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Sensitivity Analysis of the Circular Arch Bridge

Additional Graduation Research

TU Delft

Additional Graduation Research: Sensitivity Analysis of the Circular Arch Bridge

By

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Table of Contents

List of Figures

List of Tables

1. Introduction

The additional graduation research: *Sensitivity Analysis of the Circular Arch Bridge* is an integral part of the master thesis: *Structural Dynamic Response of the Circular Arch Bridge.* An electronic version of this thesis is available at http://repository.tudelft.nl/. This document is a separate report only containing the additional graduation research. For clarity and completeness of the research, it is advised to read the master thesis: *Structural Dynamic Response of the Circular Arch Bridge.*

1.1 Introduction of the research

In a world where we are all working towards a circular society, there lies an important task for the engineers. To achieve the goal of a circular society, there is a mission for the current and future generation engineers: *"Reduce, Reuse and Recycle"*. A demonstration of these so-called three R's is the Circular Arch Bridge. The Circular Arch Bridge is a demonstrator project by TU Delft and industry that shows the three R's in structural design and engineering.

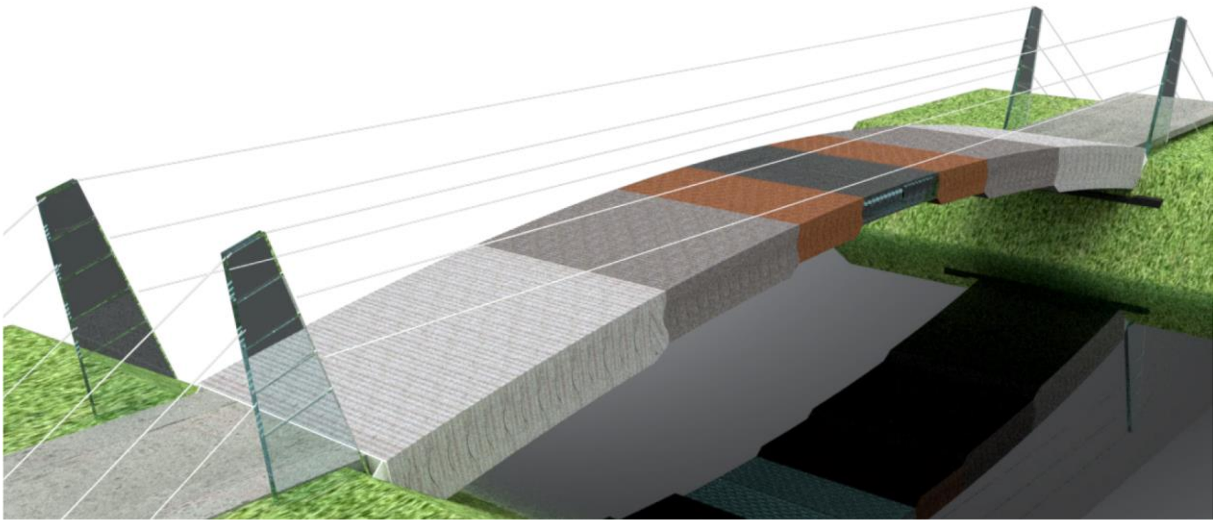

Figure 1.1: The Circular Arch Bridge, taken from (R. Nijsse, personal communications, November 17 2020);

Within the design of the Circular Arch Bridge, it has been optimised to *reduce* the amount of material needed. Due to a dry-stacked assembly, it is possible to assemble and disassemble the bridge on location. This allows for *reuse* of the separate stones. The Circular Arch Bridge consists out of four different *recycled* materials: cast glass, ceramic, circument and geopolymer concrete.

1.1.1 Problem introduction

An increasing amount of vibration problems in modern pedestrian bridges has shown that pedestrian bridges should no longer be designed for static loads only (Heinemeyer, et al., 2009) . With the Circular Arch Bridge being a pedestrian bridge, a dynamic assessment of the bridge is necessary to complete the design of the bridge.

At this point the Eurocodes do not provide special guidelines for assessing the dynamics of a hybrid structure like the Circular Arch Bridge. Besides that, the Eurocodes do not provide guidelines for the use of cast glass structural elements.

A study is needed to provide a full dynamic assessment of the Circular Arch Bridge. By live testing the bridge after construction, a better understanding of the dynamic properties of hybrid structures and structural cast glass structures is obtained. The results can be used in the development of guidelines for designing with structural glass.

1.2 Objective and methodology

1.2.1 Objective

The objective of this research to give insight in the sensitivity of the parameters within the design of the Circular Arch Bridge and give insight in the effect of design choices on the dynamic properties of the bridge.

The following assumptions have been made:

- **Design:** The available information about the design of the bridge is assumed correct and reliable.

- **Loads:** Only the self-weight of the bridge and human-induced loads have been considered present on the bridge. Wind and temperature induced loads have not been considered present.

The main research question of this research is:

What is the sensitivity of the Circular Arch Bridge when regarding the structural dynamic response?

The main research question can be answered when the following sub-questions have been answered:

- What is the sensitivity of the input parameters of the Circular Arch Bridge?

- What is the effect of big stiffness variation, for instance between a stone and the PU interlayer, on the dynamic properties of the bridge?
- What is the effect of the dry-stacked assembly on the dynamic properties of the bridge?

1.2.2 Methodology

Sensitivity Analysis

The sensitivity of the model is reviewed by performing finite element analyses. Also, finite element analyses are used to give insight in the effect that certain design choices have on the dynamic properties of the Circular Arch Bridge.

1.3 Outline

Part I – Introduction

- Chapter 1. Introduction

Part II – Additional research

- Chapter 2. Sensitivity of the

Part III – Conclusion and recommendations

- Chapter 3. Conclusions and recommendations

Part IV – Bibliography

- Bibliography

Part V – Annex

- Annex A - Sensitivity Analysis

2. Sensitivity of the Circular Arch Bridge

In order to get a better understanding of the relationship between the input and the output of the finite element model, a sensitivity analysis of the model is performed. In the sensitivity analysis the effect of changing certain input parameters on the dynamic properties of the model is analysed. The result of the analysis is an overview of the sensitivity of each selected input parameter. This overview can be used to see what certain choices in the design process have on the dynamic properties of the Circular Arch Bridge, but it can also be used to make changes to the design of the bridge when a change in the dynamic properties is desired. On top of that it gives an insight on the effect that deviation of parameters has on the dynamic properties of the bridge.

Besides a sensitivity analysis there are two design choices of which the effect on the dynamic properties of the Circular Arch Bridge are interesting to investigate. During the design it was chosen to apply a single type of interlayer in between the stones, due to this there are large stiffness variations in between the stones and the interlayer. The effect this has on the dynamic properties of the Circular Arch Bridge is addressed in this chapter.

The other design choice is the dry-stacked assembly of the bridge. The final part of this chapter will look into the effect of the dry-stacked assembly on the dynamic properties of the Circular Arch Bridge.

2.1 Sensitivity Analysis

The sensitivity analysis is performed by changing one single input parameter within the model at a time. After that the eigenvalue analysis is performed and the first ten eigenmodes of the model are obtained. An overview of the initial values of the eigenvalue analysis is given in **Table 2-1**.

Table 2-1: Results of the initial eigenvalue analysis;

Eigenvalue	Mode Type	Eigenfrequency [Hz]
1	Bending vertical	3.5375
2	Bending vertical	7.5440
3	Bending vertical	9.0743
4	Bending lateral	10.713
5	Bending vertical	15.124
6	Torsional	19.376
7	Bending vertical	23.942
8	Torsional	25.118
9	Torsional	28.100
10	Bending vertical	34.579

In the sensitivity analysis every input parameter is subjected to a 5%, 10% and 15% change of the initial value, in both negative and positive direction. **Table 2-2** shows the input parameters which are used in the sensitivity analysis.

Table 2-2: Input parameters of the sensitivity analysis, including their initial values;

Parameter	**Description**	**Initial value**	**Unit**
k_spring	Stiffness of horizontal spring support	48.000	*kN/m*
E_interface	Modulus of elasticity of the interface	30	*GPa*
E_glass	Modulus of elasticity of glass stones	70	*GPa*
E_ceramic	Modulus of elasticity of ceramic stones	5	*GPa*
E_circument	Modulus of elasticity of circument stones	70	*GPa*
E_geopolymer	Modulus of elasticity of geopolymer stones	5	*GPa*
D_glass	Density of glass stones	2500	*kg/m³*
D_ceramic	Density of ceramic stones	2000	*kg/m³*
D_circument	Density of circument stones	2500	*kg/m³*
D_geopolymer	Density of geopolymer stones	2000	*kg/m³*

For each change in the input parameters an eigenvalue analysis is performed. With the results of the eigenvalue analysis the sensitivity coefficient can be calculated. The sensitivity coefficient can be defined as the rate of change of a particular response of the model with respect to a change in a structural parameter. Within this sensitivity analysis the sensitivity coefficient is defined as the percentage change in mode frequency per 100% change in updating parameter. This is done with the use of equation **(2.1)**. (Gentile & Gallino, 2007)

$$S_i = \left(\frac{X_i}{f_i}\right) \cdot \left(\frac{df_i}{dX_i}\right) \cdot 100\% \qquad \textbf{(2.1)}$$

In which:

i is the number of the eigenmode;

S is the sensitivity;

X is the selected input parameter;

f is the eigenfrequency.

2.1.1 5% input parameter variation

In the first sensitivity analysis a variation of +/- 5% of the input parameters is applied. The sensitivity of the first ten eigenmodes are calculated and an overview is given in **Figure 2.1**. A larger view of the figure is shown in **Annex A - Sensitivity Analysis**.

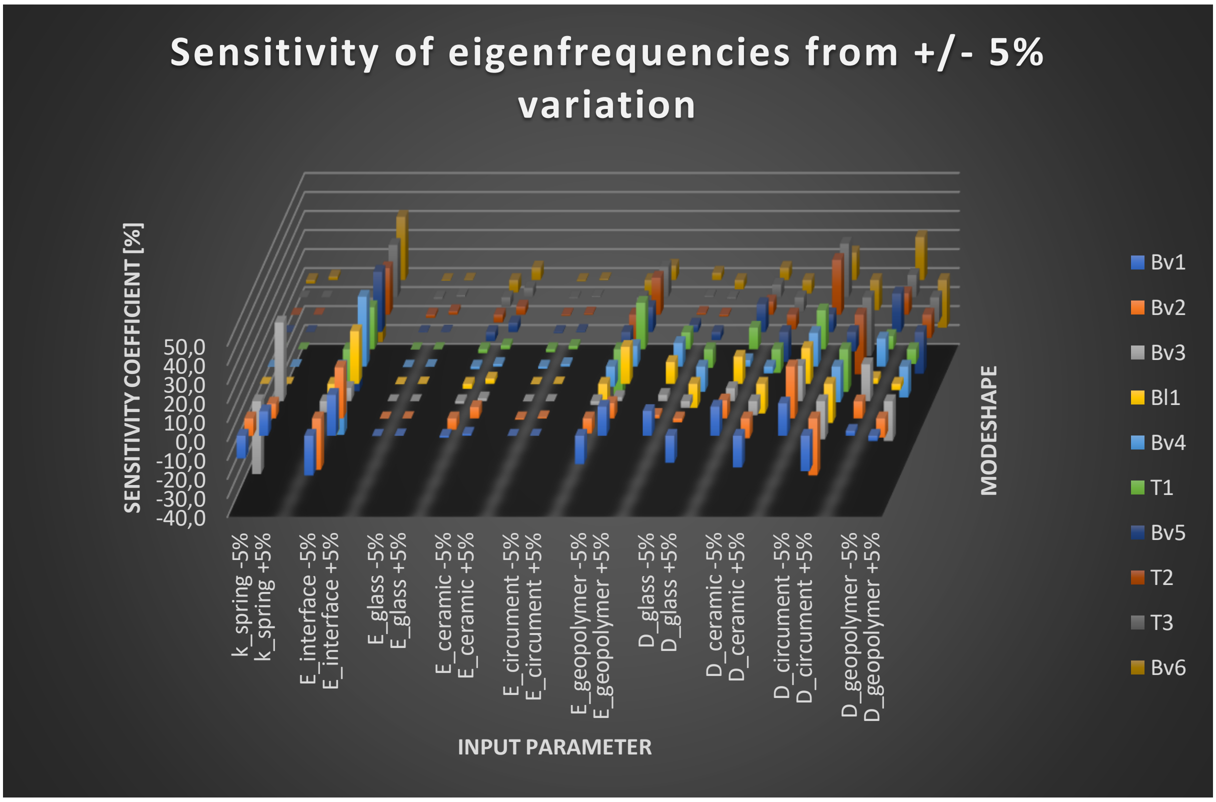

Figure 2.1: Sensitivity of eigenfrequencies from +/- 5% variation. A positive sensitivity means a higher eigenfrequency;

The values corresponding to the sensitivity analysis are given in **Table 2-3**.

Table 2-3: Sensitivity coefficient [%] at an input parameter variation of +/- 5%;

	Bv1	Bv2	Bv3	Bl1	Bv4	T1	Bv5	T2	T3	Bv6
k_spring -5%	-11,9	-9,3	-38,3	0,0	-0,1	0,0	-0,1	-0,1	0,0	-1,8
k_spring +5%	12,8	7,8	41,3	0,0	0,3	0,0	0,0	0,0	0,0	1,9
E_interface -5%	-20,9	-27,0	-5,9	-27,2	-36,0	-21,7	-31,1	-24,1	-26,9	-32,6
E_interface +5%	21,4	26,8	6,9	27,7	36,7	22,1	31,6	24,5	27,6	33,2
E_glass -5%	-0,2	-0,1	0,0	-0,2	-0,3	-0,1	-0,2	-1,7	-1,2	-0,3
E_glass +5%	0,2	0,1	0,0	0,2	0,3	0,1	0,2	1,8	1,2	0,3
E_ceramic -5%	-1,1	-5,9	-1,4	-2,7	-1,4	-2,1	-4,8	-4,1	-4,9	-6,6
E_ceramic +5%	1,1	5,9	1,5	2,7	1,4	2,1	4,9	4,3	5,0	6,6
E_circument -5%	-0,1	-0,6	-0,1	-0,2	-1,1	-1,6	-0,6	-0,5	-0,7	-0,5
E_circument +5%	0,1	0,6	0,1	0,2	1,2	1,7	0,5	0,6	0,7	0,5
E_geopolymer -5%	-14,9	-7,9	-2,0	-19,2	-10,6	-24,0	-12,9	-19,0	-15,7	-7,9
E_geopolymer +5%	15,3	8,1	2,1	19,4	10,8	24,4	13,1	19,5	16,1	7,6
D_glass -5%	13,0	1,8	3,2	11,5	12,4	8,9	3,8	0,9	0,8	3,8
D_glass +5%	-14,2	-2,1	-3,6	-12,6	-13,3	-9,8	-4,2	-0,9	-1,0	-4,8
D_ceramic -5%	15,2	9,4	6,8	14,3	3,4	11,3	14,6	6,9	6,7	6,5
D_ceramic +5%	-16,7	-10,4	-7,4	-15,6	-3,6	-12,4	-15,7	-7,6	-7,5	-7,1
D_circument -5%	16,9	27,3	18,5	18,8	17,7	20,5	9,2	28,8	28,2	14,5
D_circument +5%	-18,6	-29,9	-20,1	-20,6	-18,8	-22,5	-10,2	-31,3	-30,9	-15,8
D_geopolymer -5%	2,6	8,9	19,4	3,0	14,7	6,9	20,2	11,2	11,8	22,6
D_geopolymer +5%	-2,8	-10,0	-21,0	-3,3	-16,2	-7,7	-22,0	-12,3	-13,1	-25,0

2.1.2 10% input parameter variation

In the second sensitivity analysis a variation of +/- 10% of the input parameters is applied. The sensitivity of the first ten eigenmodes are calculated and an overview is given in **Figure 2.2**. A larger view of the figure is shown in **Annex A - Sensitivity Analysis**.

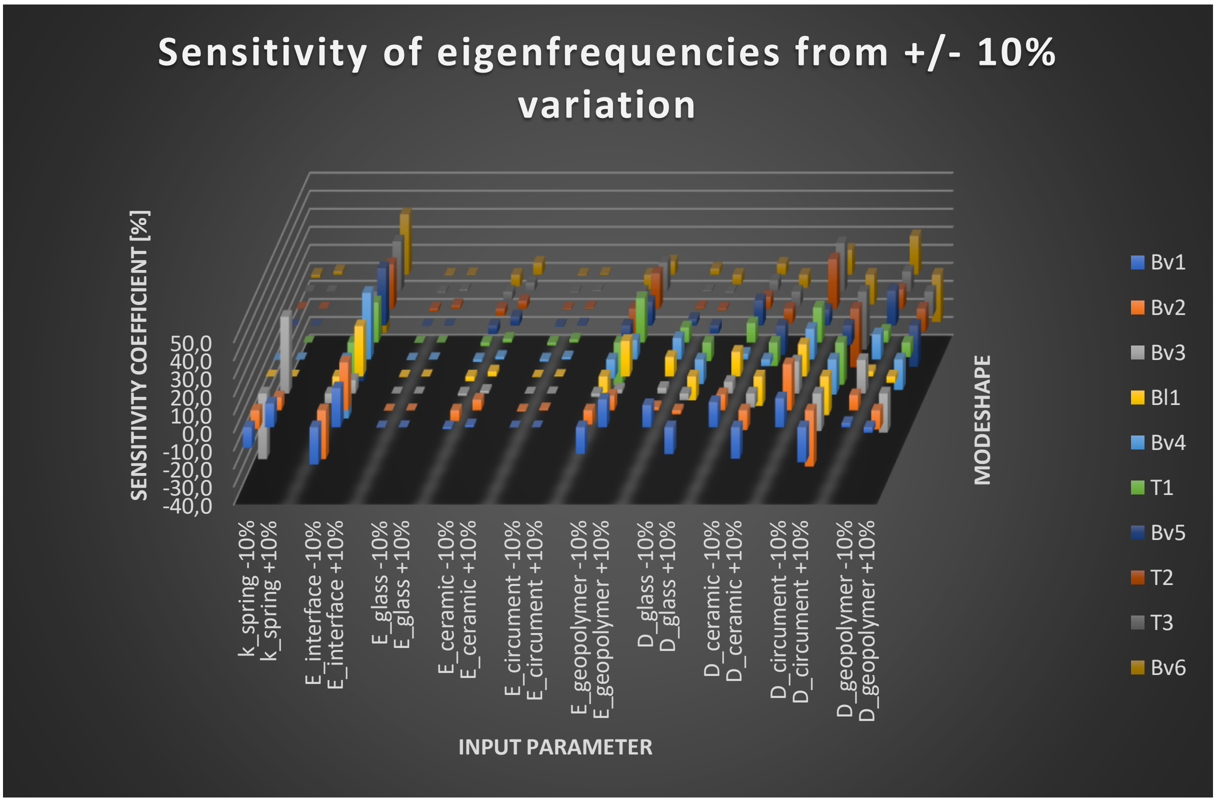

Figure 2.2: Sensitivity of eigenfrequencies from +/- 10% variation. A positive sensitivity means a higher eigenfrequency;

The values corresponding to the sensitivity analysis are given in **Table 2-4**.

Table 2-4: Sensitivity coefficient [%] at an input parameter variation of +/- 10%;

	Bv1	Bv2	Bv3	Bl1	Bv4	T1	Bv5	T2	T3	Bv6
k_spring -10%	-11,5	-10,3	-36,4	0,0	-0,1	0,0	0,0	0,0	0,0	-1,8
k_spring +10%	13,2	7,2	42,5	0,0	0,2	0,0	0,0	0,0	0,0	1,9
E_interface -10%	-20,6	-27,1	-5,5	-27,0	-32,7	-21,5	-30,9	-24,0	-26,6	-32,2
E_interface +10%	21,7	26,6	7,4	27,9	37,0	22,2	31,8	24,6	27,9	33,5
E_glass -10%	-0,2	-0,1	0,0	-0,3	-0,2	-0,1	-0,2	-1,7	-1,1	-0,3
E_glass +10%	0,2	0,1	0,0	0,2	0,3	0,1	0,2	1,8	1,2	0,3
E_ceramic -10%	-1,1	-5,9	-1,4	-2,7	-1,4	-2,0	-4,7	-4,0	-4,9	-6,5
E_ceramic +10%	1,1	5,9	1,5	2,8	1,5	2,1	4,9	4,2	5,0	6,6
E_circument -10%	-0,1	-0,6	-0,1	-0,3	-1,2	-1,6	-0,6	-0,5	-0,7	-0,5
E_circument +10%	0,1	0,6	0,1	0,3	1,2	1,7	0,6	0,6	0,7	0,5
E_geopolymer -10%	-14,7	-7,8	-2,0	-18,9	-10,5	-23,8	-12,8	-18,8	-15,4	-8,1
E_geopolymer +10%	15,5	8,1	2,2	19,7	10,7	24,6	13,1	19,6	16,4	7,4
D_glass -10%	12,3	1,8	3,1	10,9	11,9	8,4	3,6	0,9	0,8	3,4
D_glass +10%	-14,9	-2,2	-3,7	-13,2	-13,7	-10,3	-4,4	-1,0	-1,0	-5,4
D_ceramic -10%	14,0	8,9	6,4	13,7	3,2	10,7	14,0	6,6	6,4	6,1
D_ceramic +10%	-17,4	-10,9	-7,8	-16,4	-3,7	-13,0	-16,3	-8,0	-7,9	-7,4
D_circument -10%	16,1	25,6	17,7	17,9	17,0	19,4	8,8	27,4	26,9	13,8
D_circument +10%	-19,4	-31,2	-20,9	-21,5	-19,5	-23,4	-10,7	-32,6	-32,1	-16,5
D_geopolymer -10%	2,4	8,4	18,5	2,9	13,9	6,5	19,3	10,6	11,1	21,4
D_geopolymer +10%	-3,0	-10,6	-21,8	-3,5	-16,9	-8,1	-22,8	-12,9	-13,7	-26,3

2.1.3 15% input parameter variation

In the third sensitivity analysis a variation of +/- 15% of the input parameters is applied. The sensitivity of the first ten eigenmodes are calculated and an overview is given in **Figure 2.3**. A larger view of the figure is shown in **Annex A - Sensitivity Analysis**.

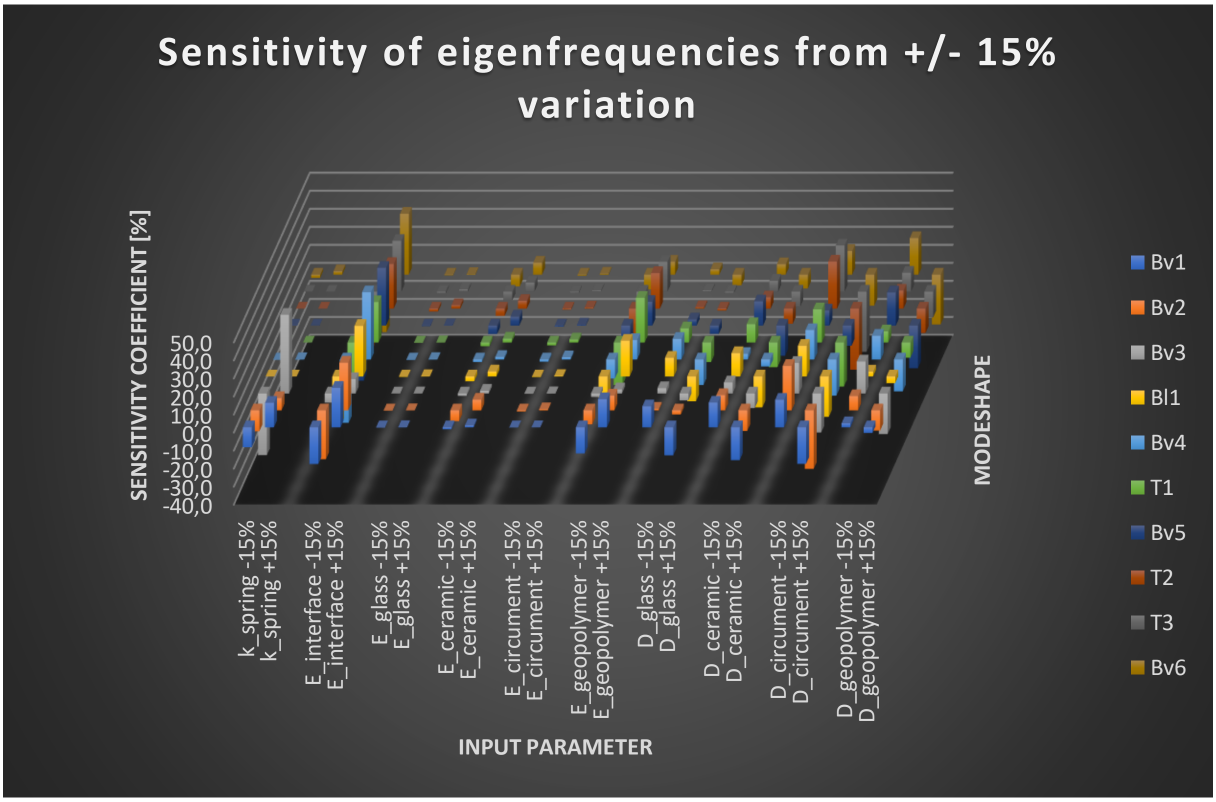

Figure 2.3: Sensitivity of eigenfrequencies from +/- 15% variation. A positive sensitivity means a higher eigenfrequency;

The values corresponding to the sensitivity analysis are given in **Table 2-5**.

Table 2-5: Sensitivity coefficient [%] at an input parameter variation of +/- 15%;

	Bv1	Bv2	Bv3	Bl1	Bv4	T1	Bv5	T2	T3	Bv6
k_spring -15%	-11,0	-11,6	-34,2	0,0	-0,1	0,0	0,0	0,0	0,0	-1,8
k_spring +15%	13,6	6,8	43,6	0,0	0,2	0,0	0,0	0,0	0,0	1,9
E_interface -15%	-20,3	-27,1	-5,1	-26,8	-35,1	-21,3	-30,6	-23,8	-26,2	-31,8
E_interface +15%	21,9	26,4	7,9	28,1	37,3	22,4	32,0	24,7	28,2	33,8
E_glass -15%	-0,2	-0,1	0,0	-0,2	-0,2	-0,1	-0,2	-1,6	-1,1	-0,3
E_glass +15%	0,2	0,1	0,0	0,2	0,3	0,1	0,2	1,9	1,3	0,3
E_ceramic -15%	-1,1	-5,9	-1,3	-2,7	-1,4	-2,1	-4,7	-4,0	-4,8	-6,5
E_ceramic +15%	1,1	5,9	1,5	2,8	1,4	2,1	5,0	4,3	5,0	6,7
E_circument -15%	-0,1	-0,6	-0,1	-0,3	-1,2	-1,6	-0,6	-0,5	-0,7	-0,5
E_circument +15%	0,1	0,6	0,1	0,3	1,2	1,7	0,6	0,6	0,7	0,5
E_geopolymer -15%	-14,5	-7,8	-1,9	-18,7	-10,5	-23,5	-12,7	-18,6	-15,2	-8,2
E_geopolymer +15%	15,6	8,2	2,2	19,8	10,7	24,8	13,2	19,7	16,6	7,2
D_glass -15%	11,6	0,9	2,9	10,3	11,4	7,9	3,4	0,8	0,8	3,0
D_glass +15%	-15,5	-2,3	-3,9	-13,8	-14,1	-10,8	-4,6	-1,1	-1,0	-5,9
D_ceramic -15%	13,7	8,4	6,1	12,9	3,1	10,2	13,4	6,2	6,0	5,8
D_ceramic +15%	-18,1	-11,4	-8,1	-17,1	-3,9	-13,7	-16,8	-8,4	-8,2	-7,7
D_circument -15%	15,3	24,7	16,9	17,0	16,3	18,4	8,3	26,1	25,6	13,1
D_circument +15%	-20,2	-32,5	-21,6	-22,4	-20,0	-24,4	-11,2	-33,8	-33,4	-17,2
D_geopolymer -15%	2,3	7,9	17,7	2,7	13,1	6,2	18,4	10,0	10,5	20,3
D_geopolymer +15%	-3,1	-11,2	-22,5	-3,7	-17,7	-8,4	-23,7	-13,5	-14,3	-27,6

2.1.4 Conclusion

The three performed sensitivity analyses can be used to draw several conclusions about the dynamic behaviour of the Circular Arch Bridge. Since the first eigenmode is in the critical range of natural frequencies for pedestrian bridges, the sensitivity of this eigenmode is the most important. This is due to the fact that a change in this frequency can have a significant effect on the dynamic behaviour of the Circular Arch Bridge. For the second eigenmode only very large changes will have an effect on the dynamic behaviour of the bridge, therefore this mode is also considered to be important. For the higher eigenmodes it is not expected that they will influence the dynamic behaviour of the bridge. The conclusions drawn below are therefore based on the first two eigenmodes, however the sensitivity of higher eigenmodes still provides important information, which can be valuable during experiments on the bridge.

A table with the results of all sensitivity analyses is used to draw the conclusions. This table is shown in **Annex A - Sensitivity Analysis**.

The most sensitive input parameter of the model is the modulus of elasticity of the interface. This input parameter has the largest effect on the first two eigenmodes and can therefore affect the dynamic behaviour of the bridge the most. Since the eigenfrequencies are defined with: $\omega = \sqrt{\frac{k}{m}}$, in which k is the stiffness and m is the mass, it is a logical conclusion that the modulus of elasticity of the interfaces is so sensitive. The interfaces are present everywhere throughout the structure, meaning that it has a large influence on the stiffness of the structure and therefore on the eigenfrequencies of the model. There is a positive correlation between the variation and the sensitivity, meaning that a reduction of the input parameter will lead to a reduction in eigenfrequency and vice versa. It would be expected that the magnitude of the sensitivity is equal for every variation size, however slight differences can be obtained. However, the differences in the sensitivity of the different variations are low and will therefore not lead to large deviations.

The second most sensitive input parameter is the density of the circument stones. The sensitivity of this input parameter has a negative correlation with the eigenfrequencies, meaning a lower density will lead to higher eigenfrequencies. This can be simply lead back to the relation of the eigenfrequencies to the mass and stiffness of the structure, since the mass is in the denominator a smaller eigenfrequency is obtained when the mass of the structure rises. Again, for this input parameter there is a small deviation in between the sensitivity of the different variations, however the differences are still very small, so it does not lead to large deviations.

The next most sensitive input parameters are the density of the ceramic stones, the modulus of elasticity of the geopolymer concrete stones and the density of the glass stones. All these input parameters have roughly the same sensitivity and no big differences of the sensitivity is observed in the different variation steps. Also, for these input parameters a positive correlation is found for the modulus of elasticity and a negative correlation is found for the density. It can be noted that when the modulus of elasticity of the different materials of the stones are regarded, only the modulus of elasticity of the geopolymer concrete is sensitive. The modulus of elasticity of the other materials of the stone are not nearly as sensitive. This can be lead back to two factors. The first factor is caused by the varying thickness of the deck of the bridge. The geopolymer concrete stones have the largest thickness, thus the largest volume of all materials, and therefore have the largest contribution in the stiffness of the structure. Since it has the largest contribution to the stiffness of the structure, it will also have the most influence on the eigenfrequencies when the stiffness of the material is changed. This is supported by the fact that the sensitivity of the modulus of elasticity of the circument stones is lower, and the sensitivity of the modulus of elasticity of glass is lower than of circument. When considering the geometry of the structure the circument stones have a smaller thickness than the geopolymer concrete stones, and the glass stones have a smaller thickness than the circument stones. The second factor that causes the modulus of elasticity to be very sensitive is that position of the material within the structure. The geopolymer concrete stones are at a location where there where larger changes in the curvature occur in the eigenmodes than for instance for the glass stones. For instance, when regarding the eigenmode T2 there is a large curvature change in the geopolymer concrete stones, while in eigenmode Bv3 there is almost no curvature change for the geopolymer concrete stones. It can be seen in the sensitivity of the modulus of elasticity of geopolymer concrete that there is a high sensitivity for the eigenfrequency of mode T2 and a low sensitivity for the eigenfrequency of mode Bv3. This also explains why the sensitivity of the modulus of elasticity of ceramic is higher than that of circument, while the thickness of the circument stones is higher so it influences the stiffness of the structure more. The ceramic stones are also at positions where there are large changes in the curvature in the eigenmodes, which causes the modulus of elasticity if ceramic stones to be more sensitive than that of circument and glass.

After that the stiffness of the support spring is the most sensitive input parameter. This input parameter has a positive correlation with the sensitivity. A very high sensitivity is observed for the third eigenmode, which is caused by a large translation of the support in this eigenmode. However, the eigenfrequency belonging to this eigenmode is not likely to get into the critical range of natural frequencies of pedestrian bridges. This is due to the fact that the stiffness of the support spring is in that case so low, that the horizontal displacement will result in a failure mechanism. In that case the design of the bridge is not stable anymore. Another remarkable feature of this input parameter is that it only affects the vertical bending modes and not the lateral bending and the torsional modes. All other input parameters affect all the eigenmodes.

The lowest significant input parameters are the density of the geopolymer concrete stones and the modulus of elasticity of the ceramic stones. The sensitivity of these parameters is a lot lower than the earlier mentioned parameters, but they are still significant.

The modulus of elasticity of the glass stones and the modulus of elasticity of the circument stones do not significantly contribute to the magnitude of the eigenfrequencies. It can be concluded that these input parameters are not sensitive.

The results of the sensitivity analysis can be valuable information for performing experiments, like a hammer test on the bridge. For instance, when there is an eigenfrequency that is only sensitive for a single input parameter, the corresponding mode shape can then be used for tuning of the model and should be investigated during experiments. When regarding the sensitivity analysis of the Circular Arch Bridge there are no mode shapes that stand out, because all the corresponding eigenfrequencies are sensitive for a large amount of input parameters. However, it is advised to at least investigate mode shapes Bv3 and Bv4 during experiments. Mode shape Bv3 is the third eigenmode with an eigenfrequency of 9.0743 Hz. This mode shape is interesting to investigate since it is very sensitive to the stiffness of the supports and significantly lower for the other input parameters. For the fifth mode shape Bv4, with an eigenfrequency of 15.124 Hz, it is observed that the sensitivity is very high for the modulus of elasticity of the interface and significantly lower for the other input parameters. Since there are no outstanding mode shapes that should be investigated, it is advised that the eigenvalue analysis is extended to a larger amount of eigenfrequencies and make a sensitivity analysis of this eigenvalue analysis. This could result into mode shapes that are sensitive to a little amount of input parameters, which can help further research on the Circular Arch Bridge.

2.2 Effect of large stiffness differences between the interlayer and stones

To understand the effect of the large stiffness differences in between the stones of the Circular Arch Bridge and the interlayers in between the stones, a comparison is made where the difference is stiffness is minimalised. The stiffnesses of the different materials is shown in **Table 2-6**.

Table 2-6: Stiffness of the different materials;

Material	Stiffness	Unit
Interlayer	30	GPa
Geopolymer Concrete	5	GPa
Circument	70	GPa
Ceramic	5	GPa
Glass	70	GPa

To minimise the large differences in the stiffness between the interlayer and the different materials, it is chosen to introduce different types of interlayers. A different type of interlayer is used for each different material, where the interlayer has a stiffness equal to the material of the stone. At the interfaces of different materials, an interlayer is used with a stiffness that is in middle of the stiffnesses of the two materials. The location of the different types of interlayers is shown in **Figure 2.4**. The stiffness of each type of interlayer is presented in **Table 2-7**.

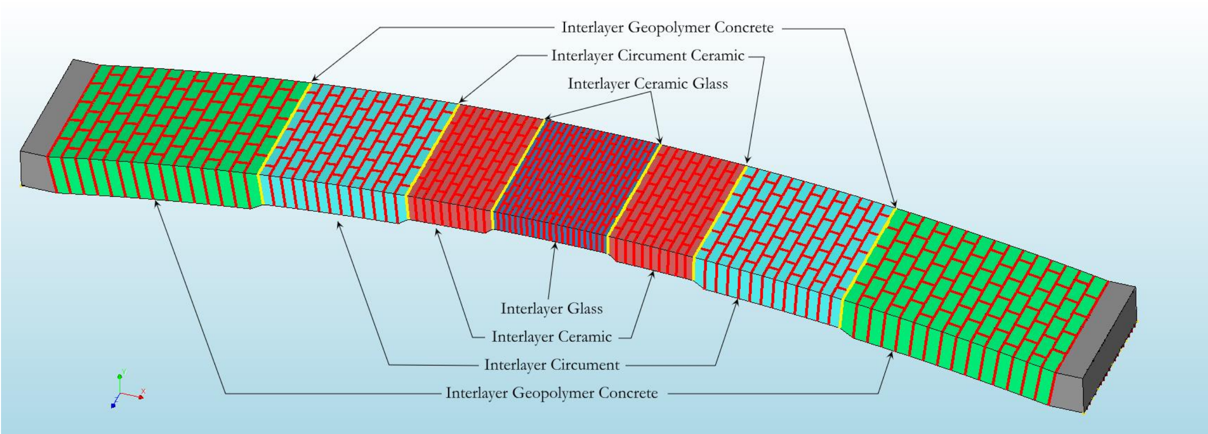

Figure 2.4: Location of the different interlayer types for minimised stiffness differences;

Table 2-7: Stiffness of different interlayer types;

Interlayer	Stiffness	Unit
Geopolymer Concrete	5	GPa
Geopolymer Concrete - Circument	37.5	GPa
Circument	70	GPa
Circument – Ceramic	37.5	GPa
Ceramic	5	GPa
Ceramic - Glass	37.5	GPa
Glass	70	GPa

An eigenvalue analysis of the model with the interlayers as given above is performed. An overview of the first ten eigenmodes and corresponding eigenfrequencies is presented in **Table 2-8**.

Table 2-8: Comparison of the eigenvalue analysis;

Eigenvalue	Mode Type	Eigenfrequency of original model [Hz]	Eigenfrequency of model with minimal stiffness differences [Hz]
1	Bending vertical	3.5375	2.4939
2	Bending vertical	7.5440	4.8880
3	Bending vertical	9.0743	8.5883
4	Bending lateral	10.713	6.5685
5	Bending vertical	15.124	11.874
6	Torsional	19.376	13.394
7	Bending vertical	23.942	15.116
8	Torsional	25.118	17.130
9	Torsional	28.100	19.805
10	Bending vertical	34.579	26.416

From the results of the eigenvalue analysis, it can be concluded that minimising the stiffness differences between the interlayer and the stones of the bridge has a large negative effect on the dynamic properties of the Circular Arch Bridge. The frequency of the first eigenmode decreased from 3.5375 Hz to 2.4939 Hz. In the initial model this eigenfrequency was in the critical range of the second harmonic of vertical and longitudinal vibrations. It was proven that no problems with the dynamic behaviour of the bridge were to be expected. In the model with the minimised differences in stiffness the eigenfrequency is very close to the critical range of the first harmonic of vertical and longitudinal vibrations.

The effect of the big stiffness differences within the Circular Arch Bridge is also investigated by running a dynamic analysis. It is chosen to perform the analysis of the vertical acceleration caused by a TC5 pedestrian load. The results of the determination of the vertical acceleration of the model with a tensile capacity is given in **Figure 2.5**.

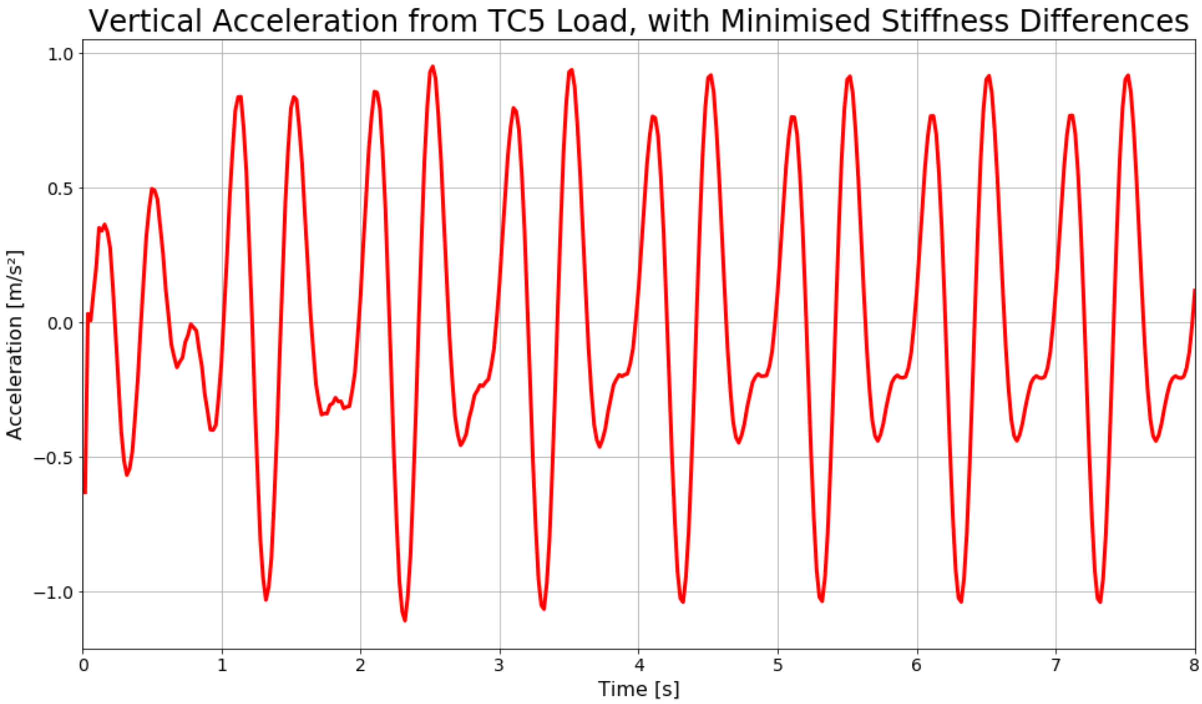

Figure 2.5: Vertical acceleration from TC5 load, with minimised stiffness differences;

The maximum observed vertical acceleration due to a TC5 load is 1.11 m/s^2. In the initial model the maximum observed vertical acceleration due to a TC5 load was 0.47 m/s^2. It is thus observed that the addition of a tensile capacity to the interlayer has significantly increased the accelerations within the Circular Arch Bridge. It can also be observed that the vertical accelerations show a very different pattern compared to the initial dynamic analysis of TC5.

The example of the dynamic analysis of TC5 shows that the dynamic behaviour of the Circular Arch Bridge will be worse than what was proven earlier. It can thus be concluded that the large stiffness differences in the Circular Arch Bridge have a negative effect on the dynamic behaviour. It is advised to use the interlayer of the initial model, since it has been proven that there are no problems with the dynamic properties of the Circular Arch Bridge.

2.3 Effect of dry-stacked assembly

Within the current design the stones of the Circular Arch Bridge have a dry-stacked assembly, meaning that there is no tensile capacity in between the stones. To investigate what effect this has on the dynamic properties of the Circular Arch Bridge, an analysis is performed in which a tensile capacity of the interlayer is introduced.

To give a realistic representation of the tensile capacity of the interlayer, an interlayer is selected that has been used in the Crystal Houses project. In this project a masonry glass façade was constructed, in which an adhesive was used to connect the glass stones. The used adhesive is *Delo Photobond 4468* (Oikonomopoulou, Bristogianni, Veer, & Nijsse, 2018). The tensile strength of this adhesive is given by the manufacturer as f_t = 14 MPa (DELO, 2022).

The effect of the dry-stacked assembly of the Circular Arch Bridge is investigated by assigning the above-mentioned tensile capacity to the interlayer within the model and running a dynamic analysis. It is chosen to perform the analysis of the vertical acceleration caused by a TC5 pedestrian load. The results of the determination of the vertical acceleration of the model with a tensile capacity is given in **Figure 2.6**.

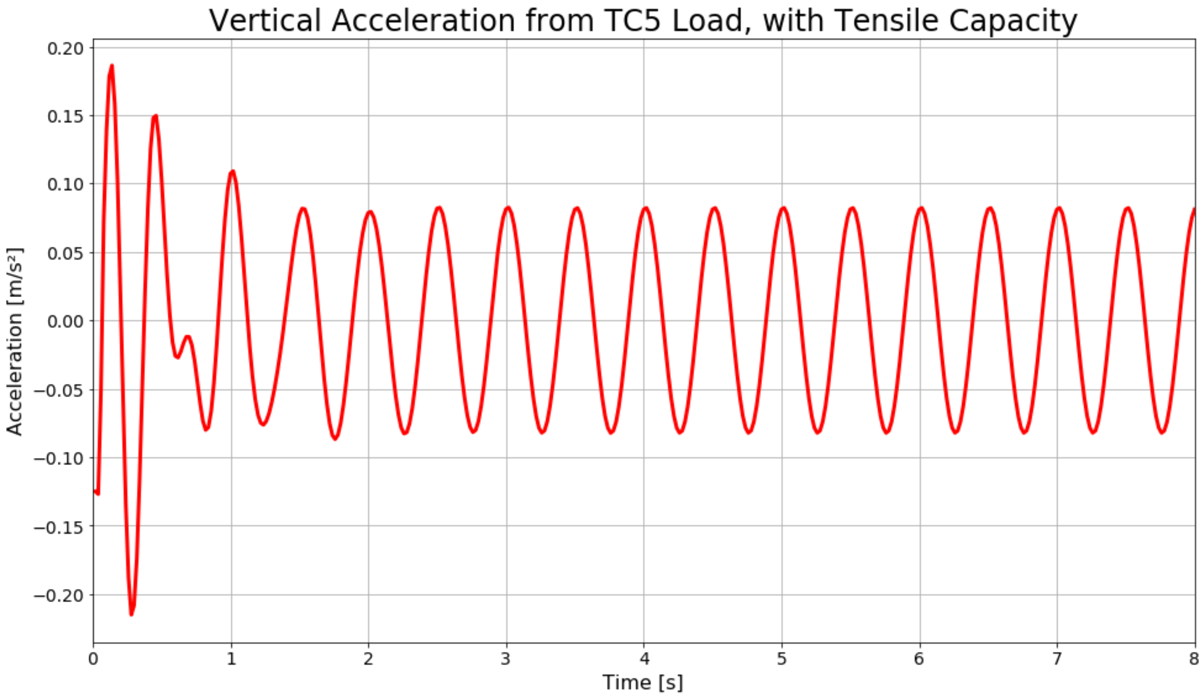

Figure 2.6: Vertical acceleration from TC5 load, with tensile capacity of interlayer;

The maximum observed vertical acceleration due to a TC5 load is 0.22 m/s². In the initial model the maximum observed vertical acceleration due to a TC5 load was 0.47 m/s². It is thus observed that the addition of a tensile capacity to the interlayer has significantly reduced the accelerations within the Circular Arch Bridge. It can therefore be concluded that the effect of the dry-stacked assembly of the Circular Arch Bridge is seriously disadvantageous for the dynamic behaviour of the bridge.

It should be noted that the conclusion drawn above is purely based on the effect of the dry-stacked assembly of the bridge. When the bridge is to be assembled with the use of an adhesive interlayer, it should be carefully considered what type of adhesive interlayer must be used. This adhesive interlayer will not only differ in tensile capacity from the interlayer used within the Circular Arch Bridge. It will also have different values for, for example the stiffness of the material. Using an adhesive interlayer could also mean that different types of interlayers have to be used for the different materials. As was concluded within the sensitivity analysis, both these changes can have significant effects on the dynamic behaviour of the bridge. If an adhesive interlayer must be used, it is advised to perform a full dynamic assessment of the Circular Arch Bridge to prevent unexpected dynamic problems from occurring.

2.4 Structural Damping

The structural damping used in the dynamic assessment of the Circular Arch Bridge is assumed to be 5%. However, this value has to be verified after construction of the bridge is finished. However, the structural damping does affect the results from the dynamic assessment. For the main load cases it is therefore investigated what the results of the dynamic assessment are for different values of structural damping. The results are shown in **Table 2-9**.

Table 2-9: Maximum vertical acceleration at different levels of structural damping;

Structural damping [%]	Maximum vertical acceleration [m/s²]			
	TC3	**TC5**	**Joggers**	**Dancing Group**
0	0.62	0.84	1.83	2.11
1	0.50	0.71	1.13	1.91
2	0.43	0.63	1.01	1.81
3	0.39	0.54	0.92	1.73
4	0.35	0.51	0.84	1.64
5	0.32	0.47	0.83	1.53

The results in **Table 2-9** can be used in further studies of the Circular Arch Bridge for an overview of how the structural damping affects the dynamic properties of the Circular Arch Bridge. In this research the results are used to give a recommendation of what the minimum level of structural damping is advised in further research of the Circular Arch Bridge. The advise on the minimum level of structural damping is based on remaining the same comfort level for the most common load case. The most common load cases of the Circular Arch Bridge are the Traffic Class 3 load case and the Joggers load case, since these load cases can happen occasionally. For the other load cases applies that their occurrence is far more exceptional to happen. For these load cases a minimum level of structural damping is given, in order to maintain the same comfort level as in the case of a structural damping of 5%.

For Traffic Class 3 applies the maximum level of comfort at a structural damping of 5%. If the vertical acceleration is larger than 0.50 m/s², a medium level of comfort applies for this load case. In order to remain in the same comfort class, the structural damping should be a higher than 1%.

In case of the Joggers load the Circular Arch Bridge provides a medium level of comfort at a structural damping of 5%. The Circular Arch Bridge will provide a minimum level of comfort when the vertical acceleration is larger than 1.00 m/s². For this load case the structural damping should therefore be larger than 2%.

It is advised that the minimum level of structural damping of the Circular Arch Bridge is 2%. At this level of structural damping, the comfort class of the most common load cases of the Circular Arch Bridge remains the same as in the dynamic assessment performed in this research.

3. Conclusions and recommendations

3.1 Conclusions

The objective of this research is to give insight in the sensitivity of the parameters within the design of the Circular Arch Bridge and give insight in the effect of design choices on the dynamic properties of the bridge.

The sensitivity of the input parameters of the finite element model is determined. The given overview of the sensitivity of the input parameters shows the influence that inaccuracy of parameters, or uncertainty of the parameters has on the dynamic properties of the Circular Arch Bridge. The most sensitive input parameter is the modulus of elasticity of the interlayer. The sensitivity analysis shows that a large amount of input parameters have a significant effect on the dynamic properties of the bridge, it is therefore important that the selected values of the parameters are accurate compared to the actual values of the to be constructed bridge.

The effect of big stiffness differences between the interlayer and the stones of the bridge on the dynamic properties is investigated. Finite element analysis shows that the big stiffness differences have a positive result on the dynamic properties of the bridge. In a model where the stiffness differences are minimised the bridge shows significantly worse dynamic behaviour.

It can be concluded that the dry-stacked assembly of the Circular Arch Bridge has a negative effect on the dynamic properties of the bridge. Finite element analysis shows that when an adhesive with a tensile capacity is used as an interlayer, the dynamic properties of the bridge are significantly better.

The vertical acceleration at different levels of structural damping has been analysed. The results are compared to the results of the dynamic assessment where structural damping is assumed to be 5%. For the load case Traffic Class 3 the minimum level of structural damping is 1% in order to be in the same comfort class as in the dynamic assessment performed in this research.

3.2 Recommendations for future research

During experiments on the bridge the third and fifth mode shapes should at least be investigated. There are no other specifically interesting mode shapes within the first ten eigenmodes. It is therefore advised that the eigenvalue analysis and the sensitivity analysis are extended to a larger amount of eigenvalues, in order to find other mode shapes that can be used during tuning of the model.

It is advised that the Circular Arch Bridge has a minimum structural damping of 2%. At this level of structural damping the comfort class of the bridge requires the same as in this research for the most common load cases: Traffic Class 3 and Jogger load.

Bibliography

DELO. (2022, January 5). *DELO Photobond 4468 Technical Datasheet.* Retrieved from DELO Adhesives: https://www.delo-adhesives.com/products/detail/delo-photobond

Gentile, C., & Gallino, N. (2007, February 14). Ambient vibration testing and structural evaluation of an historic suspension footbridge. *Advances in Engineering Software, 2008*(39), 356-366. doi:https://doi.org/10.1016/j.advengsoft.2007.01.001

Heinemeyer, C., Butz, C., Keil, A., Schlaich, M., Goldack, A., Trometer, S., . . . Caetano, E. (2009). *Design of Lightweight Footbridges for Human Induced Vibrations.* Luxembourg: Office for Official Publications of the European Communities.

Oikonomopoulou, F., Bristogianni, T., Veer, F. A., & Nijsse, R. (2018). The construction of the Crystal Houses façade: challenges and innovations. *Glass Struct Eng*(3), 87-108. doi:https://doi.org/10.1007/s40940-017-0039-4

Annex A - Sensitivity Analysis

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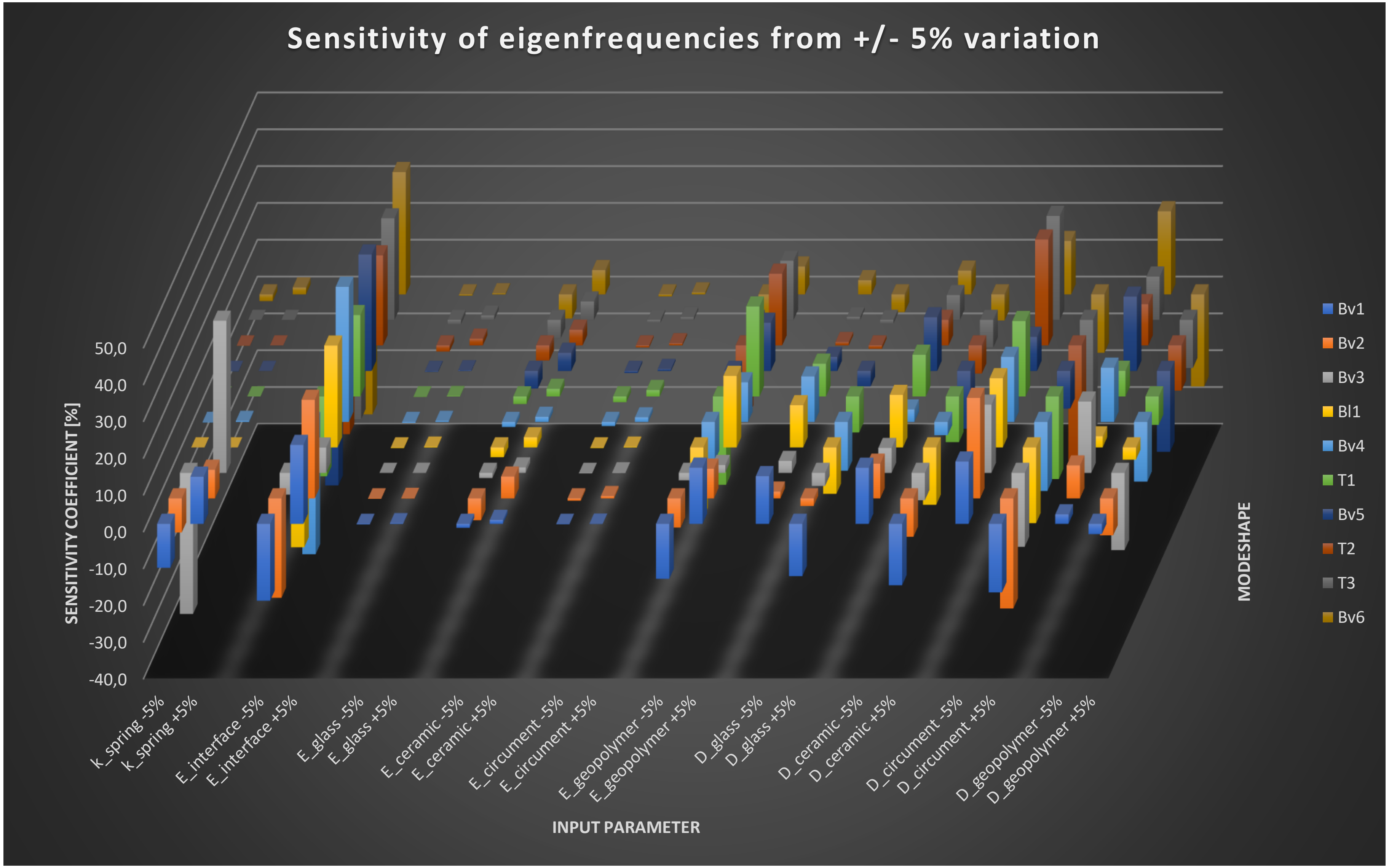
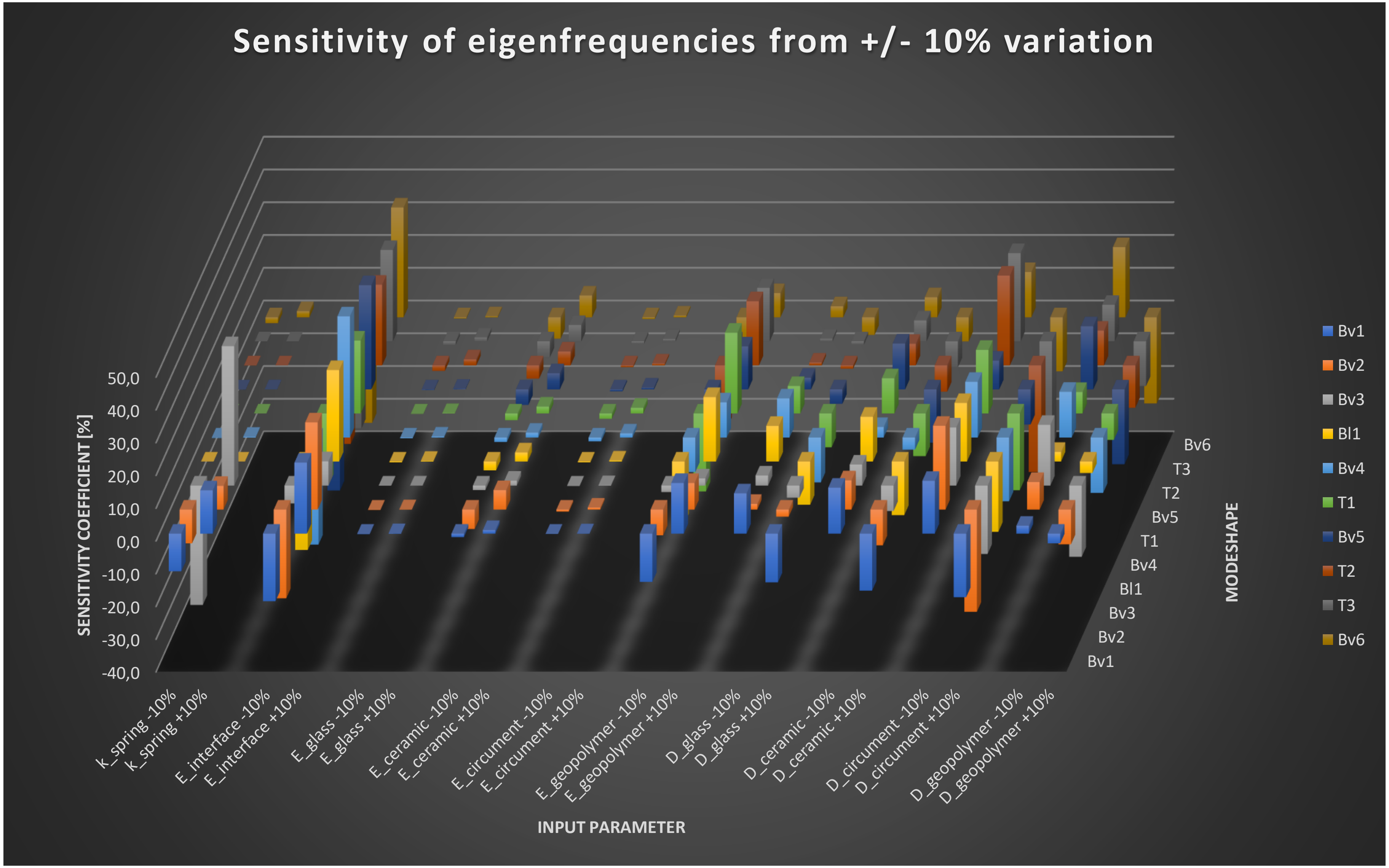
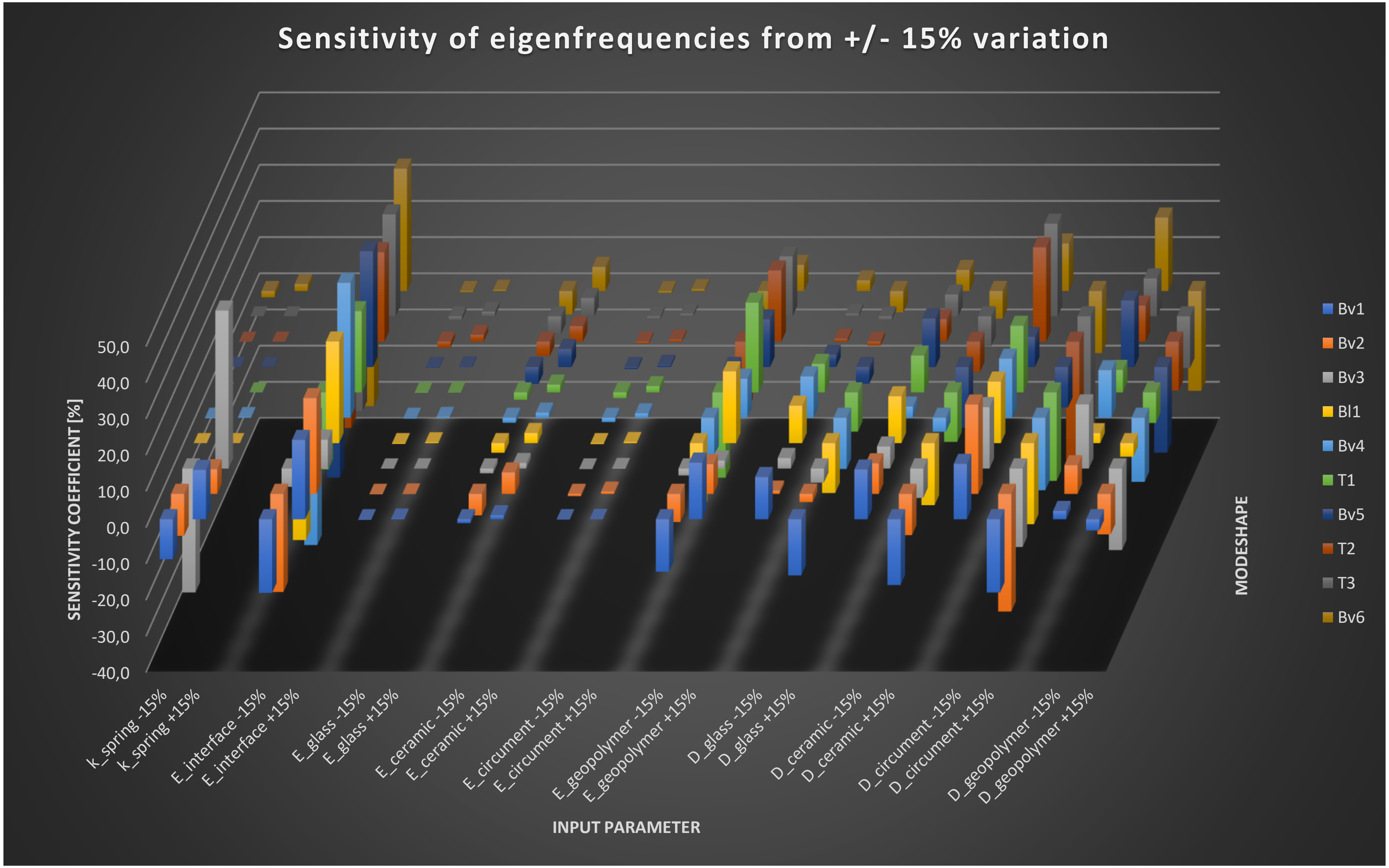


Sensitivity of eigenfrequencies from +/- 5% variation
SENSITIVITY COEFFICIENT [%]
50,0
40,0
30,0
20,0
10,0
0,0
-10,0
-20,0
-30,0
-40,0
k_spring -5%
k_spring +5%
E_interface -5%
E_interface +5%
E_glass -5%
E_glass +5%
E_ceramic -5%
E_ceramic +5%
E_circument -5%
E_circument +5%
E_geopolymer -5%
E_geopolymer +5%
D_glass -5%
D_glass +5%
D_ceramic -5%
D_ceramic +5%
D_circument -5%
D_circument +5%
D_geopolymer -5%
D_geopolymer +5%
INPUT PARAMETER
MODESHAPE
Bv1
Bv2
Bv3
Bl1
Bv4
T1
Bv5
T2
T3
Bv6



Sensitivity of eigenfrequencies from +/- 10% variation
SENSITIVITY COEFFICIENT [%]
50,0
40,0
30,0
20,0
10,0
0,0
-10,0
-20,0
-30,0
-40,0
k_spring -10%
k_spring +10%
E_interface -10%
E_interface +10%
E_glass -10%
E_glass +10%
E_ceramic -10%
E_ceramic +10%
E_circument -10%
E_circument +10%
E_geopolymer -10%
E_geopolymer +10%
D_glass -10%
D_glass +10%
D_ceramic -10%
D_ceramic +10%
D_circument -10%
D_circument +10%
D_geopolymer -10%
D_geopolymer +10%
INPUT PARAMETER
MODESHAPE
Bv6
T3
T2
Bv5
T1
Bv4
Bl1
Bv3
Bv2
Bv1



Sensitivity of eigenfrequencies from +/- 15% variation
SENSITIVITY COEFFICIENT [%]
50,0
40,0
30,0
20,0
10,0
0,0
-10,0
-20,0
-30,0
-40,0
k_spring -15%
k_spring +15%
E_interface -15%
E_interface +15%
E_glass -15%
E_glass +15%
E_ceramic -15%
E_ceramic +15%
E_circument -15%
E_circument +15%
E_geopolymer -15%
E_geopolymer +15%
D_glass -15%
D_glass +15%
D_ceramic -15%
D_ceramic +15%
D_circument -15%
D_circument +15%
D_geopolymer -15%
D_geopolymer +15%
INPUT PARAMETER
MODESHAPE
Bv1
Bv2
Bv3
Bl1
Bv4
T1
Bv5
T2
T3
Bv6

Table A - 1: Full overview of the results of the sensitivity analysis;

	Bv1	Bv2	Bv3	Bl1	Bv4	T1	Bv5	T2	T3	Bv6
E_spring -5%	-11,9	-9,3	-38,3	0,0	-0,1	0,0	-0,1	-0,1	0,0	-1,8
E_spring -10%	-11,5	-10,3	-36,4	0,0	-0,1	0,0	0,0	0,0	0,0	-1,8
E_spring -15%	-11,0	-11,6	-34,2	0,0	-0,1	0,0	0,0	0,0	0,0	-1,8
E_spring +5%	12,8	7,8	41,3	0,0	0,3	0,0	0,0	0,0	0,0	1,9
E_spring +10%	13,2	7,2	42,5	0,0	0,2	0,0	0,0	0,0	0,0	1,9
E_spring +15%	13,6	6,8	43,6	0,0	0,2	0,0	0,0	0,0	0,0	1,9
E_interface -5%	-20,9	-27,0	-5,9	-27,2	-36,0	-21,7	-31,1	-24,1	-26,9	-32,6
E_interface -10%	-20,6	-27,1	-5,5	-27,0	-32,7	-21,5	-30,9	-24,0	-26,6	-32,2
E_interface -15%	-20,3	-27,1	-5,1	-26,8	-35,1	-21,3	-30,6	-23,8	-26,2	-31,8
E_interface +5%	3,6	7,6	9,1	10,9	15,4	19,6	24,3	25,4	28,5	35,1
E_interface +10%	3,6	7,7	9,1	11,0	15,7	19,8	24,7	25,7	28,8	35,7
E_interface +15%	3,6	7,8	9,2	11,1	15,9	20,0	25,0	26,0	29,2	36,2
E_glass -5%	-0,2	-0,1	0,0	-0,2	-0,3	-0,1	-0,2	-1,7	-1,2	-0,3
E_glass -10%	-0,2	-0,1	0,0	-0,3	-0,2	-0,1	-0,2	-1,7	-1,1	-0,3
E_glass -15%	-0,2	-0,1	0,0	-0,2	-0,2	-0,1	-0,2	-1,6	-1,1	-0,3
E_glass +5%	0,2	0,1	0,0	0,2	0,3	0,1	0,2	1,8	1,2	0,3
E_glass +10%	0,2	0,1	0,0	0,2	0,3	0,1	0,2	1,8	1,2	0,3
E_glass +15%	0,2	0,1	0,0	0,2	0,3	0,1	0,2	1,9	1,3	0,3
E_ceramic -5%	-1,1	-5,9	-1,4	-2,7	-1,4	-2,1	-4,8	-4,1	-4,9	-6,6
E_ceramic -10%	-1,1	-5,9	-1,4	-2,7	-1,4	-2,0	-4,7	-4,0	-4,9	-6,5
E_ceramic -15%	-1,1	-5,9	-1,3	-2,7	-1,4	-2,1	-4,7	-4,0	-4,8	-6,5
E_ceramic +5%	1,1	5,9	1,5	2,7	1,4	2,1	4,9	4,3	5,0	6,6
E_ceramic +10%	1,1	5,9	1,5	2,8	1,5	2,1	4,9	4,2	5,0	6,6
E_ceramic +15%	1,1	5,9	1,5	2,8	1,4	2,1	5,0	4,3	5,0	6,7
E_circument -5%	-0,1	-0,6	-0,1	-0,2	-1,1	-1,6	-0,6	-0,5	-0,7	-0,5
E_circument -10%	-0,1	-0,6	-0,1	-0,3	-1,2	-1,6	-0,6	-0,5	-0,7	-0,5
E_circument -15%	-0,1	-0,6	-0,1	-0,3	-1,2	-1,6	-0,6	-0,5	-0,7	-0,5

E_circument +5%	0,1	0,6	0,1	0,2	1,2	1,7	0,5	0,6	0,7	0,5
E_circument +10%	0,1	0,6	0,1	0,3	1,2	1,7	0,6	0,6	0,7	0,5
E_circument +15%	0,1	0,6	0,1	0,3	1,2	1,7	0,6	0,6	0,7	0,5
E_geopolymer -5%	-14,9	-7,9	-2,0	-19,2	-10,6	-24,0	-12,9	-19,0	-15,7	-7,9
E_geopolymer -10%	-14,7	-7,8	-2,0	-18,9	-10,5	-23,8	-12,8	-18,8	-15,4	-8,1
E_geopolymer -15%	-14,5	-7,8	-1,9	-18,7	-10,5	-23,5	-12,7	-18,6	-15,2	-8,2
E_geopolymer +5%	15,3	8,1	2,1	19,4	10,8	24,4	13,1	19,5	16,1	7,6
E_geopolymer +10%	15,5	8,1	2,2	19,7	10,7	24,6	13,1	19,6	16,4	7,4
E_geopolymer +15%	15,6	8,2	2,2	19,8	10,7	24,8	13,2	19,7	16,6	7,2
D_glass -5%	13,0	1,8	3,2	11,5	12,4	8,9	3,8	0,9	0,8	3,8
D_glass -10%	12,3	1,8	3,1	10,9	11,9	8,4	3,6	0,9	0,8	3,4
D_glass -15%	11,6	0,9	2,9	10,3	11,4	7,9	3,4	0,8	0,8	3,0
D_glass +5%	-14,2	-2,1	-3,6	-12,6	-13,3	-9,8	-4,2	-0,9	-1,0	-4,8
D_glass +10%	-14,9	-2,2	-3,7	-13,2	-13,7	-10,3	-4,4	-1,0	-1,0	-5,4
D_glass +15%	-15,5	-2,3	-3,9	-13,8	-14,1	-10,8	-4,6	-1,1	-1,0	-5,9
D_ceramic -5%	15,2	9,4	6,8	14,3	3,4	11,3	14,6	6,9	6,7	6,5
D_ceramic -10%	14,0	8,9	6,4	13,7	3,2	10,7	14,0	6,6	6,4	6,1
D_ceramic -15%	13,7	8,4	6,1	12,9	3,1	10,2	13,4	6,2	6,0	5,8
D_ceramic +5%	-16,7	-10,4	-7,4	-15,6	-3,6	-12,4	-15,7	-7,6	-7,5	-7,1
D_ceramic +10%	-17,4	-10,9	-7,8	-16,4	-3,7	-13,0	-16,3	-8,0	-7,9	-7,4
D_ceramic +15%	-18,1	-11,4	-8,1	-17,1	-3,9	-13,7	-16,8	-8,4	-8,2	-7,7
D_circument -5%	16,9	27,3	18,5	18,8	17,7	20,5	9,2	28,8	28,2	14,5
D_circument -10%	16,1	25,6	17,7	17,9	17,0	19,4	8,8	27,4	26,9	13,8
D_circument -15%	15,3	24,7	16,9	17,0	16,3	18,4	8,3	26,1	25,6	13,1
D_circument +5%	-18,6	-29,9	-20,1	-20,6	-18,8	-22,5	-10,2	-31,3	-30,9	-15,8
D_circument +10%	-19,4	-31,2	-20,9	-21,5	-19,5	-23,4	-10,7	-32,6	-32,1	-16,5
D_circument +15%	-20,2	-32,5	-21,6	-22,4	-20,0	-24,4	-11,2	-33,8	-33,4	-17,2

D_geopolymer -5%	2,6	8,9	19,4	3,0	14,7	6,9	20,2	11,2	11,8	22,6
D_geopolymer -10%	2,4	8,4	18,5	2,9	13,9	6,5	19,3	10,6	11,1	21,4
D_geopolymer -15%	2,3	7,9	17,7	2,7	13,1	6,2	18,4	10,0	10,5	20,3
D_geopolymer +5%	-2,8	-10,0	-21,0	-3,3	-16,2	-7,7	-22,0	-12,3	-13,1	-25,0
D_geopolymer +10%	-3,0	-10,6	-21,8	-3,5	-16,9	-8,1	-22,8	-12,9	-13,7	-26,3
D_geopolymer +15%	-3,1	-11,2	-22,5	-3,7	-17,7	-8,4	-23,7	-13,5	-14,3	-27,6