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Design Tool for Timber Balconies

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RISE Report 2022:136

Abstract

DesignTtool for Timber Balconies

With the increasing environmental issues and the need to have more sustainable solutions in the construction industry and the built environment, raising awareness regarding more use of timber in multi-story structures is aimed. Ensuring the performance of timber balconies will help to increase more use of timber as the construction material in these elements. The developed tool in this study has two versions. The first one is able to calculate and control the deflection of balconies built with cross-laminated timber (CLT) panels. The second version calculates and controls the deflection and vibration of balconies made with plywood and timber studs. The material properties in the second version are verified with experimental tests performed on 30 balcony slabs. The four-point bending test and natural frequency measurements were performed at RISE laboratories. The tool is designed in Excel and has the advantages of being easy to access, easy to use, and easy to understand for the user.

Key words: Timber structures, multi-storey, tall timber structures, timber balconies, design tool.

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Preface

This work is done under the TallWood project funded by the European Regional Development Fund within Interreg Nord at RISE Research Institutes of Sweden. The aim is to increase awareness regarding more utilization of timber in the construction of multi-story structures and increase the collaboration between research and industry sectors. The developed tool will help with enhancing the serviceability issues of timber balconies produced. The results presented by the design tool are only intended to provide guidance for designers and the producing companies; the final design responsibility lies with the structural designers of timber balconies. The developed tool is available at RISE. To get access to the tool and the required instructions Sara Khanalizadehtaromi at RISE can be contacted. The constructive ideas and work of Yunbo Huang is also acknowledged here.

1 Introduction

The existing relationship between the increasing population rate, urbanization, the construction industry, and environmental issues related to them cannot be overlooked. Besides, the construction industry being responsible for a considerable amount of generated waste needs to act more sustainably by implementing sustainable solutions. One of the strategies to lower the impacts of the built environment and construction industry is the use of materials with lower embodied energy. Timber, as one of the oldest materials used in construction, has the advantage of being lightweight, high strength-to-weight ratio, and lower embodied energy compared to other construction materials. Although timber is a desirable material due to its strength-to-weight ratio, it is not being used as a construction material like concrete or steel in multi-story buildings. In Sweden, although it is stated that 90% of one- to two-story residential buildings are built with timber frames, for multi-story buildings it was just 10% built with timber frames during 2007- 2015 (Markström et al., 2019). The increasing need for a more sustainable built environment and housing in urban areas till 2050, timber construction technological advances, and emerge of engineered wood products (EWP) have resulted in an increasing trend for muti-story timber structures.

Challenges exist in the construction of multi-story timber structures including a lack of competence and skills as structural engineers are mostly working with concrete and steel and are less educated in the timber structures field. Other challenges can be named as lack of planning and design tools, and construction techniques for multi-story timber structures that are still under development (Girhammar, 2021).

With the aim to raise awareness regarding more utilization of timber as a structural element in multi-story structures, a study of balconies made with timber started at RISE research institutes of Sweden. The study is done under the TallWood project funded by the European Regional Development Fund within Interreg Nord. Previous studies show the role of balconies and the positive effects they have on the well-being of residents and their quality of life with the increase of urbanization and high-rise residential buildings (Peters, T., & Masoudinejad, S., 2022). Deflection and vibration control of balconies are necessary for serviceability considerations and ensuring no damage will be done to structural or non-structural parts of the structure.

In this work package, two versions of a design tool are developed. The first developed version calculates and controls the deflection of balconies made with cross-laminated timber (CLT) panels, while the second version can calculate and control both the deflection and vibration of balconies made with plywood and timber studs. The material properties in the second version of the tool are also verified by performing experimental tests at RISE laboratories. The tool supports industrial companies producing timber balconies with product quality improvement and more utilization of timber balconies as timber elements. The study of developing the first version was done under a master's student project course by Y. Huang at Luleå University of Technology (LTU) and as a collaboration with LTU as one of the TallWood project's partners. The report of this study is available on TallWood's webpage[1] and will not be presented here.

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[1] https://www.oamk.fi/tallwood

2 Methodology

As mentioned earlier in the previous section, the tool developed within this project has two different versions. The focus of this report is on development of the second version which is considered as a more practical version for the collaborating industrial partners of the project. Both theoretical and experimental studies were performed at this stage.

2.1 Experimental Study

The experimental test in this project included four-point bending tests and fundamental natural frequency measurements of balconies performed at RISE laboratories in Skellefteå, Sweden. Composit Balkonger AB, located in Fällfors, Sweden, provided the studied balconies. The E-modulus and bending strength of balconies were measured with bending tests performed according to EN 408:2010 with minor deviations in the placement of supports. The fundamental natural frequencies were measured for the balconies with simply supported boundary conditions.

The measurements were performed on 6 different types of balconies and on 5 from each type. The total number of balconies tested was 30. The difference between each type of balcony was in their structure. Details of the balconies' materials, dimensions, types, measurements, and results are available in a RISE lab report presented on TallWood's webpage[2] and appendix 1. Figures 2.1, 2.2, and 2.3 show performing the four-point bending test, fundamental natural frequency measurements, and structure of different types of balconies named with letters from A to F, respectively.

Figure 2.1- Performing the four-point bending test.

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[2] https://www.oamk.fi/tallwood

Figure 2.2- Performing natural frequency measurements

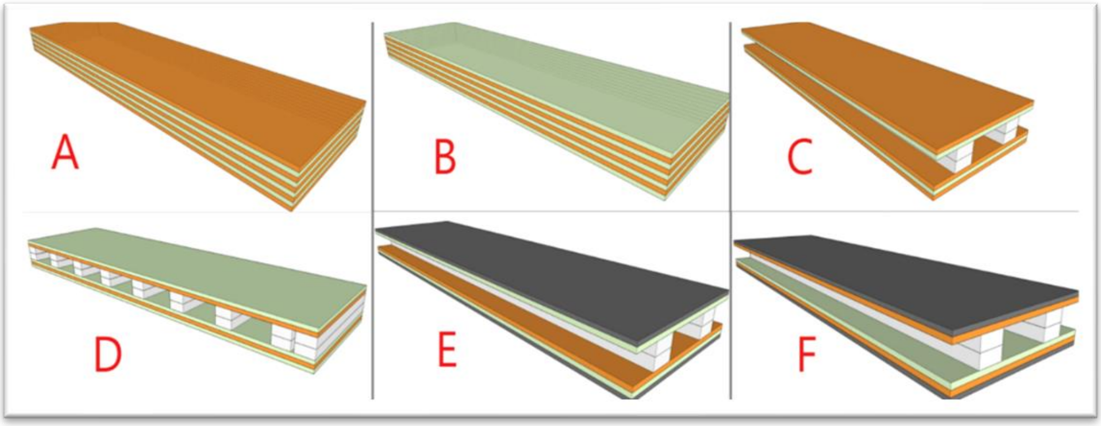


Figure 2.3- Structures of different types of balconies named with letters A to F.

Figure 2.3 shows different structures of the tested balconies. While types A and B are built with plywood the four other types have timber studs in the middle of their cross sections. The orange color demonstrates that the plywood's outermost layer is parallel to the load-bearing direction of the balcony slab. The green color shows the plywood with the outermost layer perpendicular to the load-bearing direction of the slab. The black layers in types E and F show a fire protection layer of Fermacell. More details can be found in the existing RISE lab report, mentioned in the previous paragraph. The results of measurements were used as input data to start the theoretical work and to develop the design tool with validated properties.

2.2 Theoretical Study

After performing the experimental tests and measurements, modeling the balconies in Abaqus started. The second version of the tool was developed based on the results of Abaqus simulations with automated Python scripts. Dimensions of the modeled balconies were based on the produced balconies of companies and the most common range of dimensions they have. The length of modeled balconies varied from 2 to 10 m; the width varied from 1.2 to 2.5 m, and the thickness varied from 120 to 250 mm based on the structure they were built. Figure 2.4 shows how the structure of type C balconies changes when the width of slabs increases. The varying range of possible dimensions defined for the tool was the reason for having the need for different boundary conditions. To describe different types of boundary conditions four zones were defined. These zones are shown in figure 2.5. It can be seen that for all dimensions, one side of the balcony slab lays on the wall; the placement of supports on the other sides differs. An overlapping length exists between 5.0 to 6.0 m length in zones 1 and 2, and zones 3 and 4. This allows the user to choose which zone is more desirable for this range of length.

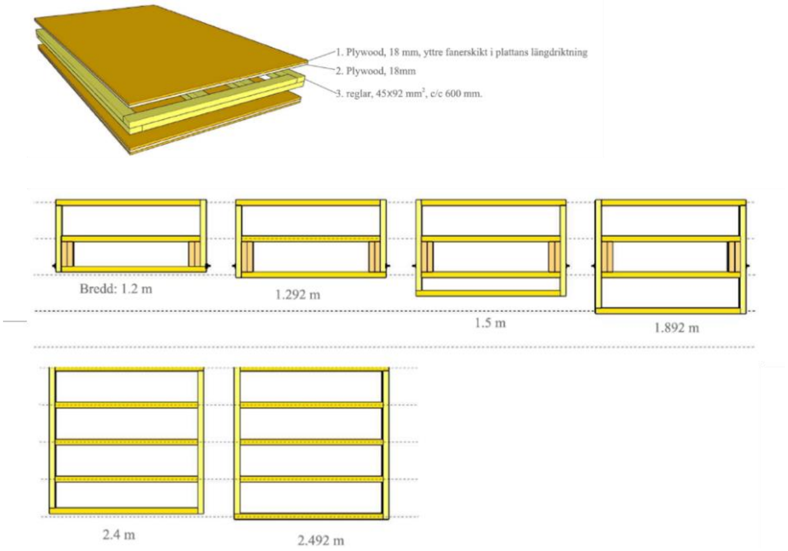


Figure 2.4- Change of the type C balconies' structure with adding studs when the width increases

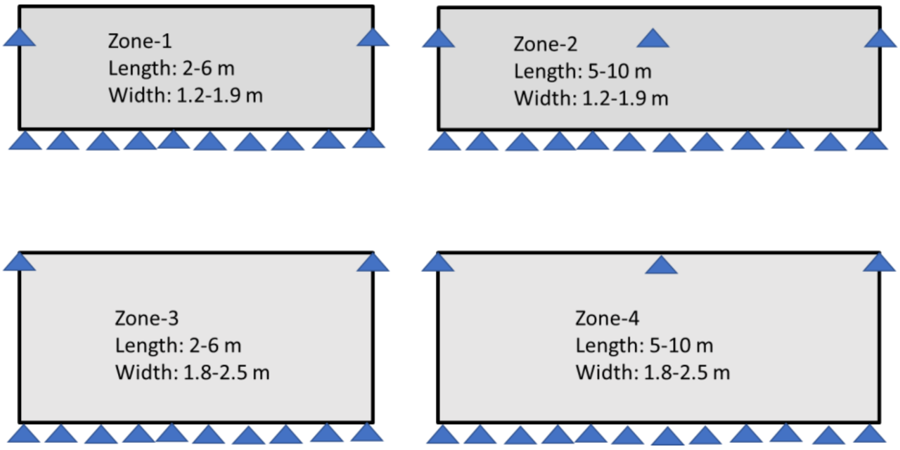


Figure 2.5- Four different zones defined to describe the boundary conditions for different ranges of dimensions in balconies.

The balcony type C in the experiment, was selected as the most common type to proceed with the modeling. The material properties used in Abaqus was firstly taken from the literature, which were then verified and adjusted based on testing results. The load applied to the Abaqus models was distributed load equal to 3 kN/m^2. With the help of Python, thousands of Abaqus results were analyzed. The results were compared to the stiffness diagrams from the experimental tests. The material properties that their results had the smallest distance from the elastic range of experimental diagrams were chosen as input for further verified modeling. This verification was done for material properties of balcony types C, E, and F. The results of this verification are presented in the results section.

As it was mentioned earlier, the dimension range varies for models in Abaqus. Around 5000 simulations were run for calculating the deflection of different combinations of dimensions in slabs, and 5000 for calculating the natural frequencies of the same models. Different simulations were based on dividing the dimensions into smaller ranges to get more accurate results from the tool.

The thickness range was divided every 10 mm from 120 to 250 mm. The length ranges were divided each 50 cm for different zones including 2 to 6 and 5 to 10 m ranges. The width ranges were divided each 10 cm from 1.2 to 1.9 and 1.8 to 2.5 m in zones 2, 3, and 4. Dividing the width range for zone 1 was an exception as it is the most common type of balcony produced and more accurate results were more desirable, so every 5 cm of the width range a new model was built in Abaqus. The process to have different combinations of balconies with different dimensions is summarized in figure 2.6. The results of these 10000 simulations were processed with Python and the created curves were transferred to Excel to develop the tool. The exported curves are presented in the next section.

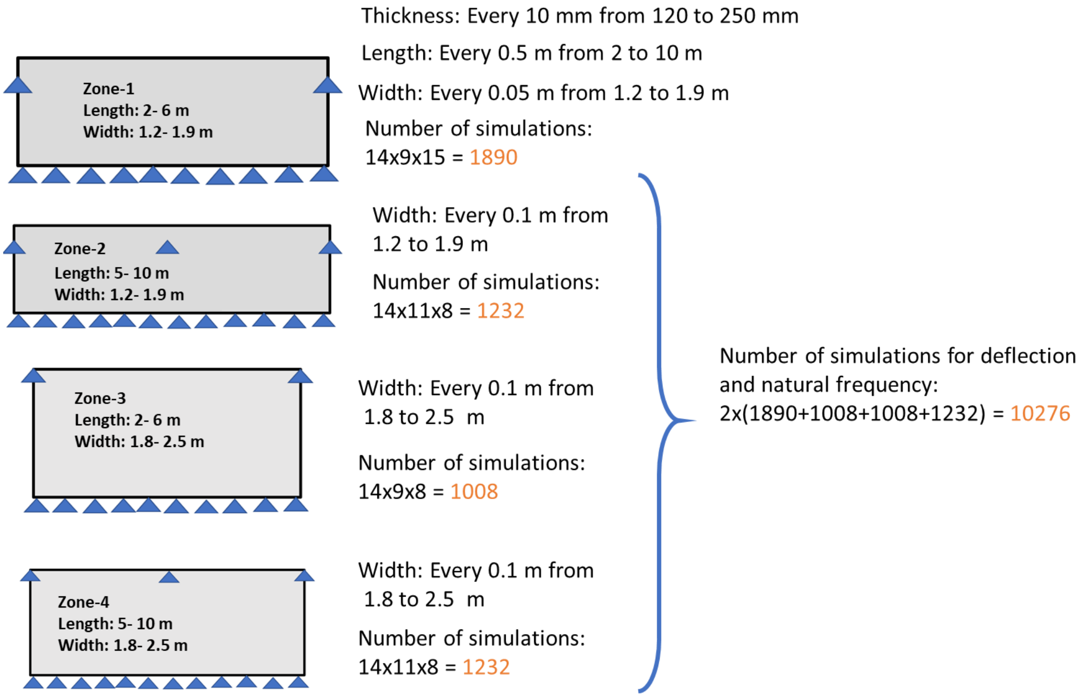


Figure 2.6- Showing the dimension combinations of Abaqus models and breaking the dimensions' ranges for modeling balconies to have more accurate results from the design tool.

3 Results

As mentioned earlier, the results of the experimental tests performed on balconies are presented in a RISE lab report that is available on TallWood project's webpage and appendix 1. Here the results of the theoretical study and the developed tool will be discussed further.

3.1 Verification of Material Properties

To verify the material properties of Abaqus models, the results from Abaqus simulations were compared to the results of the four-point bending test performed to find the material properties that are the most similar to the material properties of produced balconies. This verification was done for the three most common types of balconies. Figure 3.1 shows the verification and adaptation of the FEA diagram from Abaqus and the elastic range of tested balconies.

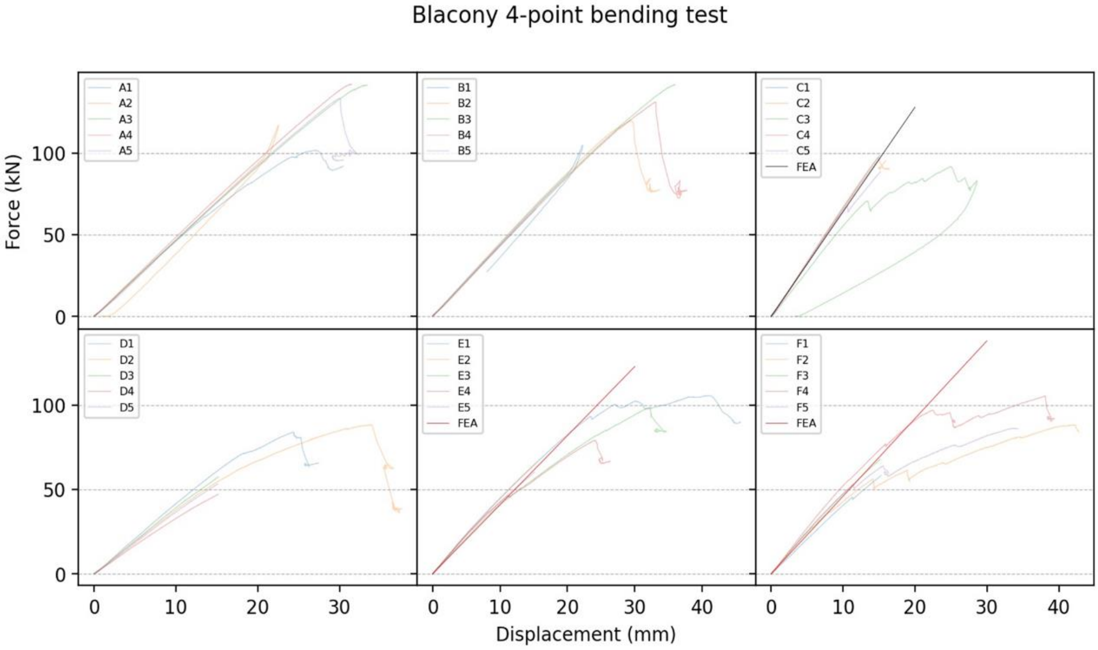


Figure 3.1- Verification of material properties of the modeled balconies in type C, E, and F with the four-point bending test performed. FEA stands for the finite element analysis and Abaqus models. Letters with numbers from 1 to 5 in each balcony type show the name of tested slabs.

3.2 Design Tool

With the verified material properties, deflection and natural frequencies were calculated with Abaqus. Figure 3.2 shows a small red point in the modeled balcony slabs of each zone where the maximum deflection occurs, and the deflection values for each zone were picked from that point.

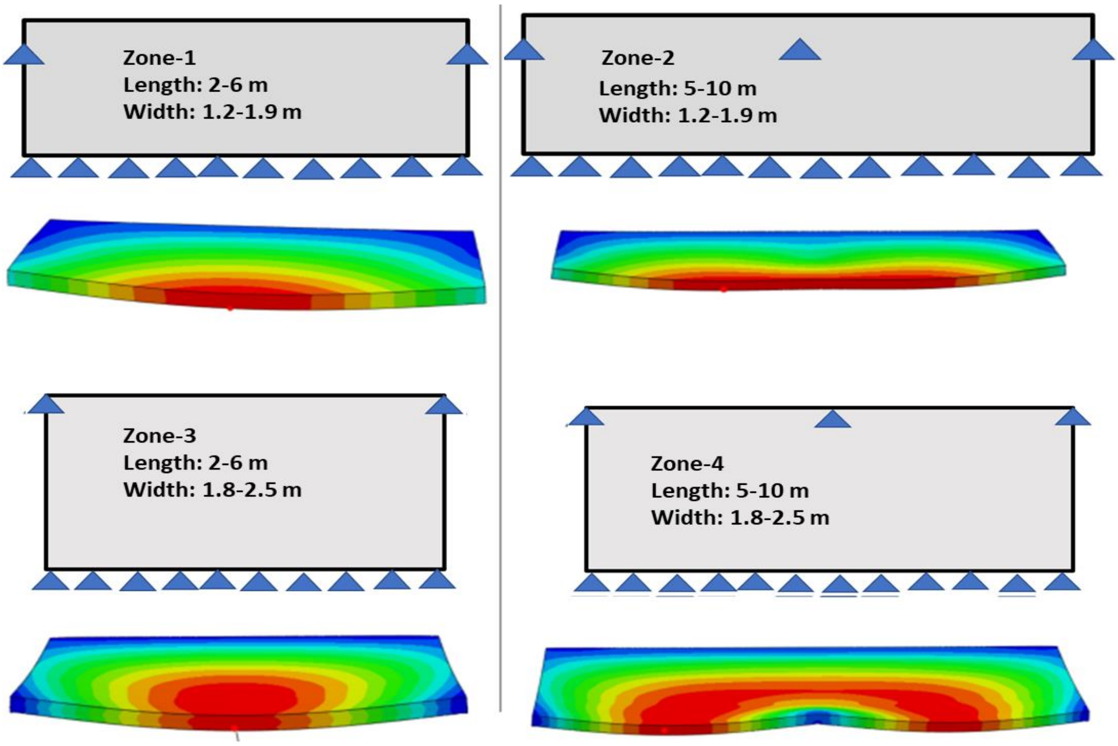


Figure 3.2- Red points showing the maximum deflection points in each zone and where the deflection values were picked from.

Figures 3.3 and 3.4 show 9 deflection and 9 natural frequency diagrams for zone 1, respectively. The vertical axis in figure 3.3 shows the deflection in mm and the horizontal axis shows the width in m. In figure 3.3, curves with different colors in each diagram show different thicknesses of the models. The length of balconies modeled in the diagram on the top left corner is 2.0 m and by increasing the length by 0.5 m in each diagram, the length in the last one is 6.0 m.

In figure 3.4, the vertical axis of the diagrams stands for the natural frequencies in Hz and the horizontal axis shows the width of balconies in m. Curves with different colors in each diagram show values for different thicknesses, and in each diagram, the length increases compared to the previous one by 0.5 m.

For zones 2, 3, and 4 the same diagrams as figures 3.3 and 3.4 were available which are not presented in this report. All these results were transferred to excel to develop the design tool. The developed design tool can be seen in figure 3.5.

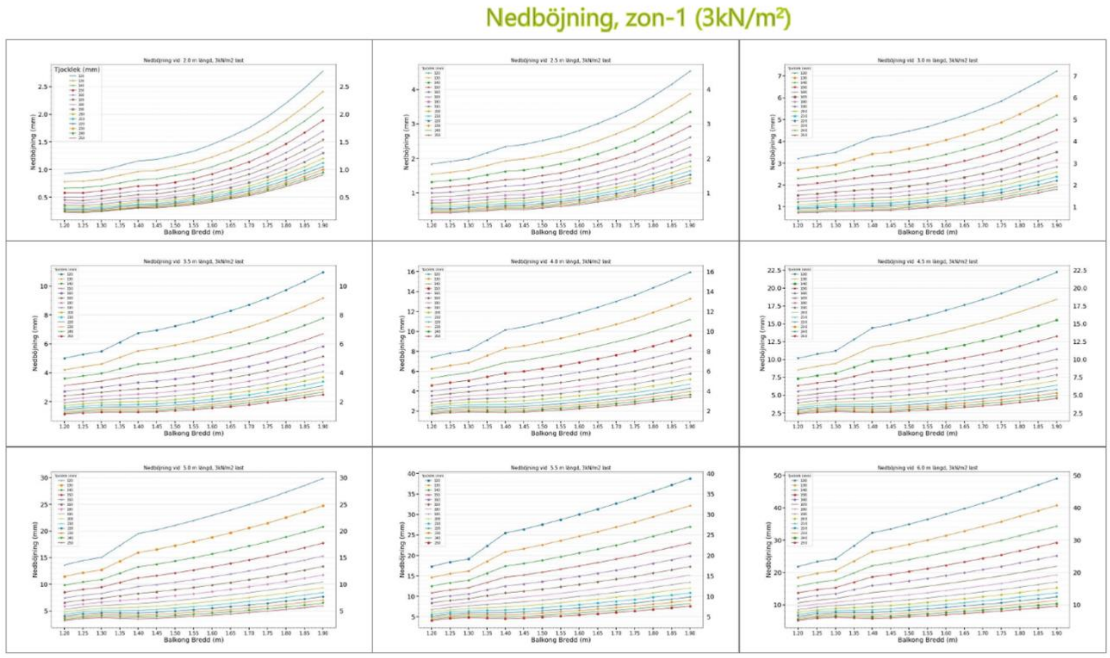


Figure 3.3- Nine diagrams showing the maximum deflection of balconies from zone 1 under distributed load of 3 kN/m^2.

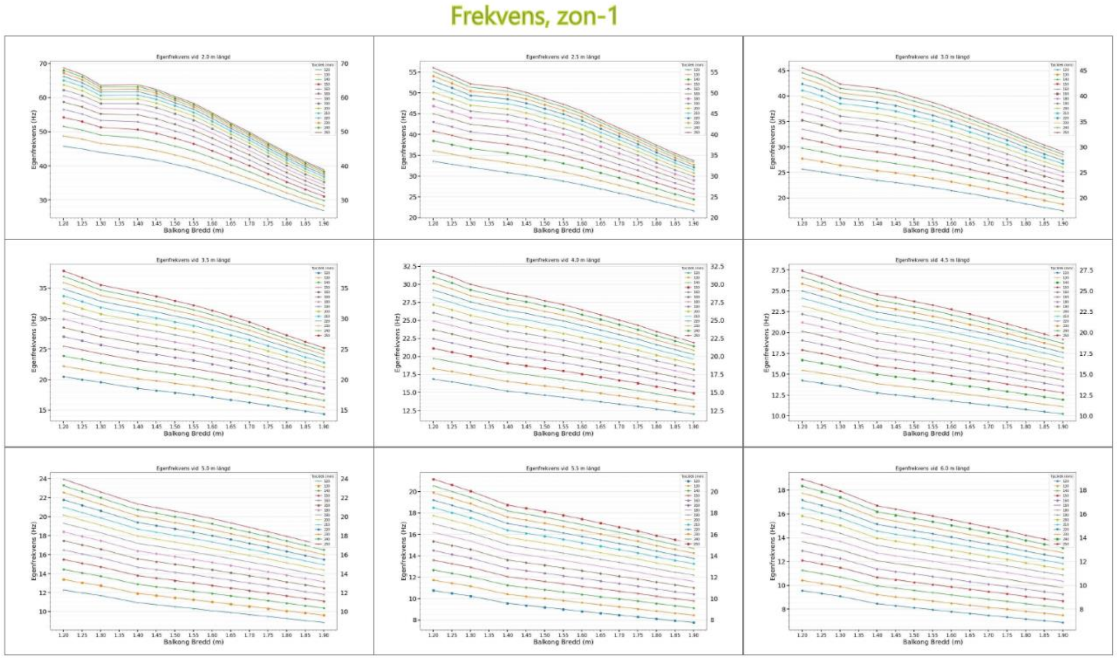
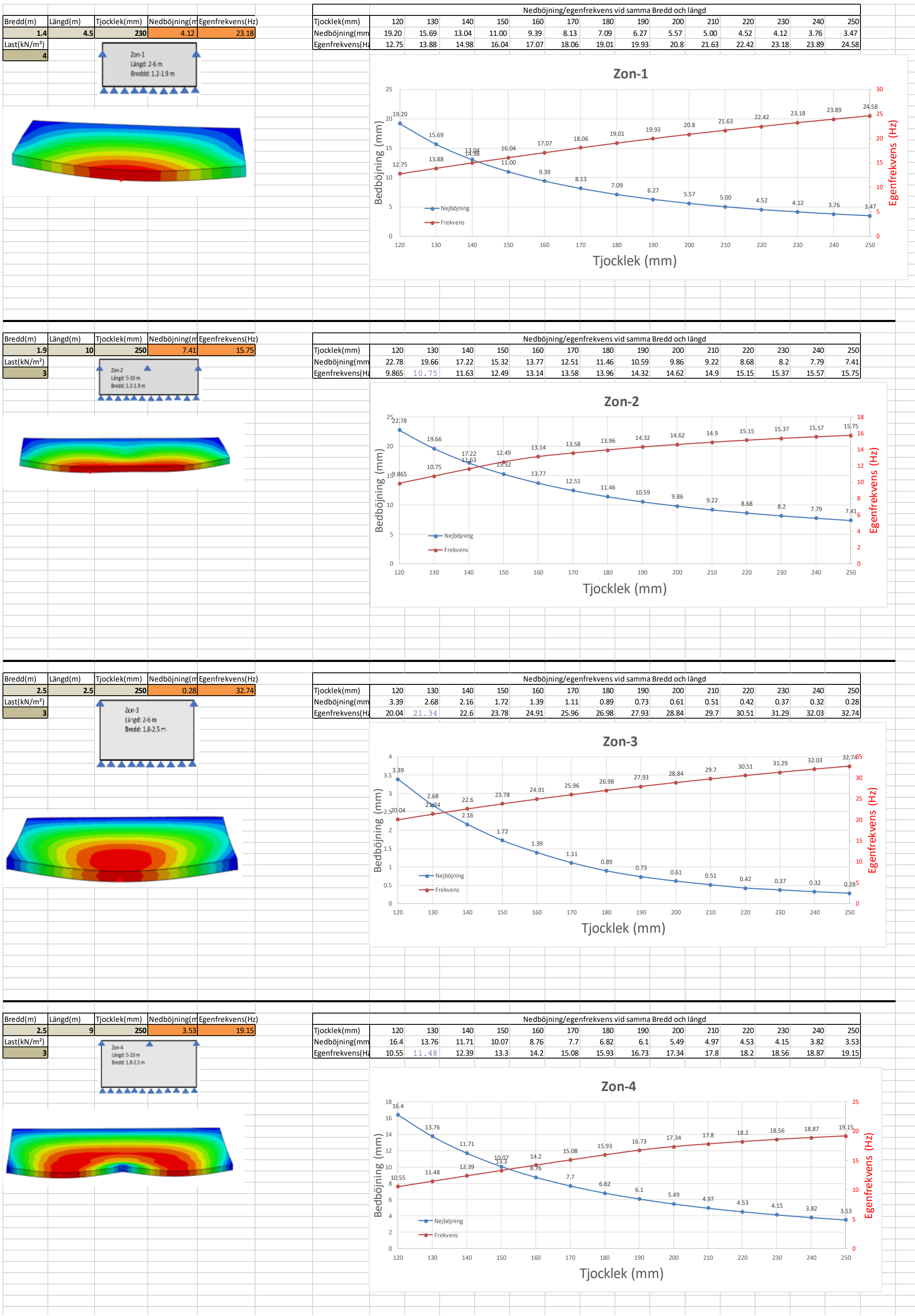


Figure 3.4- Nine diagrams showing the natural frequencies (Hz) of balconies from zone 1.



Bredd(m)	Längd(m)	Tjocklek(mm)	Nedböjning(m	Egenfrekvens(Hz)
1.4	4.5	230	4.12	23.18
Last(kN/m²)				
4				

Nedböjning/egenfrekvens vid samma Bredd och längd														
Tjocklek(mm)	120	130	140	150	160	170	180	190	200	210	220	230	240	250
Nedböjning(mm	19.20	15.69	13.04	11.00	9.39	8.13	7.09	6.27	5.57	5.00	4.52	4.12	3.76	3.47
Egenfrekvens(Hz	12.75	13.88	14.98	16.04	17.07	18.06	19.01	19.93	20.8	21.63	22.42	23.18	23.89	24.58

Bredd(m)	Längd(m)	Tjocklek(mm)	Nedböjning(m	Egenfrekvens(Hz)
1.9	10	250	7.41	15.75
Last(kN/m²)				
3				

Nedböjning/egenfrekvens vid samma Bredd och längd														
Tjocklek(mm)	120	130	140	150	160	170	180	190	200	210	220	230	240	250
Nedböjning(mm	22.78	19.66	17.22	15.32	13.77	12.51	11.46	10.59	9.86	9.22	8.68	8.2	7.79	7.41
Egenfrekvens(Hz	9.865	10.75	11.63	12.49	13.14	13.58	13.96	14.32	14.62	14.9	15.15	15.37	15.57	15.75

Bredd(m)	Längd(m)	Tjocklek(mm)	Nedböjning(m	Egenfrekvens(Hz)
2.5	2.5	250	0.28	32.74
Last(kN/m²)				
3				

Nedböjning/egenfrekvens vid samma Bredd och längd														
Tjocklek(mm)	120	130	140	150	160	170	180	190	200	210	220	230	240	250
Nedböjning(mm	3.39	2.68	2.16	1.72	1.39	1.11	0.89	0.73	0.61	0.51	0.42	0.37	0.32	0.28
Egenfrekvens(Hz	20.04	21.34	22.6	23.78	24.91	25.96	26.98	27.93	28.84	29.7	30.51	31.29	32.03	32.74

Bredd(m)	Längd(m)	Tjocklek(mm)	Nedböjning(m	Egenfrekvens(Hz)
2.5	9	250	3.53	19.15
Last(kN/m²)				
3				

Nedböjning/egenfrekvens vid samma Bredd och längd														
Tjocklek(mm)	120	130	140	150	160	170	180	190	200	210	220	230	240	250
Nedböjning(mm	16.4	13.76	11.71	10.07	8.76	7.7	6.82	6.1	5.49	4.97	4.53	4.15	3.82	3.53
Egenfrekvens(Hz	10.55	11.48	12.39	13.3	14.2	15.08	15.93	16.73	17.34	17.8	18.2	18.56	18.87	19.15

Figure 3.5- The developed design tool to calculate and control the deflection and the natural frequencies of balconies with different ranges of dimensions and boundary conditions.

Figure 3.5 shows an input section in the tool in the top left corner in which the width, length, thickness, and load applied to a balcony can be entered. The orange cells will give the deflection and the natural frequency values. The dimension ranges for length and width presented in each zone below the input section will help the user to choose the zone. The overlapping length from 5 to 6 m in length gives the user the ability to check the values for 2 different boundary conditions.

The table on the top right side of the design tool shows the deflection and the natural frequency values for entered values of width and length if different thicknesses were chosen instead of the input value of thickness. This will also help the user in the design of balcony slabs to check the result values for different thicknesses.

4 Conclusion

The aim of this study was to develop a design tool for timber balconies that is able to enhance serviceability of timber balconies. Two versions of the tool were developed. The first version was developed under a master student's study project and was able to calculate and control the deflection of balconies made with maximum 5 layers CLT panels. The second version of the tool calculates and controls the deflection and vibration of balconies made with plywood and timber studs. The material properties of the second version are verified with experimental tests performed. The tool gives the user the chance to have a better overview of values for different thicknesses of the slab and also for the length range between 5 to 6 m, the user is able to choose between two different boundary conditions. The tool is recognized as an easy-to-use tool by the companies producing timber balconies. It also has the advantage of being easy to access and easy to understand.

5 References

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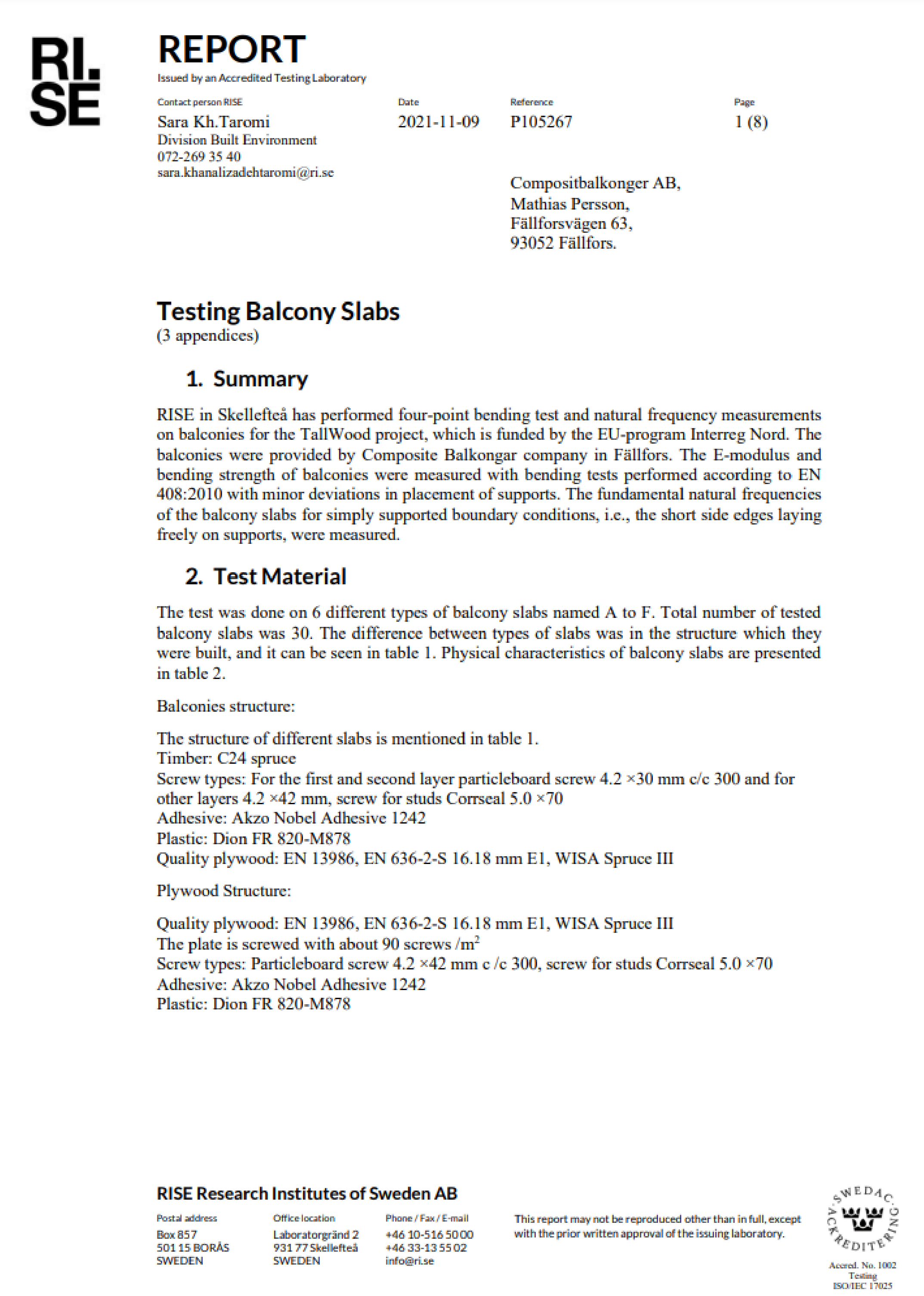
Appendices

Appendix 1: RISE lab report of the experimental test performed.



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Contact person RISE	Date	Reference	Page
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Mathias Persson,
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Testing Balcony Slabs

(3 appendices)

1. Summary

RISE in Skellefteå has performed four-point bending test and natural frequency measurements on balconies for the TallWood project, which is funded by the EU-program Interreg Nord. The balconies were provided by Composite Balkongar company in Fällfors. The E-modulus and bending strength of balconies were measured with bending tests performed according to EN 408:2010 with minor deviations in placement of supports. The fundamental natural frequencies of the balcony slabs for simply supported boundary conditions, i.e., the short side edges laying freely on supports, were measured.

2. Test Material

The test was done on 6 different types of balcony slabs named A to F. Total number of tested balcony slabs was 30. The difference between types of slabs was in the structure which they were built, and it can be seen in table 1. Physical characteristics of balcony slabs are presented in table 2.

Balconies structure:

The structure of different slabs is mentioned in table 1.
Timber: C24 spruce
Screw types: For the first and second layer particleboard screw 4.2 ×30 mm c/c 300 and for other layers 4.2 ×42 mm, screw for studs Corrseal 5.0 ×70
Adhesive: Akzo Nobel Adhesive 1242
Plastic: Dion FR 820-M878
Quality plywood: EN 13986, EN 636-2-S 16.18 mm E1, WISA Spruce III

Plywood Structure:

Quality plywood: EN 13986, EN 636-2-S 16.18 mm E1, WISA Spruce III
The plate is screwed with about 90 screws /m^2
Screw types: Particleboard screw 4.2 ×42 mm c /c 300, screw for studs Corrseal 5.0 ×70
Adhesive: Akzo Nobel Adhesive 1242
Plastic: Dion FR 820-M878

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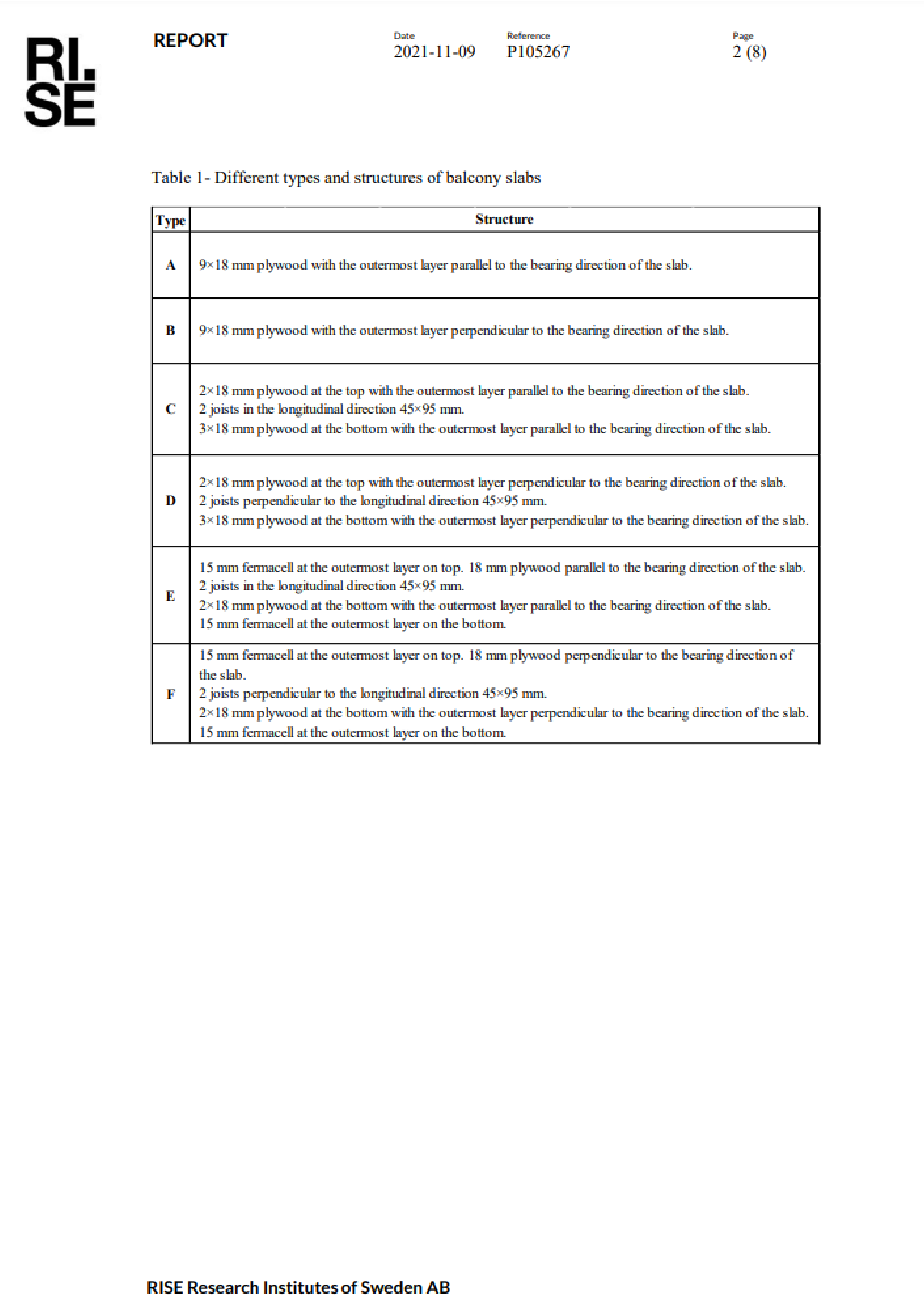

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Table 1- Different types and structures of balcony slabs

Type	Structure
A	9×18 mm plywood with the outermost layer parallel to the bearing direction of the slab.
B	9×18 mm plywood with the outermost layer perpendicular to the bearing direction of the slab.
C	2×18 mm plywood at the top with the outermost layer parallel to the bearing direction of the slab. 2 joists in the longitudinal direction 45×95 mm. 3×18 mm plywood at the bottom with the outermost layer parallel to the bearing direction of the slab.
D	2×18 mm plywood at the top with the outermost layer perpendicular to the bearing direction of the slab. 2 joists perpendicular to the longitudinal direction 45×95 mm. 3×18 mm plywood at the bottom with the outermost layer perpendicular to the bearing direction of the slab.
E	15 mm fermacell at the outermost layer on top. 18 mm plywood parallel to the bearing direction of the slab. 2 joists in the longitudinal direction 45×95 mm. 2×18 mm plywood at the bottom with the outermost layer parallel to the bearing direction of the slab. 15 mm fermacell at the outermost layer on the bottom.
F	15 mm fermacell at the outermost layer on top. 18 mm plywood perpendicular to the bearing direction of the slab. 2 joists perpendicular to the longitudinal direction 45×95 mm. 2×18 mm plywood at the bottom with the outermost layer perpendicular to the bearing direction of the slab. 15 mm fermacell at the outermost layer on the bottom.

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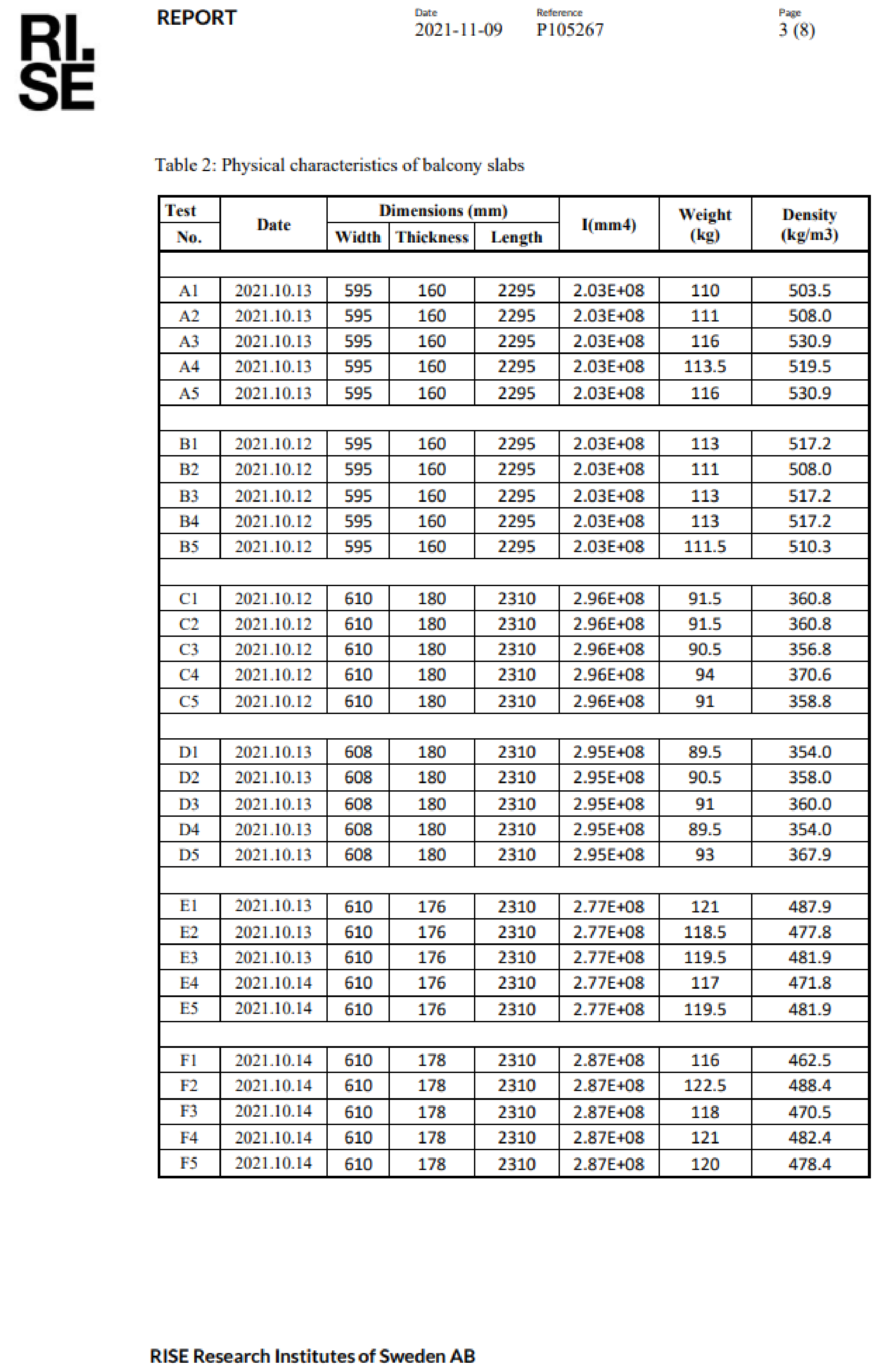
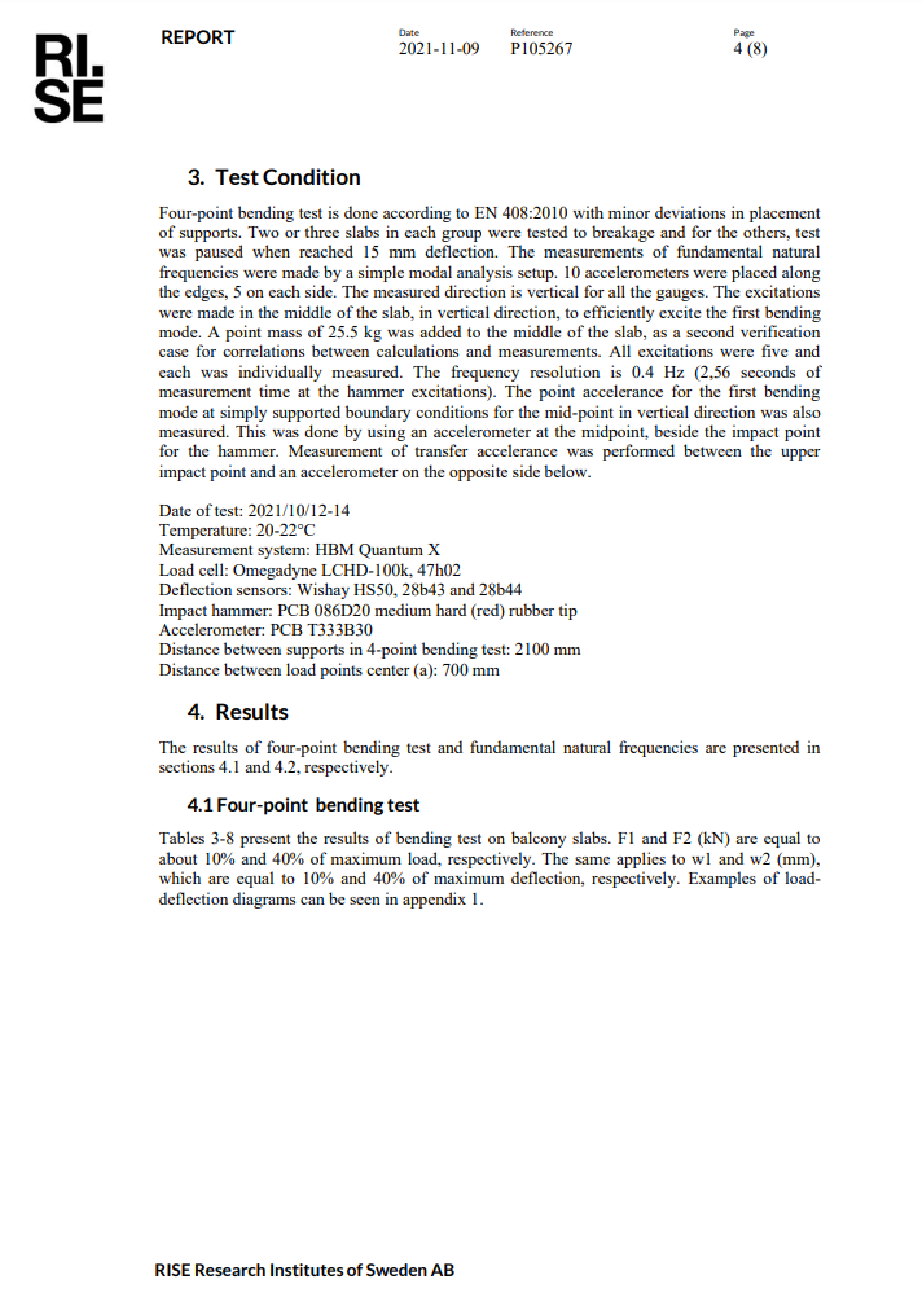


Table 2: Physical characteristics of balcony slabs

Test No.	Date	Dimensions (mm)			I(mm4)	Weight (kg)	Density (kg/m3)
		Width	Thickness	Length			
A1	2021.10.13	595	160	2295	2.03E+08	110	503.5
A2	2021.10.13	595	160	2295	2.03E+08	111	508.0
A3	2021.10.13	595	160	2295	2.03E+08	116	530.9
A4	2021.10.13	595	160	2295	2.03E+08	113.5	519.5
A5	2021.10.13	595	160	2295	2.03E+08	116	530.9
B1	2021.10.12	595	160	2295	2.03E+08	113	517.2
B2	2021.10.12	595	160	2295	2.03E+08	111	508.0
B3	2021.10.12	595	160	2295	2.03E+08	113	517.2
B4	2021.10.12	595	160	2295	2.03E+08	113	517.2
B5	2021.10.12	595	160	2295	2.03E+08	111.5	510.3
C1	2021.10.12	610	180	2310	2.96E+08	91.5	360.8
C2	2021.10.12	610	180	2310	2.96E+08	91.5	360.8
C3	2021.10.12	610	180	2310	2.96E+08	90.5	356.8
C4	2021.10.12	610	180	2310	2.96E+08	94	370.6
C5	2021.10.12	610	180	2310	2.96E+08	91	358.8
D1	2021.10.13	608	180	2310	2.95E+08	89.5	354.0
D2	2021.10.13	608	180	2310	2.95E+08	90.5	358.0
D3	2021.10.13	608	180	2310	2.95E+08	91	360.0
D4	2021.10.13	608	180	2310	2.95E+08	89.5	354.0
D5	2021.10.13	608	180	2310	2.95E+08	93	367.9
E1	2021.10.13	610	176	2310	2.77E+08	121	487.9
E2	2021.10.13	610	176	2310	2.77E+08	118.5	477.8
E3	2021.10.13	610	176	2310	2.77E+08	119.5	481.9
E4	2021.10.14	610	176	2310	2.77E+08	117	471.8
E5	2021.10.14	610	176	2310	2.77E+08	119.5	481.9
F1	2021.10.14	610	178	2310	2.87E+08	116	462.5
F2	2021.10.14	610	178	2310	2.87E+08	122.5	488.4
F3	2021.10.14	610	178	2310	2.87E+08	118	470.5
F4	2021.10.14	610	178	2310	2.87E+08	121	482.4
F5	2021.10.14	610	178	2310	2.87E+08	120	478.4



3. Test Condition

Four-point bending test is done according to EN 408:2010 with minor deviations in placement of supports. Two or three slabs in each group were tested to breakage and for the others, test was paused when reached 15 mm deflection. The measurements of fundamental natural frequencies were made by a simple modal analysis setup. 10 accelerometers were placed along the edges, 5 on each side. The measured direction is vertical for all the gauges. The excitations were made in the middle of the slab, in vertical direction, to efficiently excite the first bending mode. A point mass of 25.5 kg was added to the middle of the slab, as a second verification case for correlations between calculations and measurements. All excitations were five and each was individually measured. The frequency resolution is 0.4 Hz (2,56 seconds of measurement time at the hammer excitations). The point accelerance for the first bending mode at simply supported boundary conditions for the mid-point in vertical direction was also measured. This was done by using an accelerometer at the midpoint, beside the impact point for the hammer. Measurement of transfer accelerance was performed between the upper impact point and an accelerometer on the opposite side below.

Date of test: 2021/10/12-14
Temperature: 20-22°C
Measurement system: HBM Quantum X
Load cell: Omegadyne LCHD-100k, 47h02
Deflection sensors: Wishay HS50, 28b43 and 28b44
Impact hammer: PCB 086D20 medium hard (red) rubber tip
Accelerometer: PCB T333B30
Distance between supports in 4-point bending test: 2100 mm
Distance between load points center (a): 700 mm

4. Results

The results of four-point bending test and fundamental natural frequencies are presented in sections 4.1 and 4.2, respectively.

4.1 Four-point bending test

Tables 3-8 present the results of bending test on balcony slabs. F1 and F2 (kN) are equal to about 10% and 40% of maximum load, respectively. The same applies to w1 and w2 (mm), which are equal to 10% and 40% of maximum deflection, respectively. Examples of load-deflection diagrams can be seen in appendix 1.

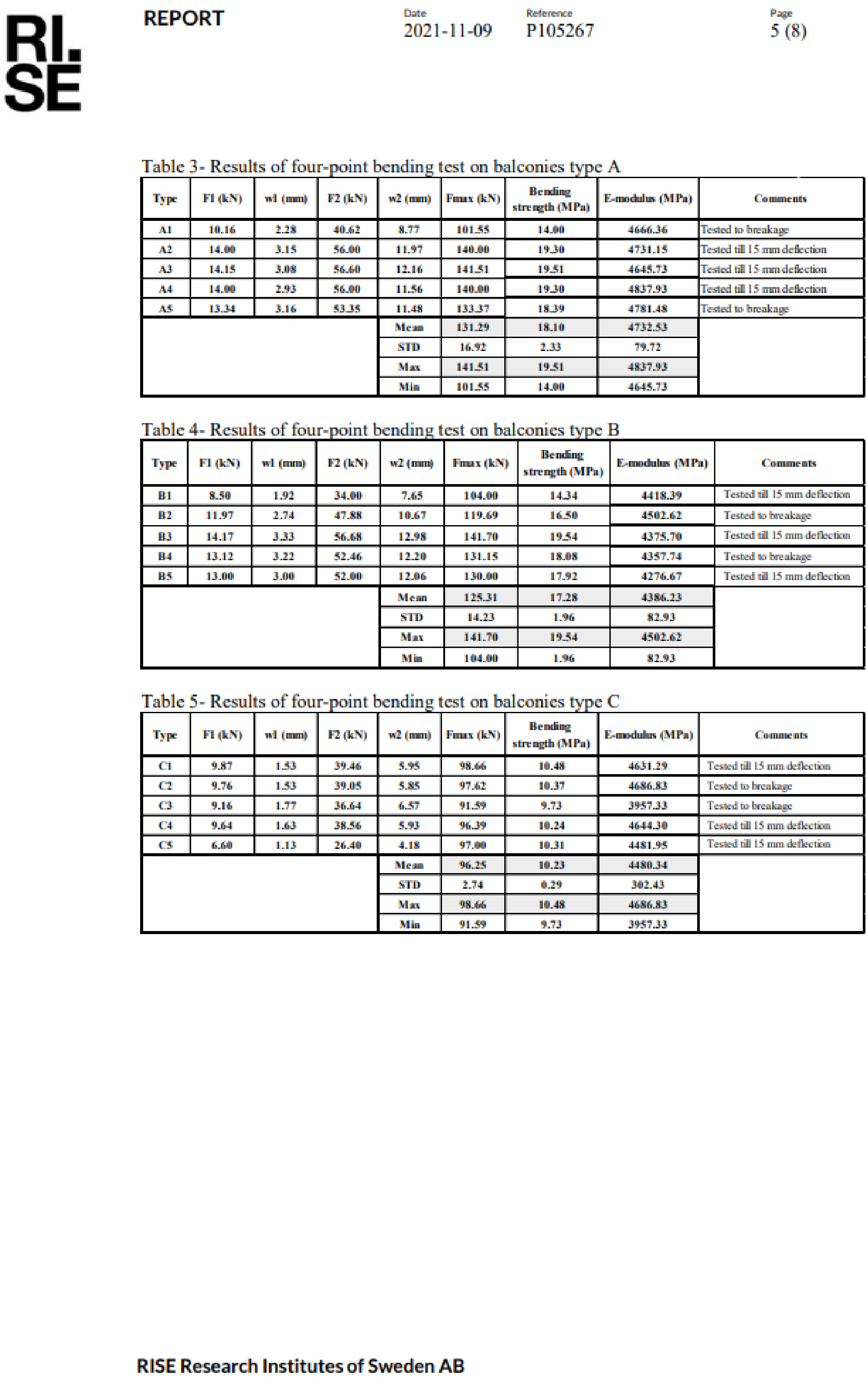


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Table 3- Results of four-point bending test on balconies type A

Type	F1 (kN)	w1 (mm)	F2 (kN)	w2 (mm)	Fmax (kN)	Bending strength (MPa)	E-modulus (MPa)	Comments
A1	10.16	2.28	40.62	8.77	101.55	14.00	4666.36	Tested to breakage
A2	14.00	3.15	56.00	11.97	140.00	19.30	4731.15	Tested till 15 mm deflection
A3	14.15	3.08	56.60	12.16	141.51	19.51	4645.73	Tested till 15 mm deflection
A4	14.00	2.93	56.00	11.56	140.00	19.30	4837.93	Tested till 15 mm deflection
A5	13.34	3.16	53.35	11.48	133.37	18.39	4781.48	Tested to breakage
				Mean	131.29	18.10	4732.53	
				STD	16.92	2.33	79.72	
				Max	141.51	19.51	4837.93	
				Min	101.55	14.00	4645.73	

Table 4- Results of four-point bending test on balconies type B

Type	F1 (kN)	w1 (mm)	F2 (kN)	w2 (mm)	Fmax (kN)	Bending strength (MPa)	E-modulus (MPa)	Comments
B1	8.50	1.92	34.00	7.65	104.00	14.34	4418.39	Tested till 15 mm deflection
B2	11.97	2.74	47.88	10.67	119.69	16.50	4502.62	Tested to breakage
B3	14.17	3.33	56.68	12.98	141.70	19.54	4375.70	Tested till 15 mm deflection
B4	13.12	3.22	52.46	12.20	131.15	18.08	4357.74	Tested to breakage
B5	13.00	3.00	52.00	12.06	130.00	17.92	4276.67	Tested till 15 mm deflection
				Mean	125.31	17.28	4386.23	
				STD	14.23	1.96	82.93	
				Max	141.70	19.54	4502.62	
				Min	104.00	1.96	82.93	

Table 5- Results of four-point bending test on balconies type C

Type	F1 (kN)	w1 (mm)	F2 (kN)	w2 (mm)	Fmax (kN)	Bending strength (MPa)	E-modulus (MPa)	Comments
C1	9.87	1.53	39.46	5.95	98.66	10.48	4631.29	Tested till 15 mm deflection
C2	9.76	1.53	39.05	5.85	97.62	10.37	4686.83	Tested to breakage
C3	9.16	1.77	36.64	6.57	91.59	9.73	3957.33	Tested to breakage
C4	9.64	1.63	38.56	5.93	96.39	10.24	4644.30	Tested till 15 mm deflection
C5	6.60	1.13	26.40	4.18	97.00	10.31	4481.95	Tested till 15 mm deflection
				Mean	96.25	10.23	4480.34	
				STD	2.74	0.29	302.43	
				Max	98.66	10.48	4686.83	
				Min	91.59	9.73	3957.33	

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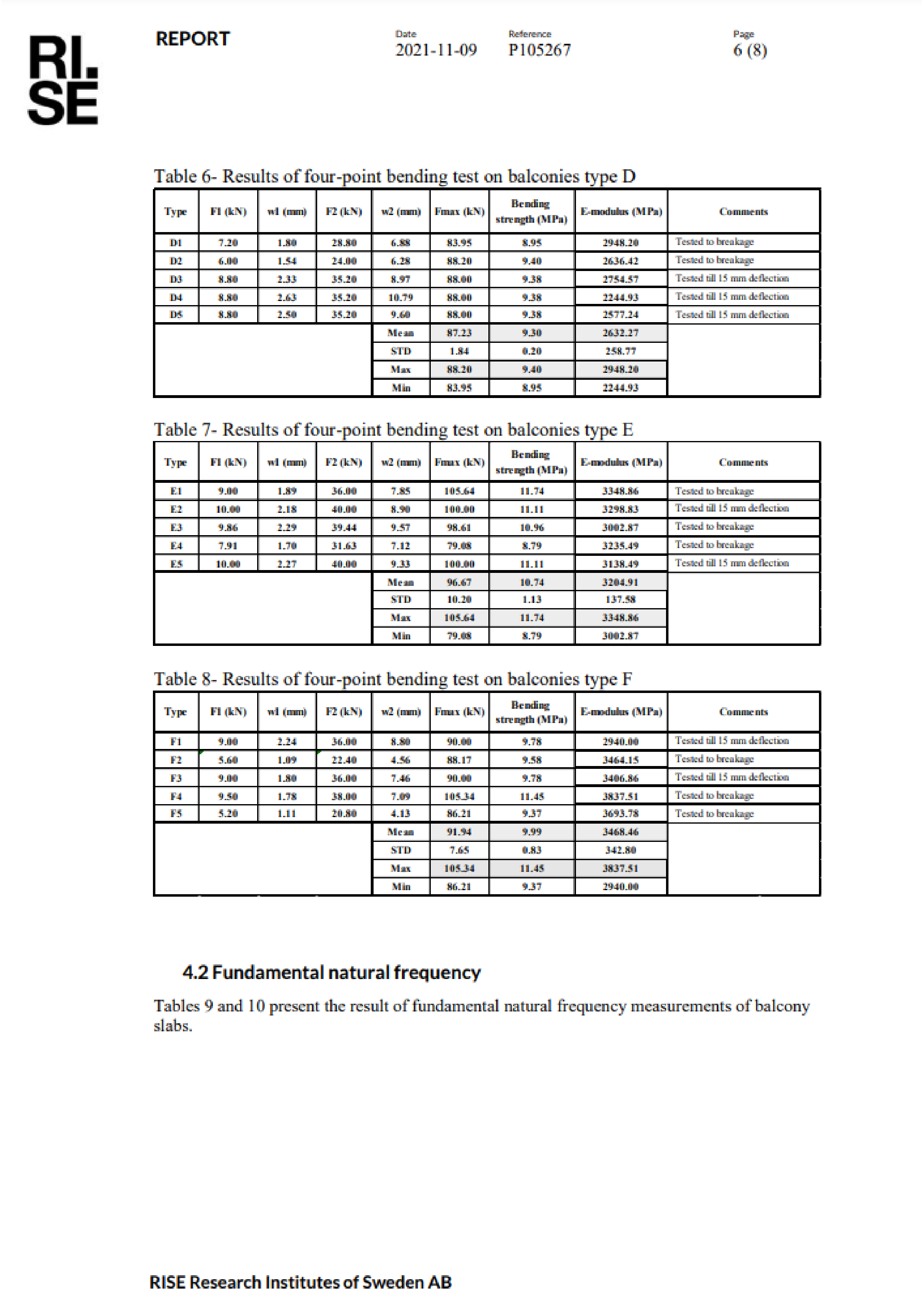

Table 6- Results of four-point bending test on balconies type D

Type	Fl (kN)	wl (mm)	F2 (kN)	w2 (mm)	Fmax (kN)	Bending strength (MPa)	E-modulus (MPa)	Comments
D1	7.20	1.80	28.80	6.88	83.95	8.95	2948.20	Tested to breakage
D2	6.00	1.54	24.00	6.28	88.20	9.40	2636.42	Tested to breakage
D3	8.80	2.33	35.20	8.97	88.00	9.38	2754.57	Tested till 15 mm deflection
D4	8.80	2.63	35.20	10.79	88.00	9.38	2244.93	Tested till 15 mm deflection
D5	8.80	2.50	35.20	9.60	88.00	9.38	2577.24	Tested till 15 mm deflection
				Mean	87.23	9.30	2632.27	
				STD	1.84	0.20	258.77	
				Max	88.20	9.40	2948.20	
				Min	83.95	8.95	2244.93	

Table 7- Results of four-point bending test on balconies type E

Type	Fl (kN)	wl (mm)	F2 (kN)	w2 (mm)	Fmax (kN)	Bending strength (MPa)	E-modulus (MPa)	Comments
E1	9.00	1.89	36.00	7.85	105.64	11.74	3348.86	Tested to breakage
E2	10.00	2.18	40.00	8.90	100.00	11.11	3298.83	Tested till 15 mm deflection
E3	9.86	2.29	39.44	9.57	98.61	10.96	3002.87	Tested to breakage
E4	7.91	1.70	31.63	7.12	79.08	8.79	3235.49	Tested to breakage
E5	10.00	2.27	40.00	9.33	100.00	11.11	3138.49	Tested till 15 mm deflection
				Mean	96.67	10.74	3204.91	
				STD	10.20	1.13	137.58	
				Max	105.64	11.74	3348.86	
				Min	79.08	8.79	3002.87	

Table 8- Results of four-point bending test on balconies type F

Type	Fl (kN)	wl (mm)	F2 (kN)	w2 (mm)	Fmax (kN)	Bending strength (MPa)	E-modulus (MPa)	Comments
F1	9.00	2.24	36.00	8.80	90.00	9.78	2940.00	Tested till 15 mm deflection
F2	5.60	1.09	22.40	4.56	88.17	9.58	3464.15	Tested to breakage
F3	9.00	1.80	36.00	7.46	90.00	9.78	3406.86	Tested till 15 mm deflection
F4	9.50	1.78	38.00	7.09	105.34	11.45	3837.51	Tested to breakage
F5	5.20	1.11	20.80	4.13	86.21	9.37	3693.78	Tested to breakage
				Mean	91.94	9.99	3468.46	
				STD	7.65	0.83	342.80	
				Max	105.34	11.45	3837.51	
				Min	86.21	9.37	2940.00	

4.2 Fundamental natural frequency

Tables 9 and 10 present the result of fundamental natural frequency measurements of balcony slabs.

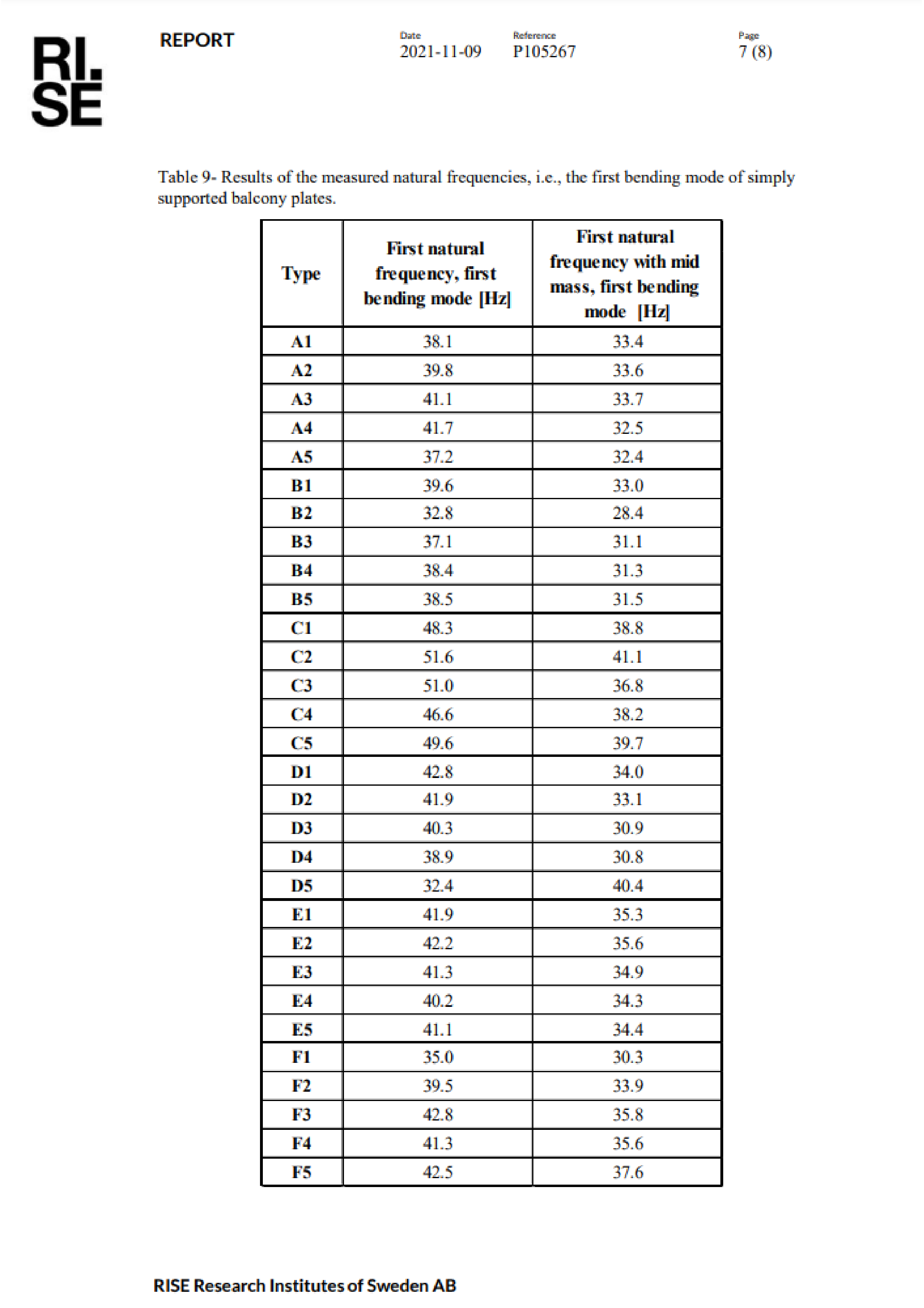

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Table 9- Results of the measured natural frequencies, i.e., the first bending mode of simply supported balcony plates.

Type	First natural frequency, first bending mode [Hz]	First natural frequency with mid mass, first bending mode [Hz]
A1	38.1	33.4
A2	39.8	33.6
A3	41.1	33.7
A4	41.7	32.5
A5	37.2	32.4
B1	39.6	33.0
B2	32.8	28.4
B3	37.1	31.1
B4	38.4	31.3
B5	38.5	31.5
C1	48.3	38.8
C2	51.6	41.1
C3	51.0	36.8
C4	46.6	38.2
C5	49.6	39.7
D1	42.8	34.0
D2	41.9	33.1
D3	40.3	30.9
D4	38.9	30.8
D5	32.4	40.4
E1	41.9	35.3
E2	42.2	35.6
E3	41.3	34.9
E4	40.2	34.3
E5	41.1	34.4
F1	35.0	30.3
F2	39.5	33.9
F3	42.8	35.8
F4	41.3	35.6
F5	42.5	37.6

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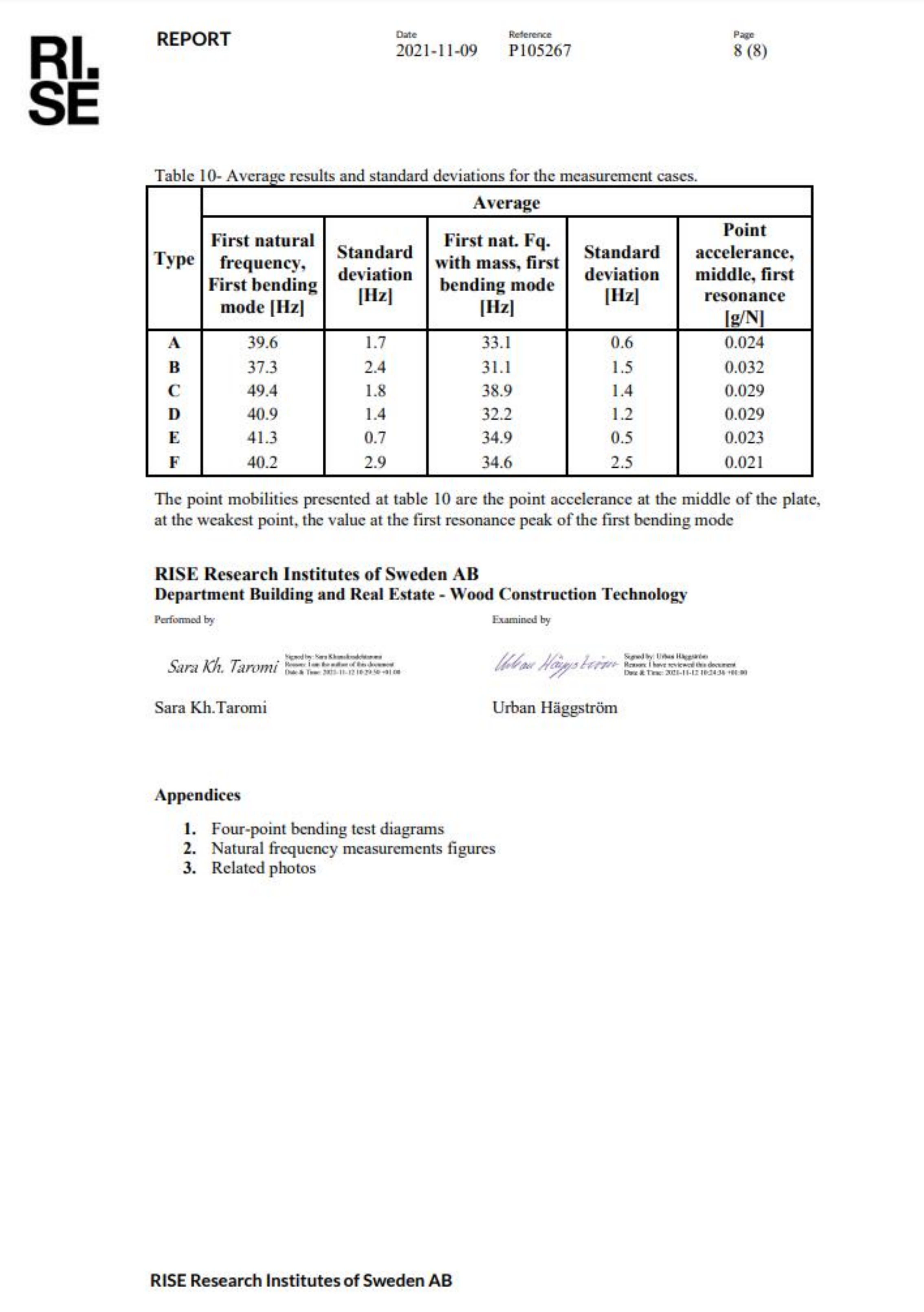

Table 10- Average results and standard deviations for the measurement cases.

Type	Average				
	First natural frequency, First bending mode [Hz]	Standard deviation [Hz]	First nat. Fq. with mass, first bending mode [Hz]	Standard deviation [Hz]	Point acceleration, middle, first resonance [g/N]
A	39.6	1.7	33.1	0.6	0.024
B	37.3	2.4	31.1	1.5	0.032
C	49.4	1.8	38.9	1.4	0.029
D	40.9	1.4	32.2	1.2	0.029
E	41.3	0.7	34.9	0.5	0.023
F	40.2	2.9	34.6	2.5	0.021

The point mobilities presented at table 10 are the point accelerance at the middle of the plate, at the weakest point, the value at the first resonance peak of the first bending mode

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Appendices

1. Four-point bending test diagrams
2. Natural frequency measurements figures
3. Related photos

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