements with Aspect Ratio < 3	16,1
Percentage of elements with Aspect Ratio > 10	18,7
Percentage of distorted elements	0
Number of distorted elements	0
Remesh failed parts with incompatible mesh	Off

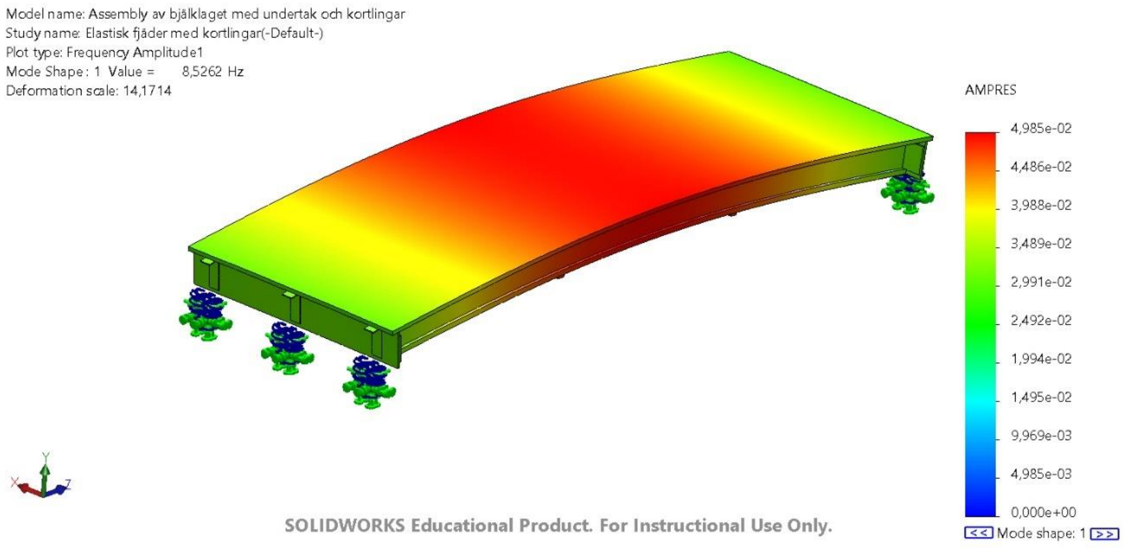
The settings used for the simulations of the floor when the suspended ceiling was included in the analysis, are shown in table 5. A curvature-based mesh was used and with the level of detail set to max.

Table 5. Setting used for the simulations of the floor when the suspended ceiling were included in the analysis.

Analysis type	Frequency
Mesh type	Solid Mesh
Number of modes	10
Solver Type	Direct sparse solver
Soft Spring	Off
Improve accuracy for contacting surfaces with incompatible mesh	On
Mesher Used	Curvature-based mesh
Jacobian points for High quality mesh	16 points
Max Element Size	266,032 mm
Min Element Size	53,2064 mm
Mesh quality	High
Total nodes	74903
Total elements	34557
Maximum Aspect Ratio	253,89
Percentage of elements with Aspect Ratio < 3	6,22
Percentage of elements with Aspect Ratio > 10	61,1
Percentage of distorted elements	0
Number of distorted elements	0
Remesh failed parts with incompatible mesh	On

4. RESULTS AND DISCUSSION

The results of the simulations in Solidworks are presented as the first five natural frequencies. The natural frequencies are given in radians per second, as well as in hertz. The time for the structure to complete a period is also presented. Deformation plots were received for each mode shape after the simulations. Figure 10 shows the mode shape for the first natural frequency for the flexibly supported floor with noggins. Since the amplitude of the mode shapes were not studied in this project, the deformation plots are not analyzed to any larger degree here. All deformation plots from the simulations are presented in Appendix A.



Model name: Assembly av bjälklaget med undertak och kortlingar
Study name: Elastisk fjäder med kortlingar(-Default-)
Plot type: Frequency Amplitude1
Mode Shape : 1 Value = 8,5262 Hz
Deformation scale: 14,1714

Figure 10. Mode shape for the first natural frequency for the flexibly supported floor with noggins.

4.1. Effect of noggins

The effect of noggins on the floor's natural frequencies was studied, with the results in table 1 and 2 used as references. With the addition of noggins to the floor the stiffness of the structure increases, especially in the direction across the beams. These changed floor properties should theoretically increase the natural frequencies, as well as increase frequency spacing. It can be seen in table 6 and 7 that the noggins have very little influence on the first few and lowest frequencies, first two for the rigidly supported floor and first four for the flexibly supported floor. When investigating the changes to the frequencies in table 1 and 2 after adding the noggins, for the rigidly supported floor seen in table 6, the first two frequencies remain almost unchanged, decreasing with less than 2 %. However, the three following frequencies increases significantly with over 40 % each. The frequency spacing also sees a slight increase, with the exception between the 3rd and 4th frequencies that went from an 11 % increase between 3rd and 4th frequencies to around 1 % increase. The spacing between the 2nd and 3rd frequency increases from 40 % to 67 %, and the distance between the 4th and 5th frequency increases from around 1 % to 13 %.

Table 6. The first five natural frequencies of the rigidly supported floor with noggins.

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Milliseconds)
1	103,0	16,4	61,0
2	112,6	17,9	55,8
3	348,4	55,4	18,0
4	351,9	56,0	17,9
5	406,1	64,6	15,5

The first five natural frequencies for the flexibly supported floor with noggins is shown in table 7. It can be seen that the noggins has little influence on the first four natural frequencies which remains almost unchanged, seeing only changes below 2 %. Only the 5th frequency show a significant change with a 12 % increase. The frequency spacing is in principal unchanged, except between the 4th and 5th frequencies which went from around 35 % difference to over 40 %.

Table 7. The first five natural frequencies of the flexibly supported floor with noggins.

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Milliseconds)
1	53,6	8,5	117,3
2	59,5	9,5	105,6
3	97,4	15,5	64,5
4	122,1	19,4	51,4
5	212,7	33,8	29,5

It seems that the noggins only shows significant influence on the natural frequencies from around 30 Hz and above, something that was detected among all results. The very large wavelengths of the lower frequencies, which causes mode shapes that makes the whole structure deform very uniformly (see figure 10), could be the reason to why the noggins show neglectable influence on the lower frequencies. Another reason could be that the initial mode shapes do not deform in the direction which the noggins provide most stiffness in (crosswise to the beams). The flexibly supported floor is less stiff than the rigidly supported floor which pushes down the natural frequencies and makes the noggins less effective.

4.2. Effect of the suspended ceiling

The effect of both a rigidly and flexibly suspended ceiling was tested for the floor with both rigid and flexible supports. The natural frequencies of the floor with a ceiling were compared to the reference frequencies of the floor without a ceiling presented in table 1 and 2. The first five natural frequencies for the rigidly supported floor with a flexibly suspended ceiling is shown in table 8. A very substantial mass is added to the structure with the suspended ceiling, and more mass usually means lower natural frequencies. Since the ceiling is also flexibly suspended, the ceiling is disconnected from the main structure and should not contribute much to the stiffness of the floor. The case should be the opposite, that the floor becomes more flexible with the flexibly suspended ceiling. The increase of mass and flexibility to the floor could explain the decreased natural frequencies in table 8 compared to the reference frequencies in table 1. The first two frequencies decrease with over 20 %, and the following three decrease with over 40 %. The added flexible ceiling also caused more clustering of the frequencies, most notably between the 2nd and 3rd frequency which went from a difference of 40 % to 20 %.

Table 8. The first five natural frequencies of the rigidly supported floor with the suspended ceiling.

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Milliseconds)
1	77,9	12,4	80,6
2	88,0	14,0	71,4
3	110,5	17,6	56,8
4	111,9	17,8	56,2
5	114,8	18,3	54,7

The flexibly suspended ceiling had similar effect on the flexibly supported floor, see table 9. The first four frequencies decreased by around 20-30 %, while the last frequency decreased with around 40 %. Modal spacing also decreased between all frequencies.

Table 9. The first five natural frequencies of the flexibly supported floor with the suspended ceiling.

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Milliseconds)
1	39,6	6,3	158,8
2	44,2	7,0	142,2
3	71,5	11,4	87,9
4	90,5	14,4	69,4
5	110,9	17,6	56,7

In the case of a rigidly suspended ceiling, in addition to the increased mass, the stiffness of the structure should also increase due to the ceiling being cohesive with the floor. It is seen in table 10 that for the rigidly supported floor, the frequencies decreased with between 10-20 % for the first two frequencies, the 3rd and 4th frequencies decreased with less than 5 %, and the 5th increased with around 4 %. The separation between frequencies remains relatively unchanged.

Table 10. The first five natural frequencies of the rigidly supported floor with a rigidly suspended ceiling.

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Milliseconds)
1	87,2	13,9	72,1
2	101,2	16,1	62,1
3	184,7	29,4	34,0
4	203,0	32,3	31,0
5	223,7	35,6	28,1

Table 11 shows the effect of the rigidly suspended floor on the flexibly supported floor. The effect is very similar as seen in table 10, with modal separation being fairly unchanged and with an overall decrease of the frequencies, most likely explained by the increased mass. The first three frequencies decreased with over 20 % and the following frequencies with around 10 %.

Table 11. The first five natural frequencies of the flexibly supported floor with a rigidly suspended ceiling.

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Milliseconds)
1	40,8	6,5	154,0
2	43,9	7,0	143,1
3	74,2	11,8	84,7
4	106,9	17,0	58,8
5	170,0	27,1	37,0

The changes in the frequencies with a rigidly suspended ceiling is not as notable as for the floors with a flexibly suspended ceiling, who sees much larger decreases in some frequencies.

This is probably explained by the higher stiffness of the structures with rigid contact between floor and ceiling.

When looking at the results of the influence from the ceilings it can be seen that when the floor is flexibly supported, the spring stiffness in the ceiling, rigidly or flexibly suspended, has almost no effect on the first three natural frequencies, seeing only changes of around 3 %. The spring stiffness in the ceiling shows more impact on the rigidly supported floor, though the pattern is similar that the spring stiffness have more influence higher up in the frequency spectrum. This indicates that in order to have most effective impact on the very low natural frequencies, especially for the flexibly supported floor, the spring stiffness in the supports must be changed.

4.3. Effect of noggins and the suspended ceiling

The effect of having both noggins and a suspended ceiling added to the floor was studied. The changes to the floor’s natural frequencies presented in table 8-11 in section 4.2 after adding the noggins were noted here. As mentioned in section 4.1, the noggins only seemed to have a significant effect from around 30 Hz and above. This trend can be seen in this section´s results as well. The rigidly supported floor with a flexibly suspended ceiling has low natural frequencies, all below 30 Hz. With the addition of noggins, the frequencies only changed overall with less than 4 % compared to the floor with just the ceiling and no noggins, see table 12.

Table 12. The first five natural frequencies of the rigidly supported floor with noggins and the suspended ceiling.

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Milliseconds)
1	80,6	12,8	77,9
2	91,3	14,5	68,8
3	113,1	18	55,6
4	114,0	18,1	55,1
5	116,2	18,5	54,1

The noggins had insignificant effect on the flexibly supported floor with a flexibly suspended ceiling, see table 13. When comparing with the floor with a ceiling but no noggins, there were only changes below 4 %, the 1st and 3rd frequencies were unchanged. The same explanation could be used here as above, that the natural frequencies are too low for the noggins to show any significant influence.

Table 13. The first five natural frequencies of the flexibly supported floor with noggins and the suspended ceiling.

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Milliseconds)
1	39,6	6,3	158,6
2	44,3	7,1	141,8
3	71,9	11,4	87,4
4	93,9	14,9	66,9
5	113,47	18,1	55,4

For the rigidly supported floor with a rigidly suspended ceiling the noggins show an effect, see table 14. The first two frequencies changed with less than 2 %, but the following frequencies, which were around 30 Hz and above, changed more significantly. The last three frequencies increased with 7-16 %.

Table 14. The first five natural frequencies of the rigidly supported floor with noggins and a rigidly suspended ceiling.

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Milliseconds)
1	88,0	14,0	71,4
2	103,1	16,4	61,0
3	220,2	35,0	28,5
4	236,3	37,6	26,6
5	240,4	38,3	26,1

The noggins showed little to no effect on the flexibly supported floor with a rigidly suspended ceiling, see table 15. This was due to the lower natural frequencies of the flexibly supported floor. There were no changes larger than 4 %, the first three frequencies were unchanged.

Table 15. The first five natural frequencies of the flexibly supported floor with noggins and a rigidly suspended ceiling.

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Milliseconds)
1	40,7	6,5	154,6
2	43,9	7,0	143,2
3	74,2	11,8	84,7
4	110,6	17,6	56,8
5	172,8	27,5	36,4

Something that was noted in the results is that when the floor is more flexible, like with flexible springs in the supports, the first five natural frequencies became so low that the noggins show very little impact. While the noggins may not show any significant influence on the first five natural frequencies, they are surely important higher up in the frequency spectrum which is not shown in these results.

4.4. Tuned floor for footstep excitation

The floor was tuned with regard to footstep excitation. The aim was to receive a fundamental frequency above 8 Hz and have as high frequency separation as possible. Based on the results in previous subsections, the spring stiffness in the supports must be increased in order to receive a higher fundamental frequency. In order to influence the higher natural frequencies, it is effective to change the spring stiffness in the ceiling, increasing it will give higher natural frequencies of the subsequent modes. If the natural frequencies are high enough, the noggins could further increase the frequencies and possibly give larger frequency separation. The influence of number, or spacing, of noggins were not investigated because alteration of the noggin montage would complicate the montage of the suspended ceiling due to very strict montage directions.

It was tested to increase the spring stiffness in both the supports and the ceiling, and also keeping the noggins, see table 16. To receive a fundamental frequency above 8 Hz, the spring stiffness in the supports had to be increased three times its original stiffness. The spring stiffness in the ceiling was also increased three times, which increased the upper modes. Compared to the floor with its original spring stiffness in both supports and ceiling, the first two and 4th frequencies increased with about 40 %, the 3rd increased with about 60 %, and the 5th increased with almost 30 %. Frequency separation was unchanged between the first two frequencies, it increased between the 2nd and 3rd frequency with around 10 %, and it decreased with around 10 % between the 3rd and 4th frequency, and the 4th and 5th frequency.

Table 16. The first five natural frequencies of the flexibly supported floor with noggins and the suspended ceiling, but with 3 times increased spring stiffness in all springs.

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Milliseconds)
1	54,6	8,7	115,1
2	62,1	9,9	101,3
3	115,8	18,4	54,2
4	132,8	21,1	47,3
5	144,4	23,0	43,5

It was checked to see the noggins' effect on the floor with increased spring stiffness, see table 17. The effect of noggins is insignificant in this case with less than 3 % change overall.

Table 17. The first five natural frequencies of the flexibly supported floor with the suspended ceiling, but with 3 times increased spring stiffness in floor hangers and without noggins.

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Milliseconds)
1	54,2	8,6	115,9
2	61,5	9,8	102,2
3	114,4	18,2	54,9
4	129,5	20,6	48,5
5	143,8	22,9	43,7

More frequency spacing than in table 16 would be preferable, and to achieve this the upper modes would have to increase. It was tested to make the ceiling suspension rigid, see table 18. This change further increased the frequencies, most notably the 4th and 5th frequencies which increased with 10 % and 30 % respectively. The frequency separation also improved. Spacing between the first three frequencies remained in principle unchanged, but between the 3rd and 4th frequencies, and 4th and 5th frequencies, spacing increased with 6 % and 19 % respectively.

Table 18. The first five natural frequencies of the flexibly supported floor with noggins and a rigidly suspended ceiling, but with 3 times increased spring stiffness in floor hangers.

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Milliseconds)
1	56,8	9,0	110,6
2	63,5	10,1	98,9
3	120,3	19,1	52,2
4	145,5	23,2	43,2
5	204,9	32,6	30,7

Table 19 presents the natural frequencies of the floor in table 18 but without noggins. The removal of the noggins affected only the 5th frequency, decreasing it with 10 %.

Table 19. The first five natural frequencies of the flexibly supported floor with a rigidly suspended ceiling, but with 3 times increased spring stiffness in floor hangers and without noggins.

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Milliseconds)
1	56,9	9,1	110,5
2	63,5	10,1	98,9
3	119,9	19,1	52,4
4	142,9	22,7	44,0
5	183,5	29,2	34,2

Just entirely based on the established tuning directions with footstep excitation and frequency separation, the results in table 18 would be the most optimal. However, with regard to sound insulation, having the flexible separation between floor and ceiling is very beneficial since it disconnects the two components, which in principle makes the whole floor a double construction. For that reason, it would be more preferable to have the flexible springs in the ceiling hangers even though the frequencies become more clustered. An important parameter that was not investigated in this project is the amplitude of the responses, which is important for the serviceability of the floor. If the amplitude is low for certain modes, it should not be as critical to have more clustered natural frequencies. It is also unclear how much separation it must be between adjacent frequencies to avoid increased amplitude of the vibration response.

5. CONCLUSIONS AND FUTURE WORK

Based on the results and the discussion, the following conclusions have been made:

- The noggins show less influence on the floor’s natural frequencies the more flexible the floor is. This was due to the noggins not having any influence when the natural frequencies were too low, which occurred when the floor was more flexible. A frequency of approximately 30 Hz was discovered as a threshold value at which the noggins start to show significant influence on the natural frequencies and made them increase, which is preferable. When the floor is flexibly supported the natural frequencies became too low (below 30 Hz) for the noggins to show any influence on the frequencies.

- The addition of the ceiling caused the natural frequencies of the floor to go down overall due to the substantial weight that was added to the whole structure. With flexible springs in the ceiling hangers, the reduction of the frequencies became more major, especially in the subsequent frequencies (3rd, 4th and 5th). Higher spring stiffness in the ceiling hangers improved frequency separation, partially due to it making the subsequent natural frequencies higher, and therefore also making the noggins show more influence and further increasing the natural frequencies.

- The stiffness of the springs in the structure was changed to partially receive a first natural frequency above 8 Hz to avoid low frequency disturbances from footsteps, and partially to receive as much frequency separation as possible. When the spring stiffness in the supports was increased, and the ceiling suspension was made rigid, a floor with a first natural frequency above 8 Hz and with the most frequency separation was received

5.1. Future work

This project continued the research regarding the acoustic performance for Masonite Beams’ developed floor. To date, the acoustic performance regarding natural frequencies has been studied for the floor in its “basic structure” with beams, floorboards and hangers. The effect on the floor´s acoustic performance when adding noggins and a suspended ceiling has also been studied. The amplitude of the floors’ responses in different modes has still not been investigated. This is an important parameter that should be studied in future work. The effect of different floor spans and floorboards thicknesses on the acoustic performance could also be investigated in future work. Lastly, how these different variables could be applied to a calculation tool for designing, requires work in the future.

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APPENDIX A

Figure A-1 shows the mode shapes for the rigidly supported floor with noggins. The parameter “AMPRES” defines the resultant amplitude of the deformation.

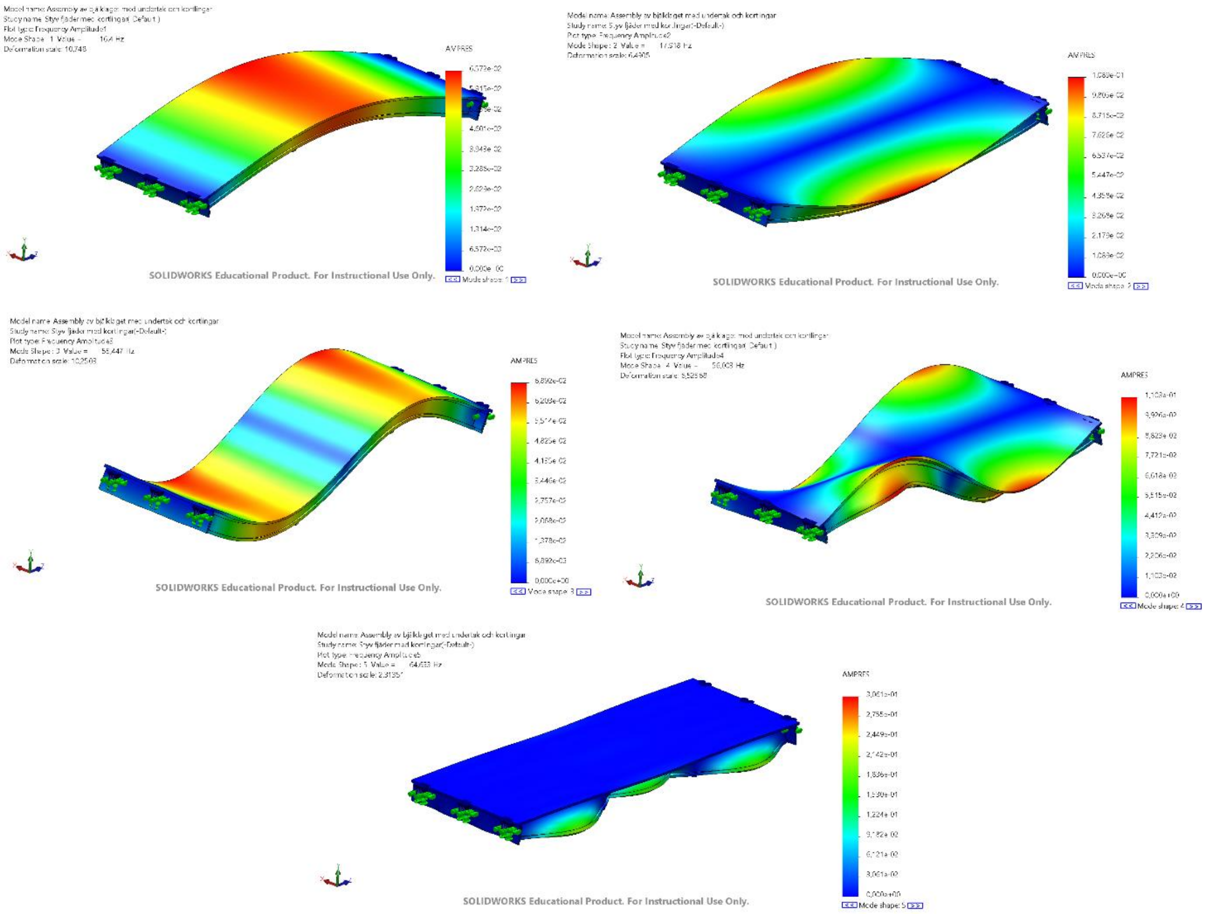

Figure A-1. Mode shapes for the rigidly supported floor with noggins.

Figure A-2 shows the mode shapes for the flexibly supported floor with noggins.

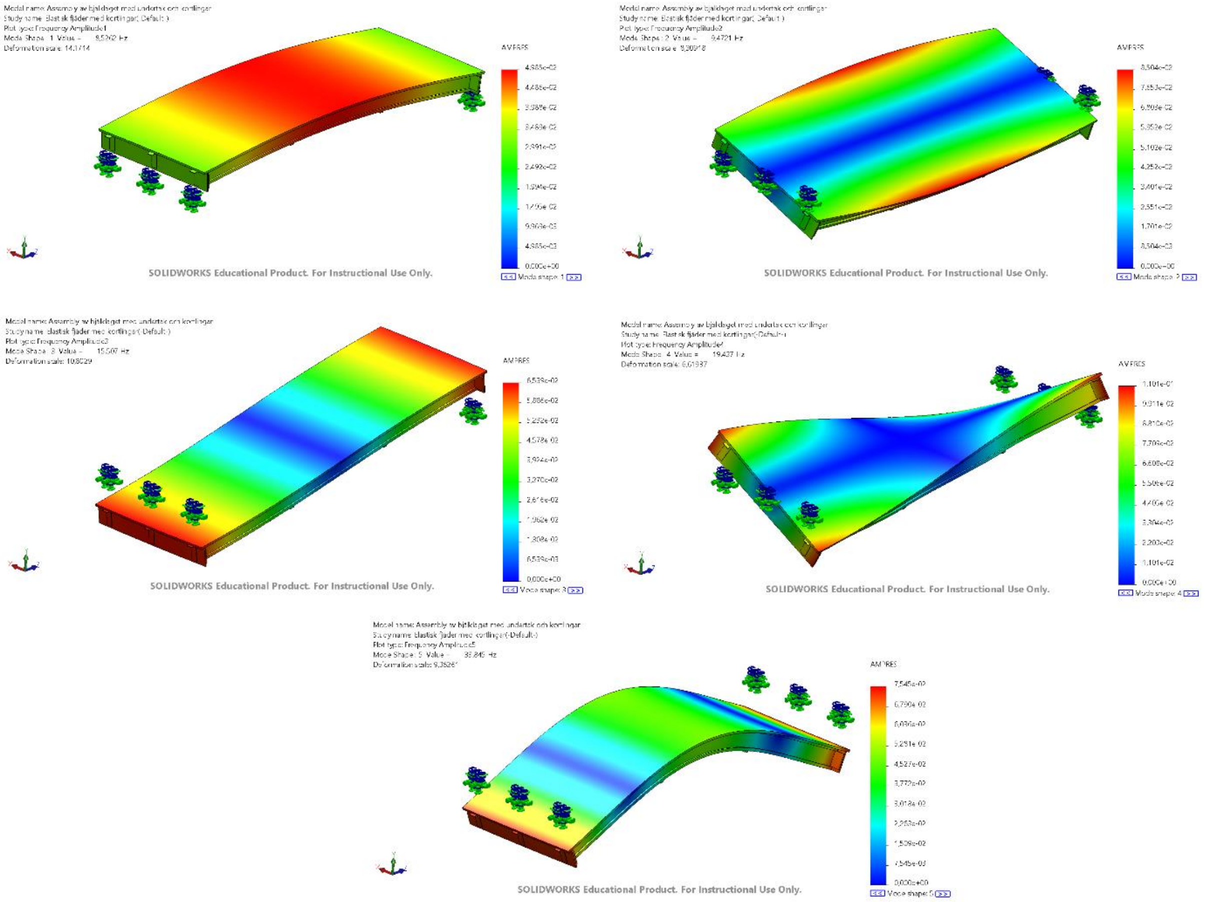

Figure A-2. Mode shapes for the flexibly supported floor with noggins.

Figure A-3 shows the mode shapes for the rigidly supported floor with a flexibly suspended ceiling.

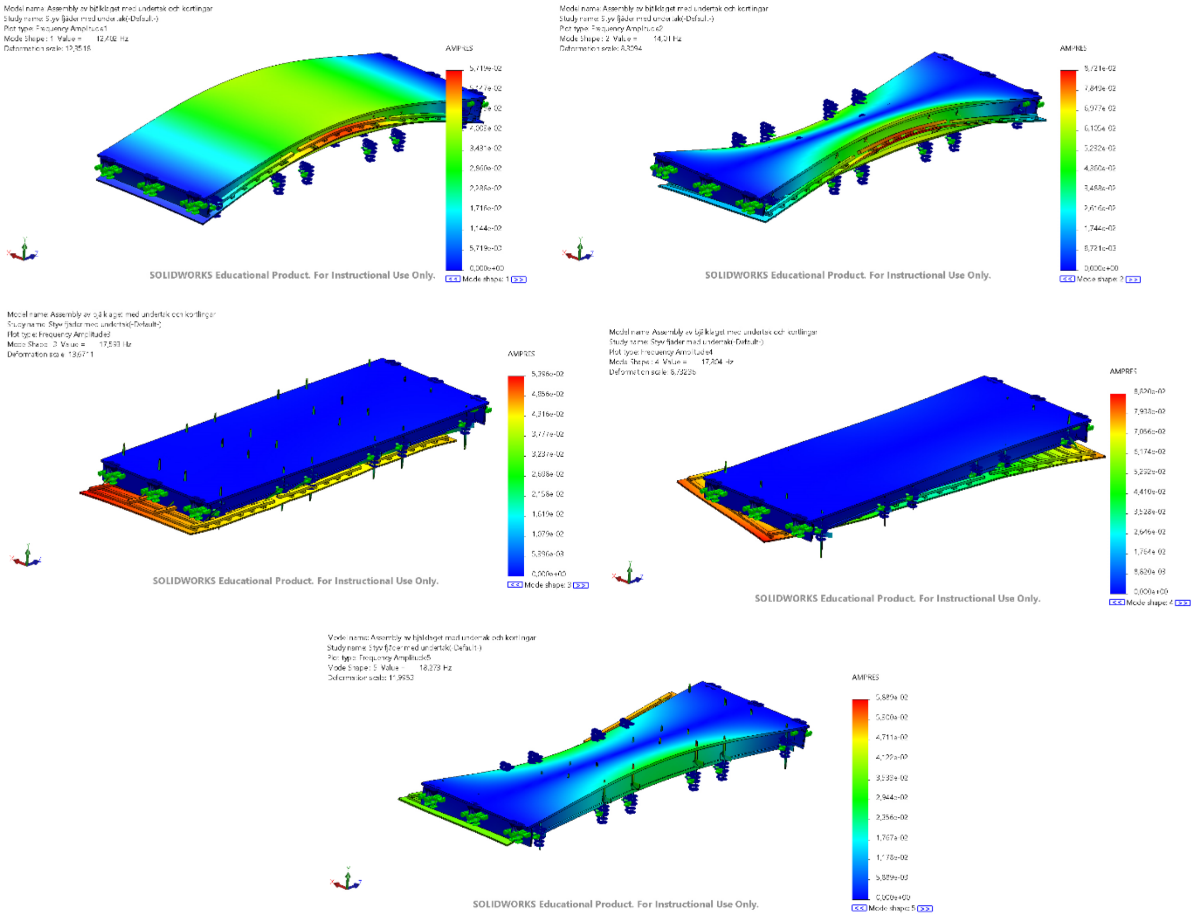

Figure A-3 Mode shapes for the rigidly supported floor with a flexibly suspended ceiling.

Figure A-4 shows the mode shapes for the flexibly supported floor with a flexibly suspended ceiling.

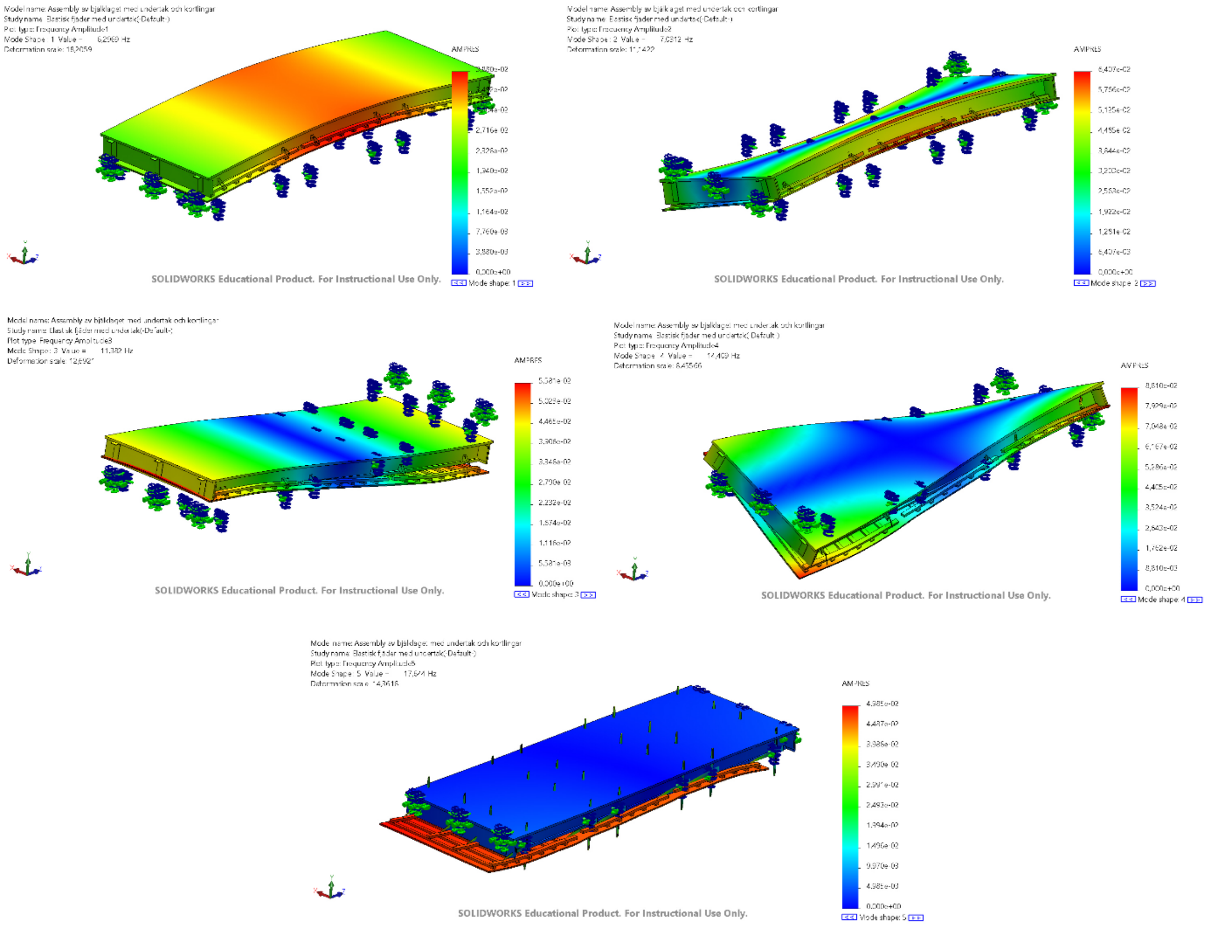

Figure A-4. Mode shapes for the flexibly supported floor with a flexibly suspended ceiling.

Figure A-5 shows the mode shapes for the rigidly supported floor with a rigidly suspended ceiling.

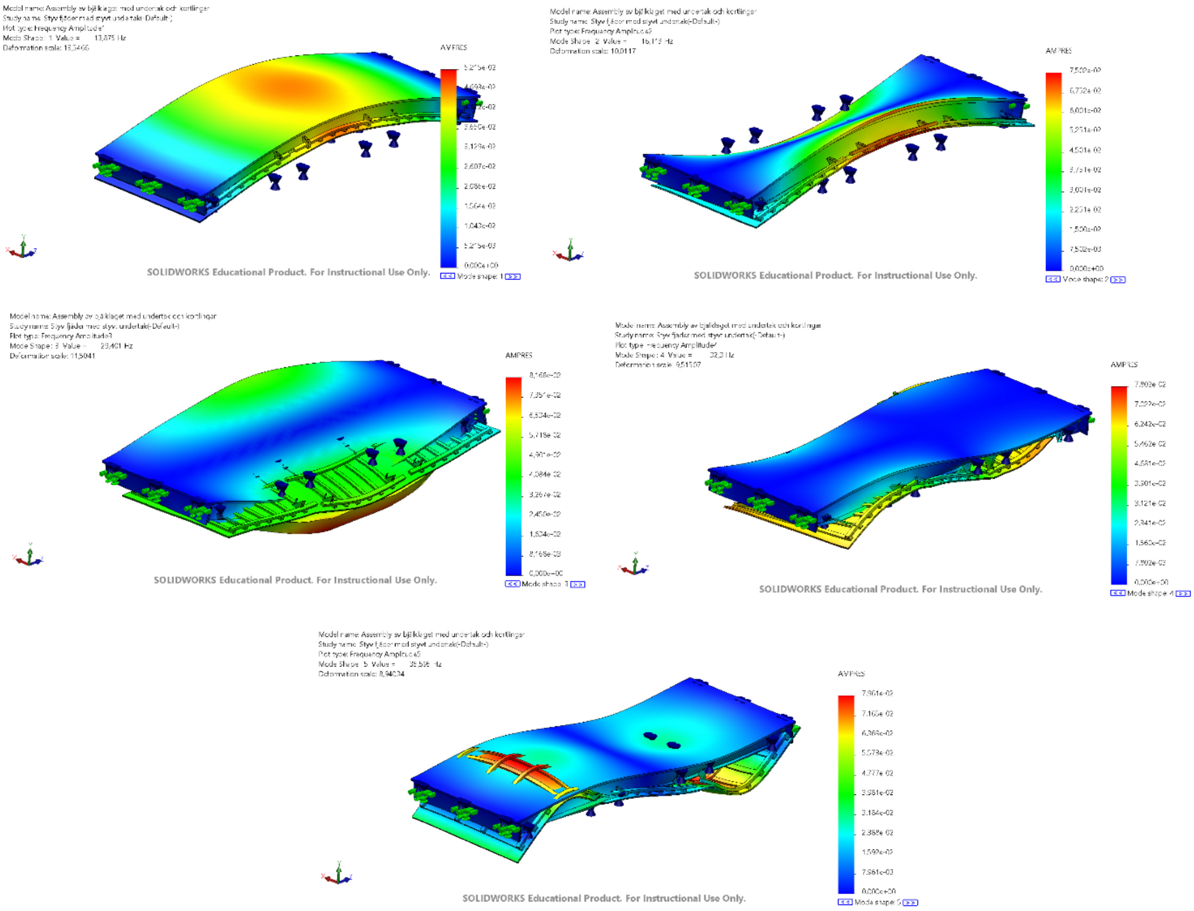

Figure A-5. Mode shapes for the rigidly supported floor with a rigidly suspended ceiling.

Figure A-6 shows the mode shapes for the flexibly supported floor with a rigidly suspended ceiling.

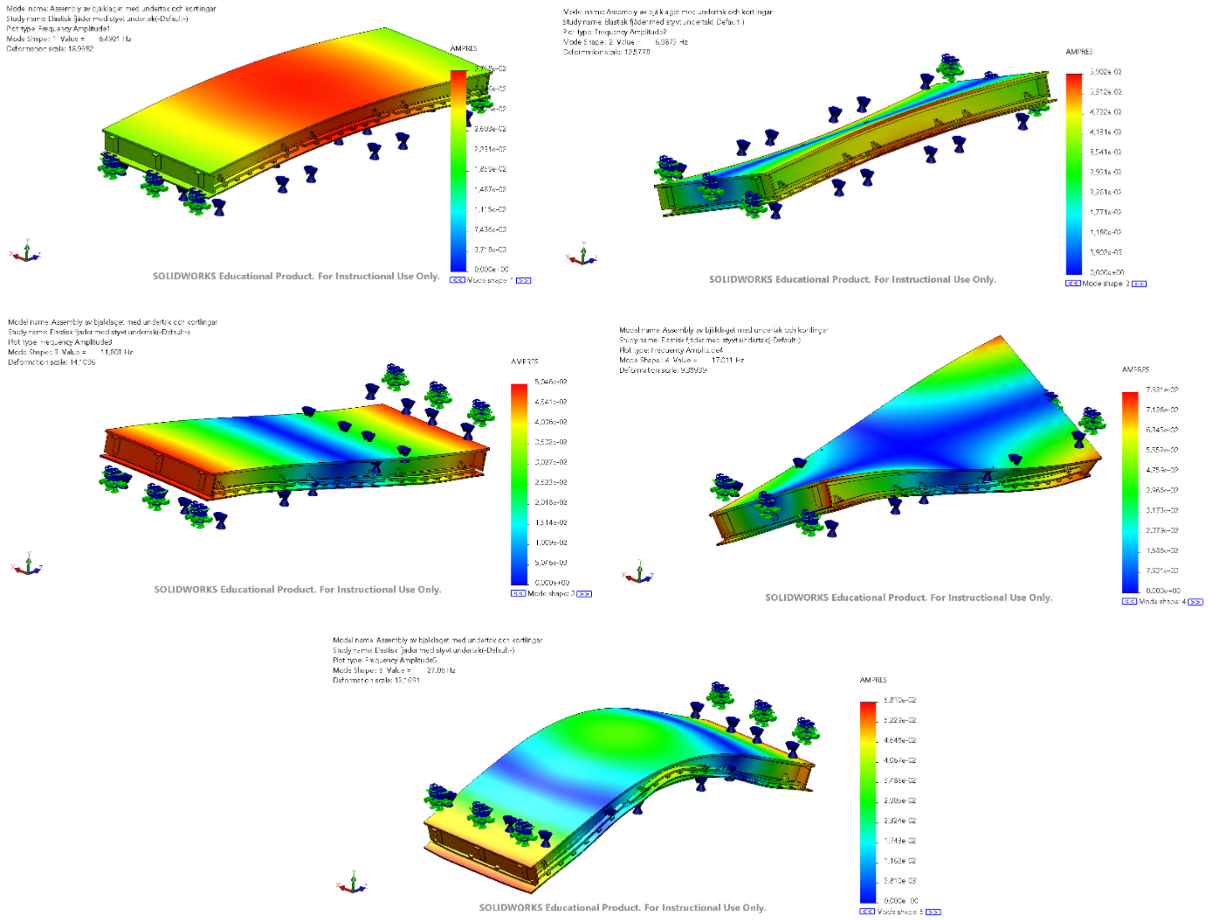

Figure A-6. Mode shapes for the flexibly supported floor with a rigidly suspended ceiling.

Figure A-7 shows the mode shapes for the rigidly supported floor with a flexibly suspended ceiling and noggins.

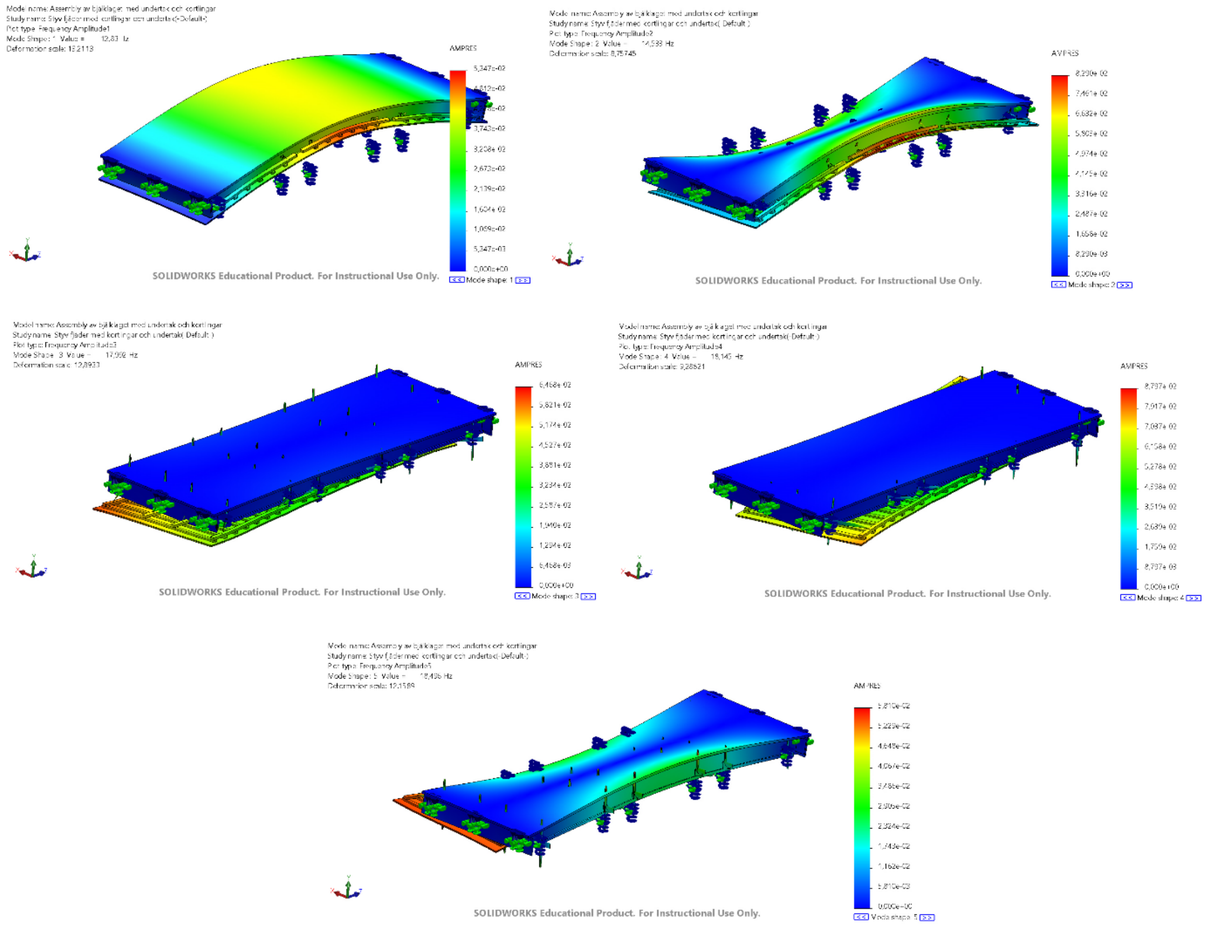

Figure A-7. Mode shapes for the rigidly supported floor with a flexibly suspended ceiling and noggins.

Figure A-8 shows the mode shapes for the flexibly supported floor with a flexibly suspended ceiling and noggins.

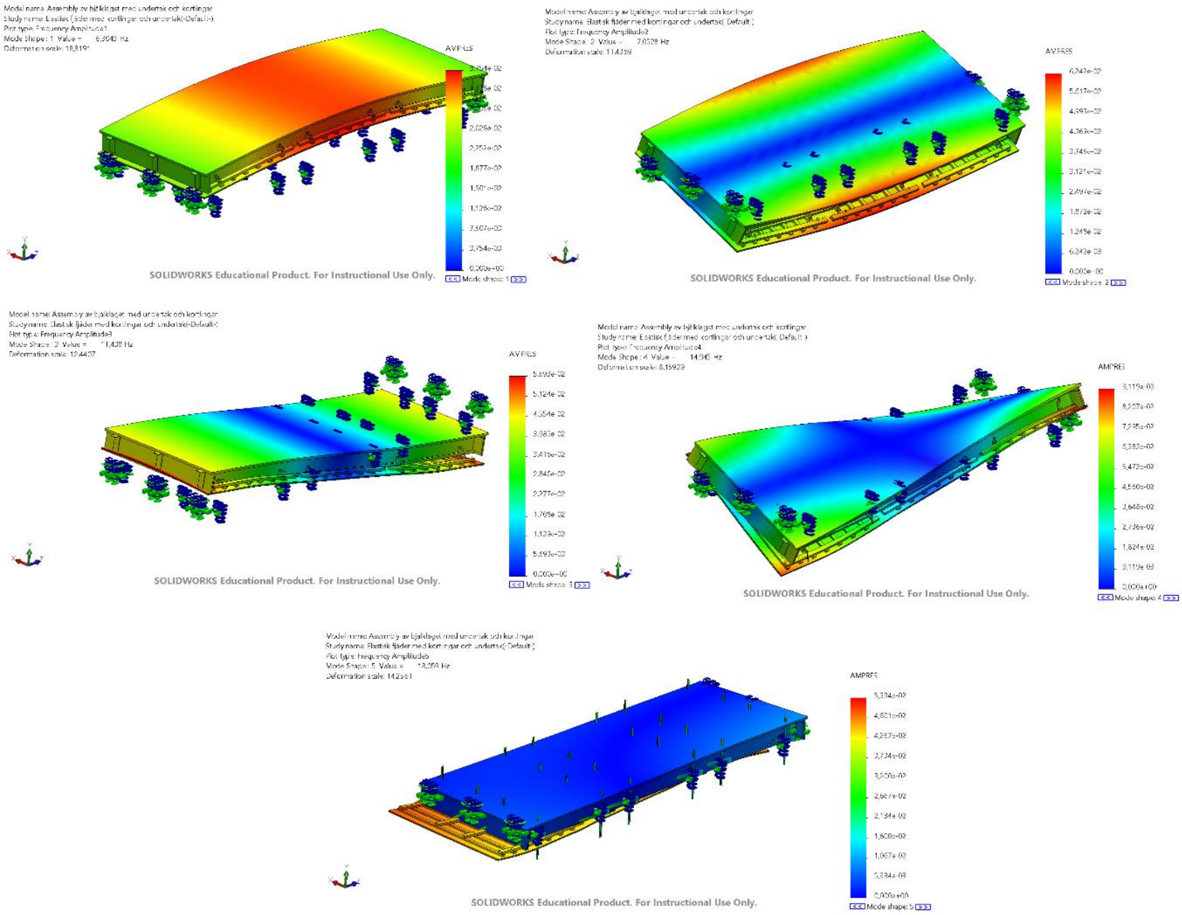

Figure A-8. Mode shapes for the flexibly supported floor with a flexibly suspended ceiling and noggins.

Figure A-9 shows the mode shapes for the rigidly supported floor with a rigidly suspended ceiling and noggins.

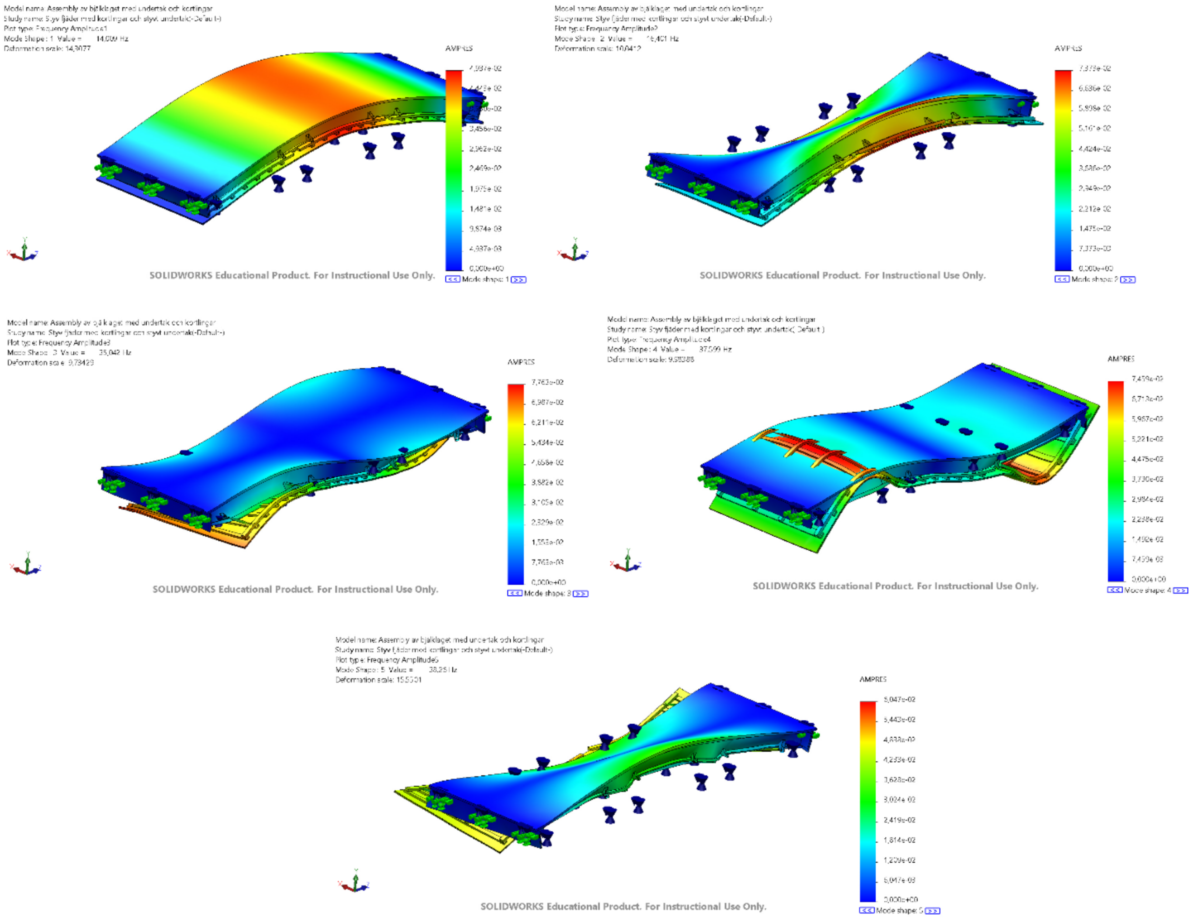

Figure A-9. Mode shapes for the rigidly supported floor with a rigidly suspended ceiling and noggins.

Figure A-10 shows the mode shapes for the flexibly supported floor with a rigidly suspended ceiling and noggins.

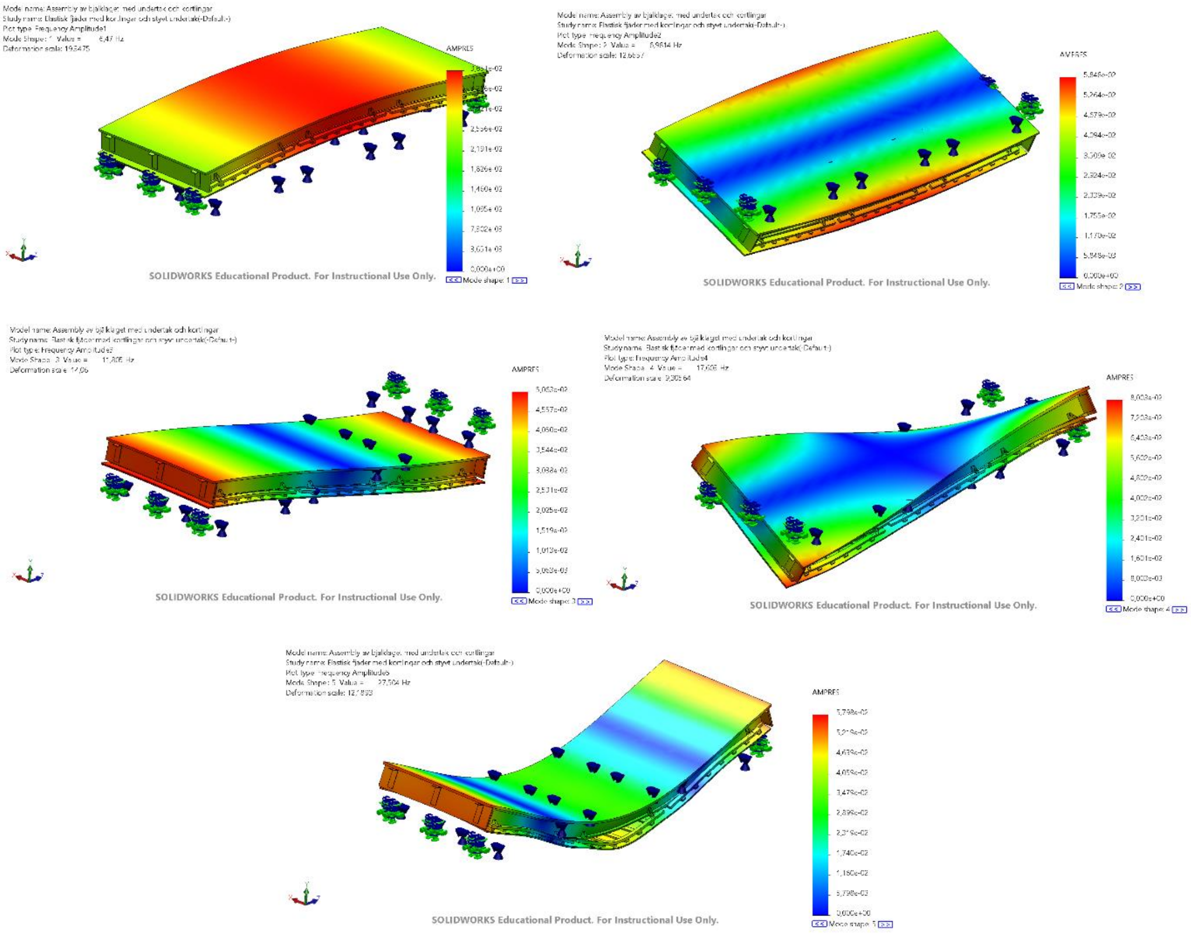

Figure A-10. Mode shapes for the flexibly supported floor with a rigidly suspended ceiling and noggins.

Figure A-11 shows the mode shapes for the floor with three times increased spring stiffness in the supports and the suspended ceiling, and with noggins.

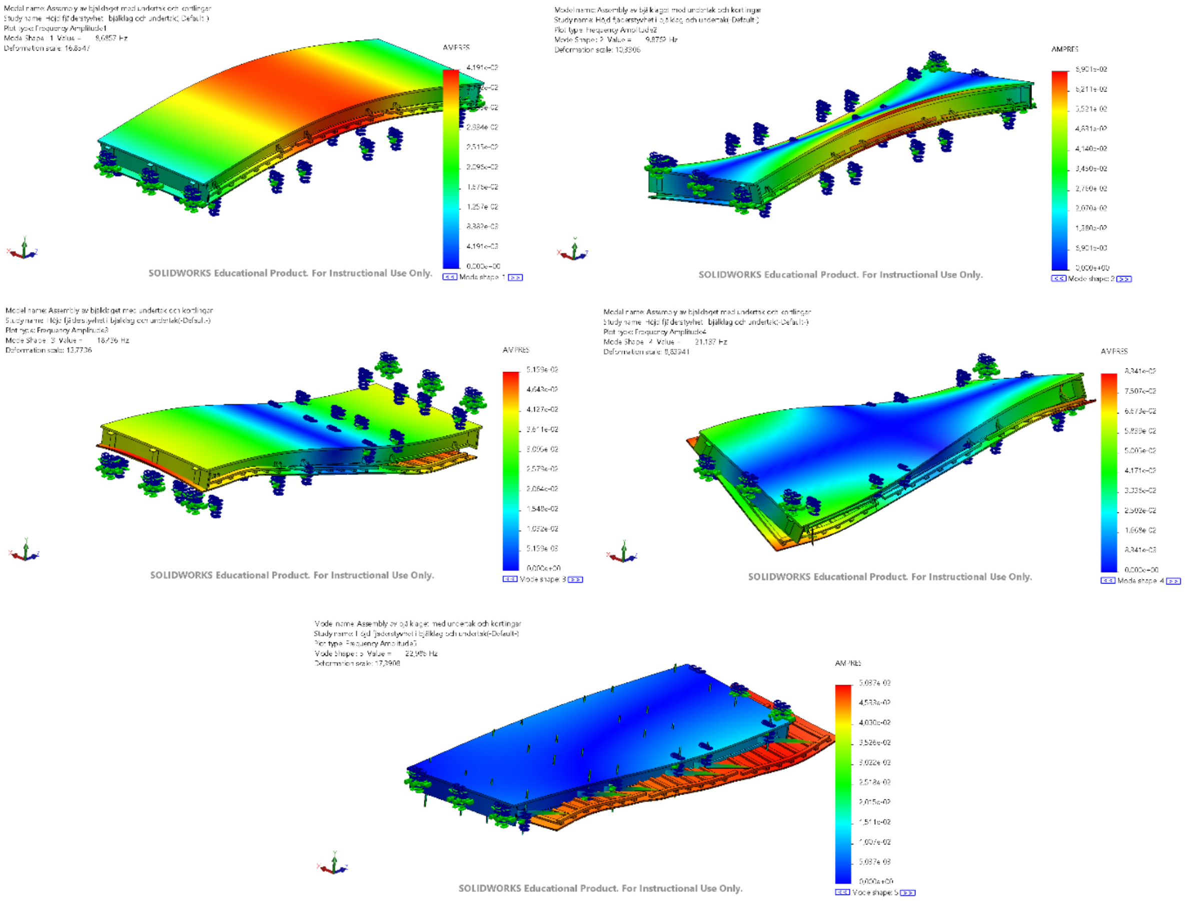

Figure A-11. Mode shapes for the floor with three times increased spring stiffness in the supports and the suspended ceiling, and with noggins.

Figure A-12 shows the mode shapes for the floor with three times increased spring stiffness in the supports and the suspended ceiling, but without noggins.

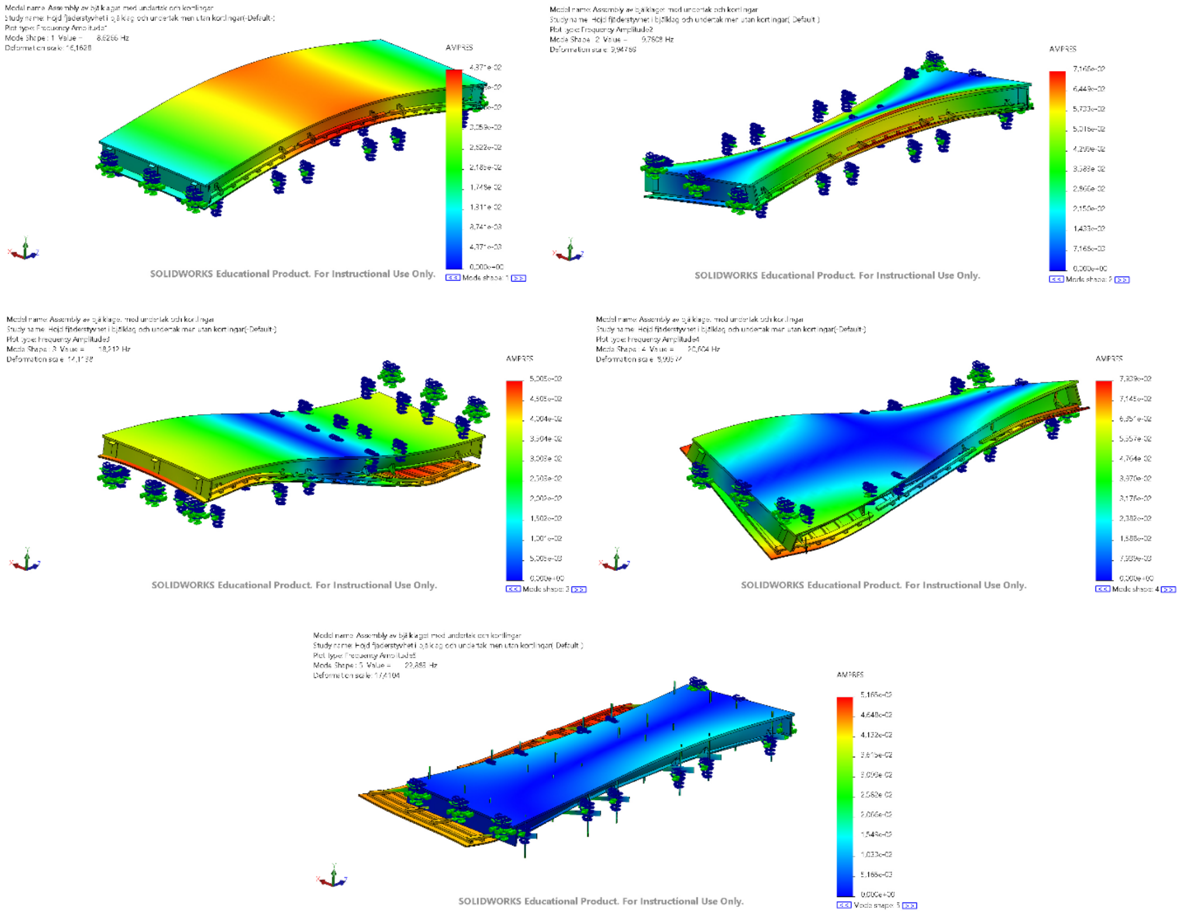

Figure A-12. Mode shapes for the floor with three times increased spring stiffness in the supports and the suspended ceiling, but without noggins.

Figure A-13 shows the mode shapes for the floor with three times increased spring stiffness in the supports, with a rigidly suspended ceiling, and with noggins.

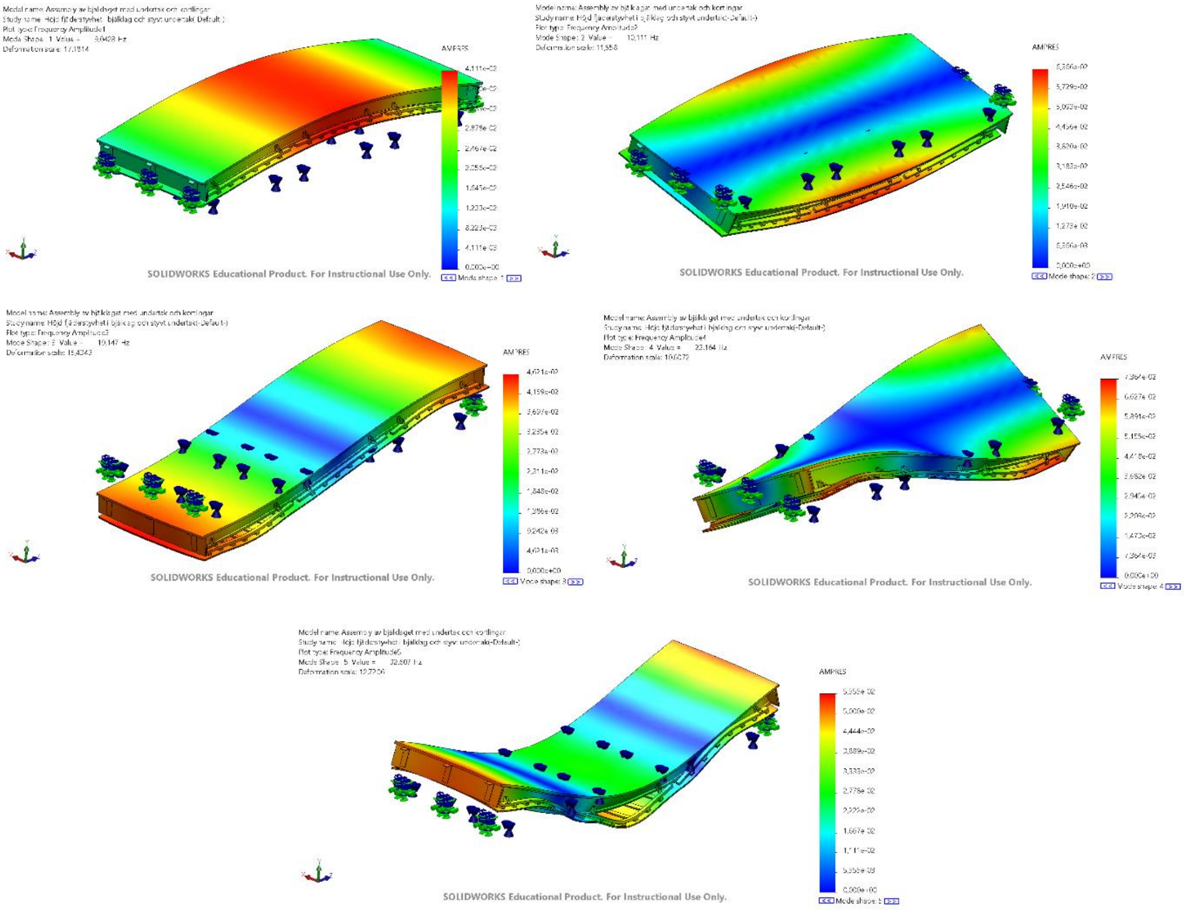

Figure A-13. Mode shapes for the floor with three times increased spring stiffness in the supports, with a rigidly suspended ceiling, and with noggins.

Figure A-14 shows the mode shapes for the floor with three times increased spring stiffness in the supports and with a rigidly suspended ceiling, but without noggins.

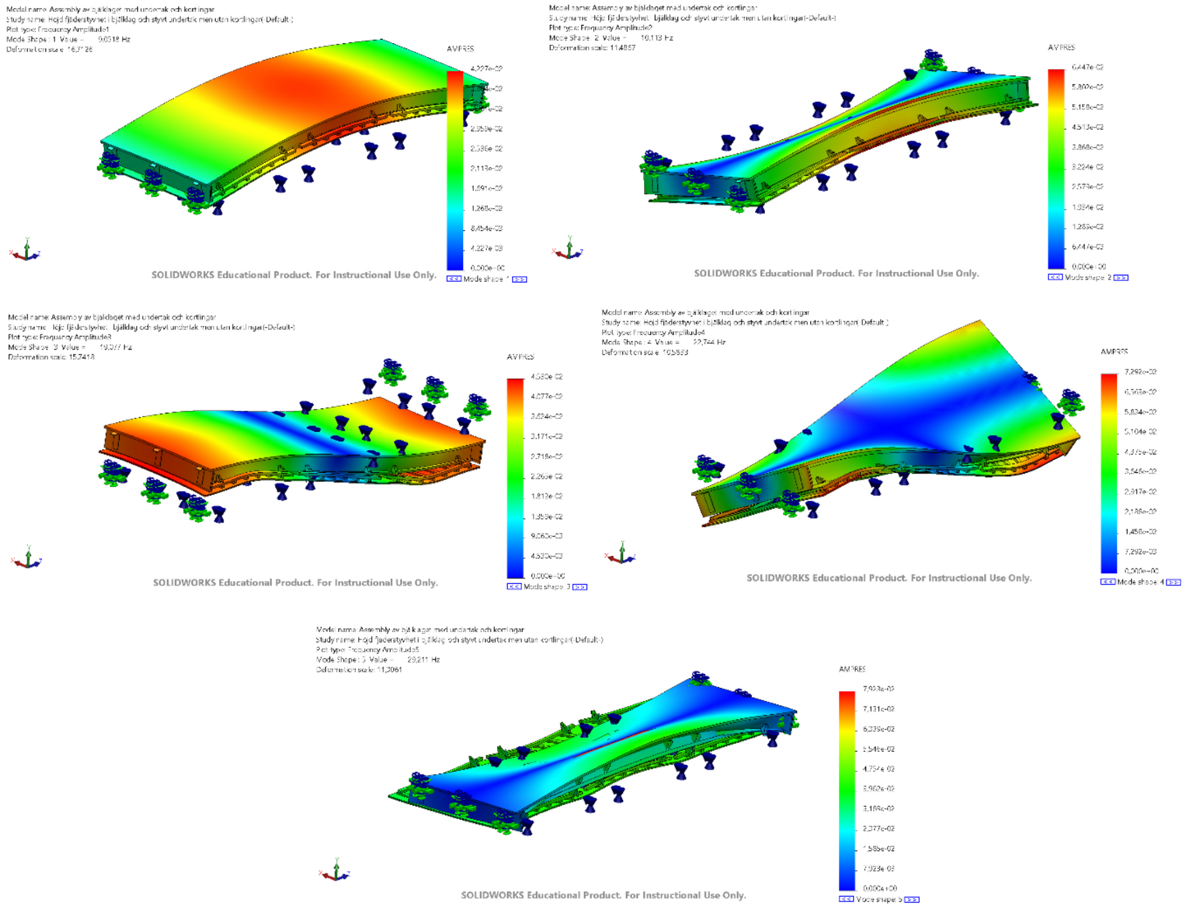

Figure A-14. Mode shapes for the floor with three times increased spring stiffness in the supports and with a rigidly suspended ceiling, but without noggins.