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Original Article

Interdisciplinary App-Programming for The Protection of Artworks (Part I): A Calculator of Backingboard Constructions For Canvas Paintings

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Abstract

Research, presentation, education, and preservation are the four main tasks of museums. The presentation of art works in permanent and temporary exhibitions results in mechanical stress from vibrations and shocks. Early or late damage to the fragile objects is therefore foreseeable. In preventive conservation, measures are being researched to avoid this risk. For example, to protect canvas paintings from shock and vibration, backingboard constructions are applied.

This paper focuses on developing an app to automate the developing process of backingboard constructions and help conservators make informed decisions when selecting backingboard material combinations. The paper explains the simplification of a complex backingboard construction calculation method, on which the backingboard app is based, and the technical decisions, user interface development. Additionally, the app's program structure is revealed.

The evaluation process of the developed app comprised two phases: a user-friendliness questionnaire and a comparison of the first natural frequencies of original paintings, calculated using the app, with FEA calculations and measurement data. Through iterative improvements, the app was significantly optimized in terms of usability and functionality.

The results show that the vibration behavior of canvas paintings with linear or slightly nonlinear properties can be very well represented using the backingboard app accessible by the url www.backingboard.app. Recommendations for backingboard designs based on this knowledge typically result in vibration reductions of between 60 and 80 %. In contrast, backingboard designs developed without considering the vibration behavior of the paintings and the principle of subsystem distuning generally exhibit a maximum reduction of 40%.

Introduction

Works of art are continuously exposed to a variety of external influences during exhibition in a museum, storage in depots, or transportation for instance on loan. In the field of preventive conservation, these influences are referred to as the “ten agents of deterioration” [1], which represent the principal threats to cultural heritage objects. Among them, physical forces constitute a major risk factor and include statical as well as dynamical loads such as friction, vibration, and shock [2]. Their sources can generally be categorized as building-related, handling- and transport-related, or caused by acoustic excitation. Especially shock and vibration responses can accelerate the degradation of works of art.

In the case of canvas paintings, dynamical loads cause the textile support to oscillate forward and backward within the stretcher. This repeated stretching and compression of the canvas can result in micro-cracking within the ground and paint layers. Since canvas paintings are very heterogenous in their material combinations, this motion can lead to serious damage over time. In the past decade, the need to protect canvasses from shock and vibration has been recognized, and several studies have been conducted on this topic.

The application of backingboards to the reverse of canvas paintings, originally aimed to shield them from dust, pest, climate changes and effects of mechanical violences [3], is common conservation practices. However, the materials used for these backings differ widely and range from flexible textiles to rigid boards. In addition to the original task, backingboards can also be applied to dampen incoming vibration and to reduce vibration transmission. Therefore, soft and damping materials can be inserted between the board and the reverse of the canvas. Several studies have demonstrated the potential of these backingboard constructions (an example is shown in figure 1) to mitigate vibrations. However, effective vibration dampening

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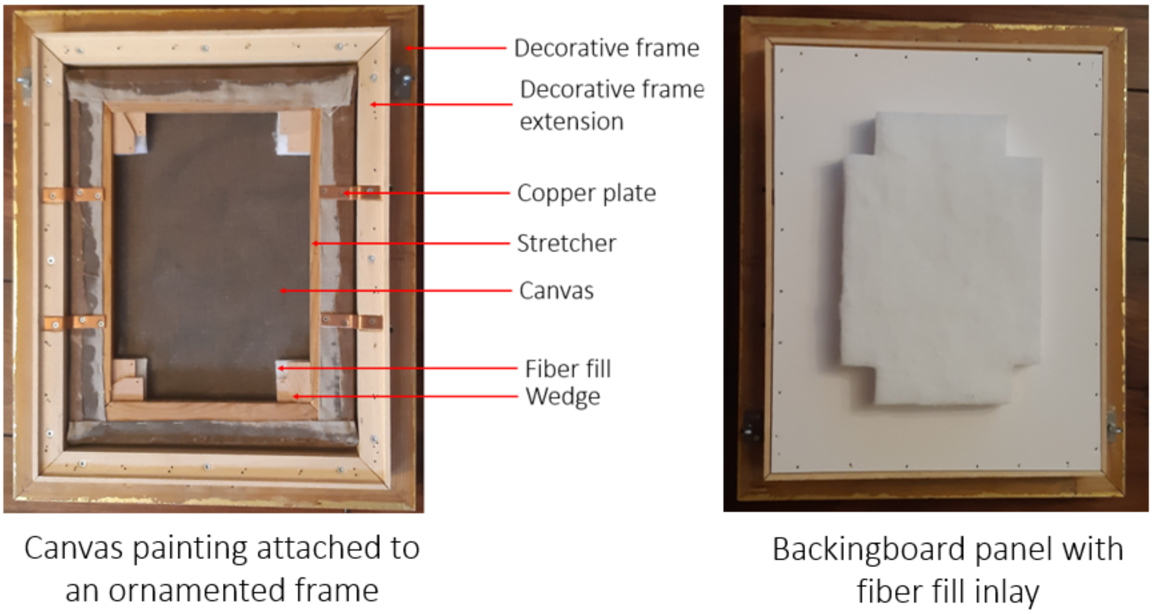

Figure 1: *Composition of a backingboard construction*

strongly depends on the choice of materials. An inappropriate selection may result in negligible damping effects or even cause additional stress and damage to the painting.

State of the art

Vibration-induced stress poses a significant risk to canvas paintings during handling, transport and exhibition. Research over the past 30 years has therefore focused on understanding and mitigating the mechanical response of paintings to excitation through various backingboard systems.

Early work by Green in 1991 [4] demonstrated that stiffening a painting´s support effectively increases its natural frequency and reduces vibration amplitudes. However, he also noted that the effectiveness depends strongly on size and stiffness, with larger backingboards resonating at lower frequencies. These principles were later transferred into practical guidelines in the Art in Transit Handbook [5], which advocated the use of foam inserts between the backingboard and the reverse of the painting as well as different attachment methods. These guidelines became standard practice in paintings conservation.

The methodological basis for later vibration studies was established through the development of a dedicated test stand combining an electrodynamic shaker to excite the painting's frame and triangulation lasers measuring the response of the canvas by Kracht in 2011 [6]. This setup enabled the non-destructive analysis of canvas paintings' vibration behaviour with high precision and provided the foundation for subsequent analytical investigations and modelling applied in later studies.

At the same time, Bäschlin et al. conducted investigations into the comparison of various backingboards with and without foam and fleece inlays, identifying rigid honeycomb cardboards in combination with glazing as highly effective due to their high stiffness and favourable eigenfrequency higher than 45 Hz [7]. An article about preventive practices at the Tate Gallery [8] later stated the use of rigid backingboards to reduce vibration transfer, but emphasized careful control of cushioning inserts, since excessive thickness can compromise canvas tension.

Subsequent vibration studies on original artworks demonstrated the benefits of customized systems. In 2018, Radermacher, Hedinger and Kracht showed that backingboards with polyester fleece inlays substantially increase the lowest natural frequency and improve overall stability [9]. Integrating finite element analysis (FEA) with experimental vibration testing, Lipp and Kracht demonstrated that each painting exhibits a characteristic vibration response that can be optimized through individually fitted backingboards [10]. Uniform contact between the canvas reverse and fleece inlay proved essential for consistent damping performance [11].

Recent applications extended these findings to transport conditions. In 2023, Bisschoff, Leeuwestein and Kracht achieved up to 96% vibration reduction in Van Gogh paintings through optimized framing, fitted backingboards and improved crate systems [12]. Comparable results were reported in 2025 for works by Kandinsky [13] and Van Gogh [14], confirming the effectiveness of backingboard systems with selected padding material for vibration mitigation.

Overall, the research trajectory reveals a shift from general recommendations towards data-driven, painting specific optimization. Effective vibration control now depends on a balanced combination of material stiffness, damping through cushioning layers, and precise mechanical coupling between the canvas painting and its backing structure.

The engineering perspective

From the engineering point of view, a backingboard construction is a reversible structural modification method potentially able to reduce vibration. Thereby, the vibration behaviour of the object in question plays a dominant role. Due to the heterogeneity of the composition of paintings and their different stages of ageing, they differ widely. Consequently, no generally accepted excitation limit as well as no general backingboard constructions could be established in preventive conservation [15-17]. Regarding backingboard constructions, a tailored solution based on the finite element analysis (FEA) and incorporating measurement data is the key to an effective vibration and stress reduction. A concrete approach was first explained by Kracht in [18].

Kracht's tailored backingboard construction design begins with measuring the vibration behaviour of the painting. Secondly, a questionnaire about the mounting/tensioning, materials, condition etc. is addressed to the responsible conservator to gather as much a-priori information about the painting in question as possible. This information is used to derive a basic model for instance a Kirchhoff-plate or a Reissner-Mindlin shell. This model is then passed to a model-updating routine. Here, the optimization using the first four natural frequencies has proven to be reliable. The certainty of matching the first four natural frequencies with the simulation results depends on the level of detail in the modelling. Local peculiarities, such as differences in pigment or binding media, changes from previous conservation work, or weaving defects in the canvas, are assigned their own areas in the FEA geometry. Parameters like density, stiffness, and thickness of each area are the degrees of freedom used to align the simulation results with the measurement results.

In the second step a backingboard construction consisting of a fleece layer and a panel is virtually added to the optimized FEA model of the painting. This can happen in several ways, either the fleece and panel layers are modelled as solids with defined contact zones, or the paintings and the backingboard construction are merged to a composite. In the second case the possible sliding between the layers is not considered, therefore the calculation has to be performed using reduced compensation stiffnesses.

In the final step, the best material combination for the backingboard construction is determined. If a pure optimization process is operated, for example, with the goal of achieving a specific mechanical stress during a particular excitation situation, the output is a combination of parameters (Young's modulus or density) that describes the materials. At best, local characteristics are considered, so that the parameters are location dependent. Since manufacturers of nonwovens and panels are unable to translate such highly specified requirements into products, the optimization process is reduced to software experiments with data from materials that are available on the market. However, the workflow of conservators in daily museum practice can only be efficient, if they operate independently of other departments. Therefore, this paper focuses on developing an app to automate the developing process of backingboard constructions and help conservators make informed decisions when choosing backingboard combinations.

For all these reasons, the question arises to what extent can an app reduce or even replace the effort required for detailed engineering to adapt backing board constructions to the vibration requirements of canvas paintings?

Methods

A good app fulfills its purpose, is fast, saves time, looks and feels good [19]. To ultimately satisfy both, a user-friendliness and a functionality perspective, the requirements must be examined, the implementation well-planned as well as carefully executed, and the result evaluated in test runs. Depending on how satisfactory the test runs are, iterations, i.e., improvements should be carried out. Once the app reaches a level of maturity where only minor improvements of the app are possible or needed, this paper discusses a comparison between the results and possibilities of the app and those of the engineer.

The app development began with a series of technical decisions, such as how the app should be made accessible to the conservators and which programming language should be used. Secondly, the information requirements and information flow for the development process of the backingboard construction were visualized in Nassi-Sniderman diagrams and flow charts. Since the app could not be coupled with a FEA program, all calculations had to be performed analytically. So, a simplification of the backingboard construction design method described by Kracht was necessary.

In the next step the user interface had to be established considering user-friendliness and gathering all required information. In this part of the app development, there was an interactive exchange with the senior conservator Franziska Lipp, who is also co-author of this paper. The subsequent evaluation process of the developed app comprised two phases: a user-friendliness questionnaire and a comparison of the first natural frequencies of original paintings, calculated using the app, with FEA calculations and measurement data. Through iterative improvements, the app was significantly optimized in terms of usability and functionality. The development phases are described in more detail below. Through iteration, the app was significantly improved in terms of both user-friendliness and functionality. The development stages are described in more detail below.

Simplification of Kracht's backingboard construction design method

The proposed backing board app makes its decision for a specific material combination based on analytical calculations and according to a predefined logic. This means that local information about the painting in question must be transformed into global information.

An example of a parameter that significantly increases the stiffness of the canvas are impasto paint layers. Therefore, the sizes of local, impasto-painted areas are summed up. This sum is then compared to the total painting area. Depending on this proportion, factors are defined that increase the Young's modulus.

Another example concerns the tension of the painting on the stretcher. The local stresses around the tacking nails, which result in the cusping of the canvas, can analytically not be taken into account. However, conservators are very good at assessing comparably and reliably the tension of the canvas. Therefore, categories like "low tension", "medium tension", or "high tension" similar to that of a drum membrane have been defined. Based on the conservators' assessment, factors have been then defined that increase the Young's modulus, too.

All factors, as well as the default values for the canvas material parameter such as density, Young's modulus, Poisson's ratio, and thickness, are average values based on the evaluation of over 100 originals. The factors and default values can be found in the decision trees in Appendix.

Furthermore, the optimization process had to be simplified. Instead of complex optimization using the automated least-squares method, the traditional detuning of oscillatory subsystems was applied. This generally works by tuning the vibration behavior of the subsystems so that their dominant natural vibrations do not influence each other. This can be ensured by having a sufficiently large difference between the corresponding natural frequencies. Additional high damping prevents the subsystems from resonating, for example due to shock excitation.

Both the distuning and the implementation of significant damping are ensured through a pre-selection of suitable materials. A very rigid board provides distuning. Non-woven

Table 1: *Pre-selected materials for the backingboard app*

Function	Name	Abbreviation	Manufacturer
Padding material	Caruso Isobond WLG 35	WLG35	Caruso GmbH, Germany https://caruso-ebersdorf.de/en/
Padding material	Caruso Isobond WLG 40	WLG40	
Padding material	Caruso Isobond WLG 45	WLG45	
Backplate	Honeycomb cardboard 13	HC13	Klug conservation, Germany https://www.klug-conservation.com/
Backplate	Honeycomb cardboard 7	HC7	
Backplate	Corrugated cardboard 4.5	EBB4.5	

fabrics are suitable as padding material because they possess high damping values. The materials must also meet high standards for sustainable preservation. Finally, after mechanical and chemical testing (Oddy test), the materials listed in table 1 were selected for the backingboard app.

Technical decisions

The development of the software aims to transform a complex method into an application that is as simple and accessible as possible, minimizing the entry barrier for users. From the very beginning, during the fundamental decisions regarding the type of application and the development environment, both the developers' perspective and that of the target group (the conservators) had to be taken into account.

Web-based applications were quickly identified as the ideal type of implementation, as—unlike desktop applications, they do not require installation and can be used directly in a web browser. This makes them platform-independent and usable across different devices and operating systems. Consequently, the entry barrier for users is low, as accessing the software requires minimal effort. Furthermore, the centralized structure of a web-based application—where the application is reloaded from a server upon each access—allows new features or improvements to be made instantly available to all users, thereby simplifying the ongoing development and maintenance process.

The interactive nature of web applications is primarily enabled by the programming language JavaScript. In addition to writing pure JavaScript code, web developers have access to a broad ecosystem of frontend frameworks such as React, Vue, or Svelte, which are based on JavaScript or its type-safe superset TypeScript. In contrast, developers from engineering disciplines are often more familiar with compiled programming languages such as C, C++, Rust, or Fortran, or with scripting languages like MATLAB or Python. Within this project, prior experience with Python—especially in the context of Python-based Jupyter Notebooks—provided a natural starting point to bridge this gap in language environments. A Jupyter Notebook is a web-based interactive computing platform that combines code, equations, and text, enabling the execution of Python code directly within the browser.

Typically, the infrastructure required to run an interactive Jupyter Notebook is installed and launched locally. Without prior experience, this setup process can pose a certain barrier to entry. To facilitate interdisciplinary collaboration during the early stages of development and to obtain early user feedback, we employed the service "Binder" (mybinder.org). This service allows Jupyter Notebooks hosted on GitHub to be launched directly in the browser and shared easily via a link.

An interactive and clearly structured interface for data input and output is essential for a positive user experience. For the development of such an interface, we employed the Python library Jupyter Widgets (https://github.com/jupyter-widgets/ipywidgets). These widgets are configured within Python code and generate interactive input fields or layout elements (e.g., tabs). This approach enables structured user guidance through the parameter input process, provides opportunities to include explanations where necessary, and facilitates the presentation and interpretation of computational results.

While deploying the application via the Binder service proved very useful during the development phase, we observed connection issues and long loading times when a larger number of users accessed the application simultaneously. Additionally, the complete notebook - including the underlying source code - displayed to users, which can be distracting or even discouraging.

To convert the embedded notebook-based application into a standalone web application, we employed the tool Voilà (https://github.com/voila-dashboards/voila) and packaged the application together with its dependencies into a read-only and portable Docker image. A corresponding Docker container - an instance of this image - can be deployed on a dedicated server or through a container hosting service. This container can then be accessed via a URL, providing users with an experience comparable to that of a conventional website.

Visualisation of the algorithm

The decision tree was designed to make the logical flow of the backingboard construction app comprehensible even to users without an engineering background. The decision hierarchy was structured according to the logical sequence of input acquisition, condition evaluation, and result recommendation, reflecting the workflow of the backingboard construction design procedure. It was gradually refined throughout the development process.

The decision tree was based on a questionnaire established in the previous research [10], which served as the foundation for identifying the information required from conservators. While the questionnaire made it possible to identify which parameters influence the mechanical response or the resulting design choice, it did not intuitively reveal how these parameters interact within the overall logic. Therefore, the decision tree was developed to translate these interrelations into a structured form, visualizing the decision-making process and clarifying the pathways from input parameters to recommendations. The questionnaire included not only the dimensional parameters essential for recommendation, but also condition-related factors, like the quality of pretensioning and the deformation of the canvas, that influence the mechanical response of the artwork.

Variations in these parameters lead to changes in stiffness or density, which in turn influence the dynamic response of the system, or directly alter the suitability of the recommended backingboard construction. By mapping these dependencies within the decision tree, the model makes the effect of each parameter change explicit and traceable. In the initial stage, however, the decision tree was only based on the mandatory physical parameters for simplification, focusing on the core input values required for the basic recommendation derived from the questionnaire. Since these parameters vary with each artwork, they must be directly provided by the user rather than estimated automatically, to ensure more accurate frequency calculation and the resulting backingboard construction recommendation. For the sake of computational simplicity, the system temporarily assumed a quadrangle geometry consisting of three layers: canvas, stretcher, and decorative frame.

In subsequent stages of development, parameters omitted for simplification were reintroduced and extended – along with additional practical factors – to more accurately reflect the range of variables contained in the original questionnaire. As the development progressed, additional parameters and conditional branches were introduced to account for more complex artwork configurations and practical measurement conditions. Although the components of the system remained the same, the possible measurement combinations could vary. Therefore, the application allowed users to specify how their artwork was measured – individually, partially, or as a whole – so that the program could automatically extract the necessary parameters for frequency calculation and further recommendations.

In addition to the measurement structure, further parameters influencing both the calculation and the recommendation were refined during development, particularly the artwork's geometry and its environmental configuration. The shape options were expanded beyond the quadrangle form to include oval and circular geometries. Because a change in shape alters the frequency calculation formula and consequently the recommendation, this option was introduced during the development of the decision tree. Moreover, because the dominant vibration characteristics differ depending on the environment – steady low amplitudes during exhibition, random excitations during transport, or controlled movements during restoration – the appropriate backingboard construction may vary accordingly. To reflect these differing conditions, this option was likewise incorporated during development.

Ultimately, the entire recommendation logic was visualized in a structured decision tree to clarify the logical pathways between user inputs and backingboard construction recommendations. This visual representation replaced the static, text-based logic with a transparent and auditable structure, enabling both developers and conservators to trace the reasoning process. It also allows users to intuitively follow the decision flow and understand how their individual selections influence the resulting backingboard construction recommendation, while simultaneously serving as documentation of the programming logic for development reference.

To accommodate both the technical and the creative perspectives, two designs were chosen for representing the decision tree. The Nassi-Sniderman diagram (NSD) precisely represents the program structure – but at the expense of comprehensibility. The level of abstraction in the NSD is very high. In contrast, the flowchart depicts the workflow and is therefore very clear. However, it does not make the routines visible.

Development of the user interface

Building upon this foundation, the underlying logic of the decision tree was translated into an interactive user interface, allowing the conceptual structure to be experienced directly by users.

As the decision tree gradually evolved, the user interface was refined in parallel to reflect the growing complexity of the workflow. In the earliest version, the application was deliberately kept simple, displaying only the mandatory input fields, calculated frequency, and backingboard construction recommendation on a single interface.

With the increasing number of parameters derived from the expanded decision tree, the interface was reorganized to enable users to enter detailed input values more systematically and to intuitively grasp the meaning of each parameter before providing their input. To support this, the layout adopted a tab-based structure, translated the previously established logical sequence into corresponding user interface stages – Preliminary, input fields of Canvas/Stretcher/Decorative frame, and Results. Each tab was provided with concise explanations and visual emphasis to guide users through the process.

As development progressed, a three-level tab arrangement was introduced, positioning related tabs under their respective stages and adding explanatory notes where needed. The system was further enhanced to dynamically display only the tabs relevant to the users' selections, while ensuring clarity by hiding unnecessary sections. The content within each tab was updated in real time to reflect user inputs, providing immediate visual feedback, and ensuring a smooth, responsive workflow. This restructuring improved navigability and coherence, thereby enabling users to progress through the backingboard construction design process step by step in alignment with the underlying decision tree.

Results

The main result of this work is the app for backingboard constructions that assists the conservators in material selection regarding canvas paintings specific vibration reduction. The app can be accessed at www.backingboard.app.

Secondary results can be derived from the completed user-friendliness questionnaires as well as from comparisons of the results of the backingboard app with the evaluation calculations and measurements to review and improve functionality. These are presented below.

Feedback survey

The feedback survey was conducted to evaluate the clarity, comprehensibility, and overall usability of the backingboard construction application, as well as to identify potential variations in user interaction and interpretation. Participants included nine professional conservators from Europe and eleven international postmaster conservation students from the University of Amsterdam (UvA). Feedback was collected through a structured questionnaire designed to capture both qualitative and quantitative assessments, focusing on participant's general impressions of the application, their evaluation of the content in each tab, and numerical ratings on a ten-point Likert scale. The following section summarizes the principal findings derived from the collected responses.

Preliminary

Users suggested that additional visual materials, such as reference images or illustrations, would help them better understand the meaning of each parameter option. They also recommended providing an introductory explanation of the application – including its maximum supported size and the types of artwork it is suitable for – before use. In practice, users noted that it is often difficult to measure the canvas, the stretcher, and the decorative frame separately. Therefore, the application

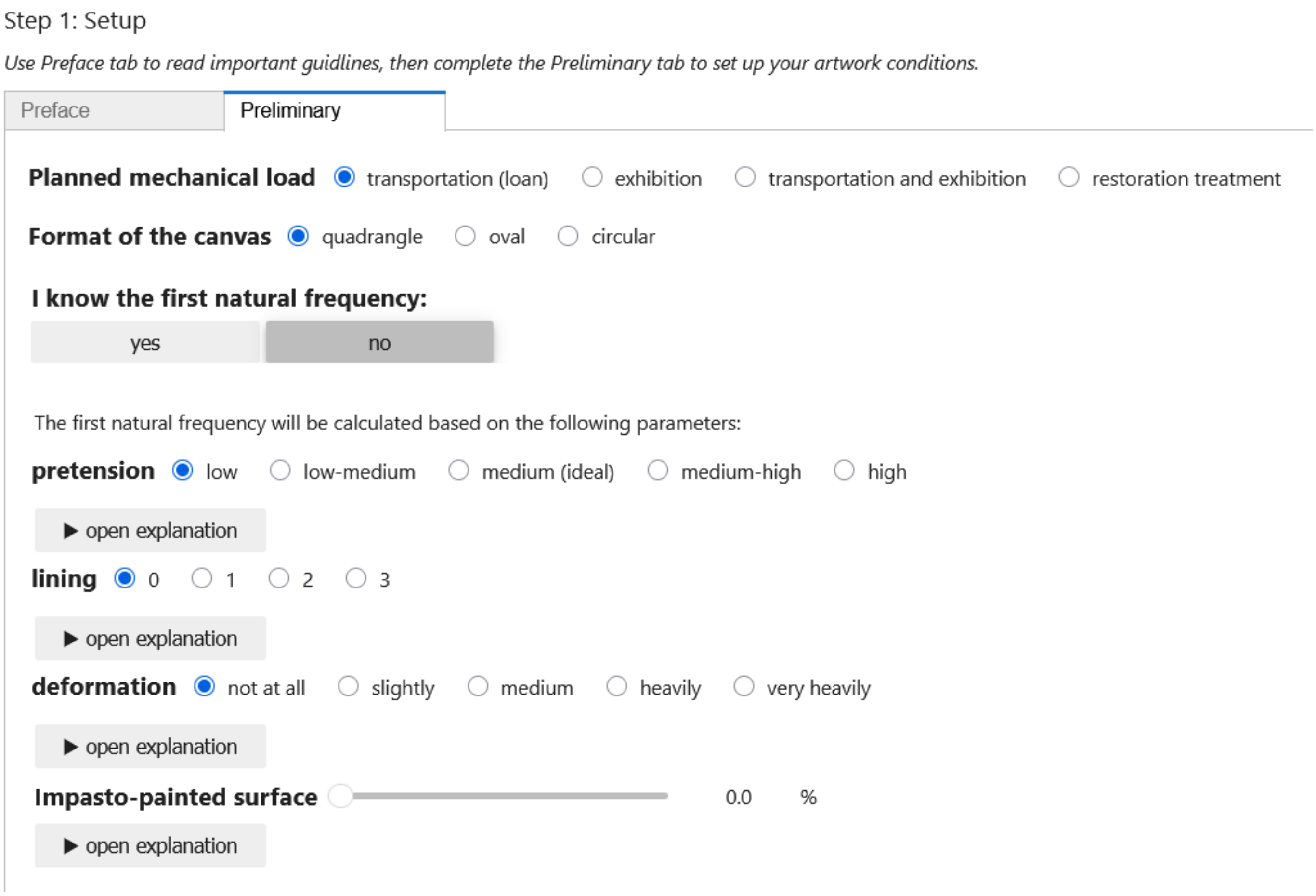

Figure 2: *Final user interface of the preliminary tab*

should allow for the selection of combined measurement options to better reflect realistic conditions. Moreover, it was suggested that selectable parameter ranges in the Preliminary step be extended to accommodate a wider variety of artwork configurations. The final user interface gathering preliminary information about the painting is shown in figure 2.

Input field – Canvas, Stretcher, Decorative frame

The questions regarding the size of the picture, the stretcher frame, and the decorative frame were found to be clear and straightforward. However, it also turns out that some German users had difficulties entering decimal numbers due to the different number conventions (comma vs. period). Since the application is designed for an international user base, it was recommended to clearly indicate that the period is used as the decimal separator. Consequently, the reference to the correct decimal separator has been included in the preface.

Results

Users expressed the need for clearer explanations on why backingboard construction installation is important and how it improves specific aspects such as vibration frequency. They also suggested including a visual or numerical preview of the expected improvements. It was further recommended that key elements of the results be visually highlighted to enhance readability. Users who were unable to obtain a result generally understood that their input values exceeded the defined range of the program and, consequently, suggested developing a more advanced version of the application. In addition, some users wished for a broader range of recommended backingboard construction materials to allow more flexibility in the selection process.

Due to the desire to clearly illustrate the protective potential of backing board constructions, an introductory tab was implemented. This introduction explains the operating principles of backingboard constructions and proves them with scientific studies.

The desire to equip even larger paintings with custom-designed backing board constructions is entirely understandable. However, this is not feasible within the scope of a student project. For the same reason, the backingboard app refers to three materials for the padding (fiberfill) and three materials for backplates.

Other

Several users proposed that warning messages or cautionary notes should be included to alert users to potential issues if the backingboard construction is not installed as described. Furthermore, some users pointed out that the terminology used in the application differs from that used in museum practice and suggested revising it to align more closely with professional conservation terminology.

The discussion highlighted that practical implementation in the conservation field requires a high level of technical detail and professional accuracy. It also emphasized that realistic parameter options are essential for effective application in real-world contexts. Moreover, the findings underlined the need to enhance usability, reliability, and intuitive interaction to foster

Table 2: *Properties of 10 original paintings*

Painting No.	Width [mm]	Height [mm]	Average thickness of canvas [mm]	Number of lining layer	Impasto-painted surface	deformation	pretension
1	1034	500	4.2	1	45%	very heavily	medium
2	1007	500	6	2	30%	medium	medium
3	400	600	3	0	15%	medium	high
4	752	1005	2.1	0	0%	slightly	low-medium
5	502	525	1.9	0	0%	slightly	medium
6	510	512	1.9	0	0%	slightly	medium
7	900	700	1.8	1	0%	slightly	medium
8	735	600	1.4	0	0%	slightly	medium
9	805	605	1.3	0	0%	slightly	medium
10	655	755	2	0	0%	slightly	medium

user confidence. Finally, it was considered crucial that the target user group can understand and trust not only the theoretical foundation of the application but also the logic underlying its user interface. These insights suggest that future development should focus on enhancing practical relevance, user accessibility, and professional credibility.

Overall, the users described the application as intuitive, user-friendly, clear, and straightforward. Most participants stated that they would use the application again in future conservation projects.

Development of the functionality evaluation

To evaluate the functionality of the application, the natural frequencies of ten original paintings were either directly measured or compared with the results obtained from the application and FEA calculations. The selected case studies represented a diverse range of artworks differing in size and condition, all within the maximum dimensions supported by the application (1500 mm × 1000 mm or 1000 mm × 1500 mm). For each painting, the width, height, average surface thickness, and overall condition were measured in advance (see table 2) and entered into the backingboard app to obtain the corresponding frequencies and recommended material combinations.

The frequencies calculated by the backingboard app were first compared with the FEA results to verify the deviation range, after which both sets of results were further compared with the experimentally measured frequencies to assess their validity. The software Abaqus CAE was used for operating the FEA calculations. The setup is documented in table 3.

Table 3: *Summary of Abaqus setup*

Part type	**3D Shell planer**
Section assignment	Layup section applied to the 3D shell part
Mesh type	S8R
Mesh size	Global mesh size between 0.005m and 0.01m, depending on the model geometry
Boundary condition	U3 fixed on all four edges
Analysis type	Modal analysis using the Lanczos method

The natural frequencies of the paintings before the attachment of the backingboard construction were first compared, and the Abaqus analysis settings were as follows. Identical modelling parameters were applied to all ten paintings. Each model was defined as a three-layer composite shell (3D shell planer part) consisting of the canvas, padding, and backboard panel. The analysis employed S8R elements with a global mesh size ranging from 0.005 m to 0.01 m, depending on the model geometry. All edges were constrained in the out-of-plane direction (U3 fixed), and a modal analysis using the Lanczos method was performed to extract the first ten natural frequencies.

The first natural frequencies obtained from three methods were compared with each other, as presented in table 4. The comparison between the backingboard app and FEA results revealed excellent agreement, with deviations ranging from 0.01 % to 0.28 % across all cases. These differences fall within the range of rounding errors, demonstrating the high reliability of the frequency calculations performed by the application.

In contrast, significantly larger discrepancies were observed when comparing the calculated frequencies with the experimentally measured frequencies, with deviations reaching up to 50.31 %. These variations can be attributed primarily to uncertainties in the input parameters describing the actual condition of each artwork. For example, Painting No.1 was noticeably heavy; however, since the weight value was omitted, it could not be incorporated into the density calculation logic of the application. Similarly, discrepancies between the measured and input canvas thickness likely contributed to substantial errors in several cases. Thickness is a highly sensitive parameter in frequency calculation, as it appears as a cubic term in the expression for bending stiffness. This sensitivity is evident in the case of Painting No.8: when the measured thickness of 1.4 mm was replaced with the base thickness of 2mm provided by the application, the calculated frequency changed to 4.62 Hz, reducing the deviation to 28.9 % - approximately half of the original error.

Having validated the accuracy of the application for predicting frequencies of paintings without backingboard construction, the analysis proceeded to evaluate the application's backingboard construction material recommendations. The natural frequencies of the paintings after the attachment of the backingboard construction materials recommended by the application were then compared. The Abaqus settings were kept identical to those

Table 4: *First natural Frequencies [Hz] of ten paintings before attachment of backingboard construction and deviations [%]*

Painting No.	1	2	3	4	5	6	7	8	9	10
Application (A)	8.9	13.5	13.5	2.7	7.2	7.3	3.1	3.2	2.8	4.1
FEA (F)	8.85	13.45	13.2	2.66	7.18	7.24	3.08	3.22	2.77	4.07
Measured (M)	11	14.5	12.8	2.4	6.6	7.1	4.8	6.5	4.7	9.1
Deviation (A,F)	-0.18	-0.28	-0.25	-0.01	-0.23	-0.23	-0.01	-0.07	-0.05	-0.05
Deviation (A,M)	19.36	6.97	-5.86	-10.8	-9.09	-2.25	35.83	50.31	41.06	55.27

Table 5: *Properties of materials of backingboard construction*

Material	Thickness [mm]	Density [kg/m³]	E-Modul [N/mm²]
Padding			
WLG45	30	17.3	0.2
WLG40	30	23.3	0.4
WLG35	30	43.7	0.6
Backboard panel			
HC13	13	103.8	100
HC7	7	192.86	100
EBB4.5	4.5	208.9	100

Table 6: *Recommended backingboard construction materials*

Painting No.	1	2	3	4	5	6	7	8	9	10
Padding material	WLG 045	WLG 040	WLG 040	WLG 045	WLG 045	WLG 045	WLG 045	WLG 045	WLG 045	WLG 045
Backing- board panel	HC7, HC13	HC7, HC13	EBB4.5, HC7, HC13	HC7, HC13	EBB4.5, HC7, HC13	EBB4.5, HC7, HC13	HC7, HC13	HC7, HC13	HC7, HC13	HC7, HC13

Table 7: *First natural frequencies [Hz] of ten paintings equipped with recommended backingboard construction and deviations [%]*

Painting No.	1	2	3	4	5	6	7	8	9	10
1st tries with FEA (1F)	26.9	35.1	58.9	24.6	46.1	46.3	27.9	34.6	33.1	31.4
2nd tries with FEA (2F)	29.9	-	-	28.0	-	-	29.0	-	-	-
Deviation (1F/30)	-10.4	16.9	96.4	-18.2	53.6	54.3	-7.10	15.3	10.4	4.55
Deviation (2F/30)	-0.28	-	-	-6.80	-	-	-3.30	-	-	-

used in the previous analysis (Table 2), except that the three layers – canvas, padding, and backboard panel – were defined as a three-layer-composite (via Composite Layup).

The properties of the materials implemented in the backingboard app are documented in table 5. The backingboard app recommends for each painting one padding material and one or more materials for the backingboard panel. A complete backingboard construction material combination is formed by selecting one padding material and one material for a backboard panel from these recommendations.

To verify the adequacy of these recommendations, the least stiff recommended material was initially selected, and FEA was performed to evaluate whether the implementation of the recommended backingboard construction would provide adequate stabilization. A calculated frequency exceeding 30Hz indicates that the artwork with backingboard construction is sufficiently stabilized and the subsystems are distuned. When the frequency falls below 30 Hz, progressively stiffer materials are selected and evaluated iteratively until either 30 Hz is reached, or all available materials have been tested. The materials for the backingboard constructions of the ten original paintings (table 2) recommended by the backingboard app are documented in table 6.

The calculated first natural frequencies of the ten paintings equipped with the recommended backingboard constructions are documented in table 7.

Seven of the ten paintings – excluding painting No. 1, 4 and 7 – exhibited frequencies above 30 Hz with the least stiff recommended materials, demonstrating adequate stabilization. For the remaining three paintings, stiffer material combinations were evaluated; however, the calculated frequencies remained slightly below 30 Hz. Nevertheless, considering the minor deviations and possible inaccuracies in the input parameters, these material recommendations can still be regarded as satisfactory.

Following the comparison between the FEA calculations and experimentally measured frequencies presented in table 4, an additional validation approach using the "rule of mixture" for estimating the first natural frequency of paintings equipped with the recommended backingboard construction was initially considered as part of the backingboard app. The intent was to provide users with predicted frequency values as a reference for understanding the expected stabilization. Although the "rule of mixtures" offers a straightforward approximation, the calculated results exhibited substantial discrepancies when compared with both FEA calculations and the backingboard app results. These large deviations raised concerns regarding consistency and accuracy.

Consequently, this approach was excluded from the backingboard app. Instead, efforts were focused on refining the parameters used in the application and continuously improving the decision tree, thereby enhancing accuracy through more detailed parameterization and systematic model refinement rather than simplified analytical methods using the rule of mixtures.

Conclusions

In conclusion, the first natural frequencies calculated by the backingboard app are of significant reliability. However, the remaining deviations also reveal certain limitations. Such deviations are likely attributed to uncertainties in the input parameters, arising from the difficulty of precisely measuring the paintings, as well as to the simplifications applied in the FEA calculation. Accurate and complete user input is also essential, as the omission of measured values can substantially affect the accuracy of calculations. It is anticipated that these limitations can be mitigated in future research through parameter studies aimed at further improving the accuracy of the application. Improved solutions require more detailed models and more accurate input data. For example, it is worth investigating whether considering the age of a painting or taking individual vibration measures could improve the accuracy of the results.

Moreover, cases exhibiting nonlinear behavior – for instance, paintings with visible wrinkles (strong wavelike deformation) on surface - were also evaluated using the application, revealing a comparatively lower accuracy in the calculated results, highlighting the need for further refinement of the application to better capture such nonlinear effects. The results suggest that automating decision-making processes for paintings with highly nonlinear vibration behavior without detailed measurements and the involvement of an engineer with appropriate expertise does not lead to correct results [18].

Nevertheless, the results show that paintings with less extreme properties like these strong nonlinearities can be very well represented using the backingboard app. Recommendations for backingboard designs based on this data typically result in vibration reductions of between 60 and 80 %. Backingboard designs developed without considering the vibration behavior of the paintings and the principle of subsystem distuning generally exhibit a maximum reduction of 40 % [12].

Furthermore, this free backingboard app enables conservators at small and mid-size museums or institutions with limited budget to make better decisions when equipping canvas paintings with backingboards constructions for vibration reduction purposes.

Beyond, the backingboard app can be used as a training tool to familiarize conservators, especially students and young professionals, with the topic of canvas paintings specific backingboard construction.

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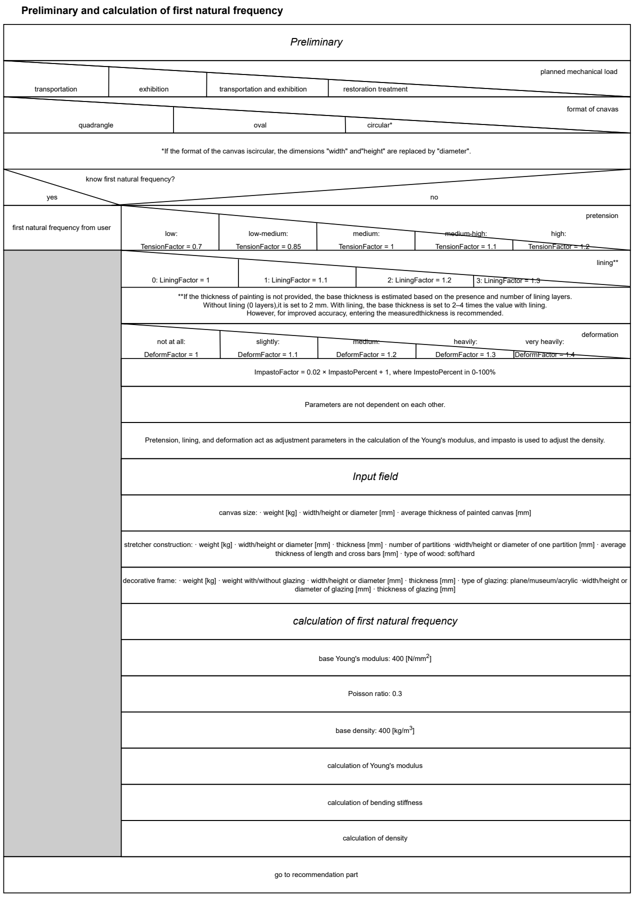
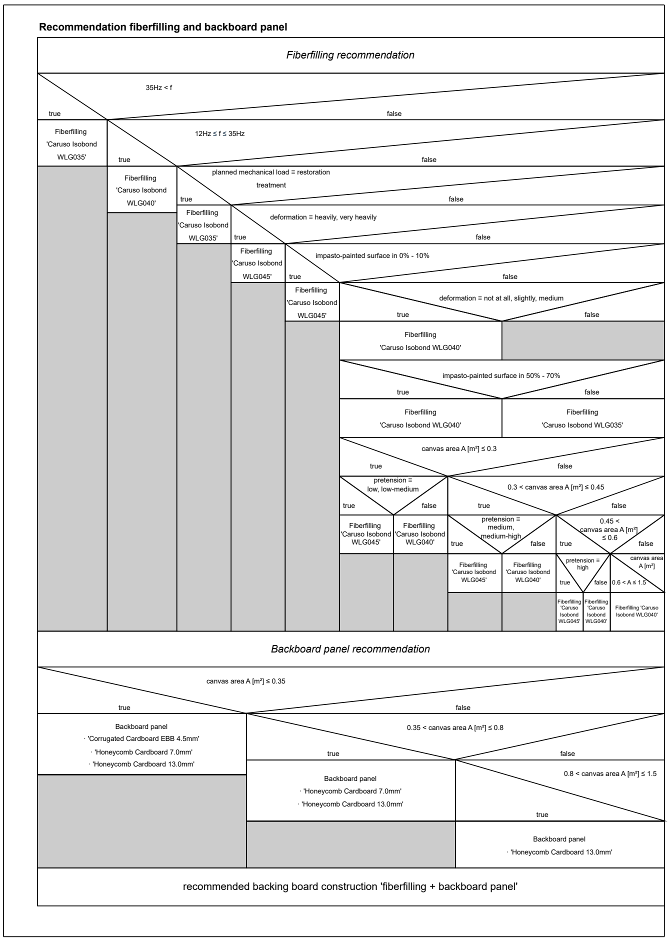
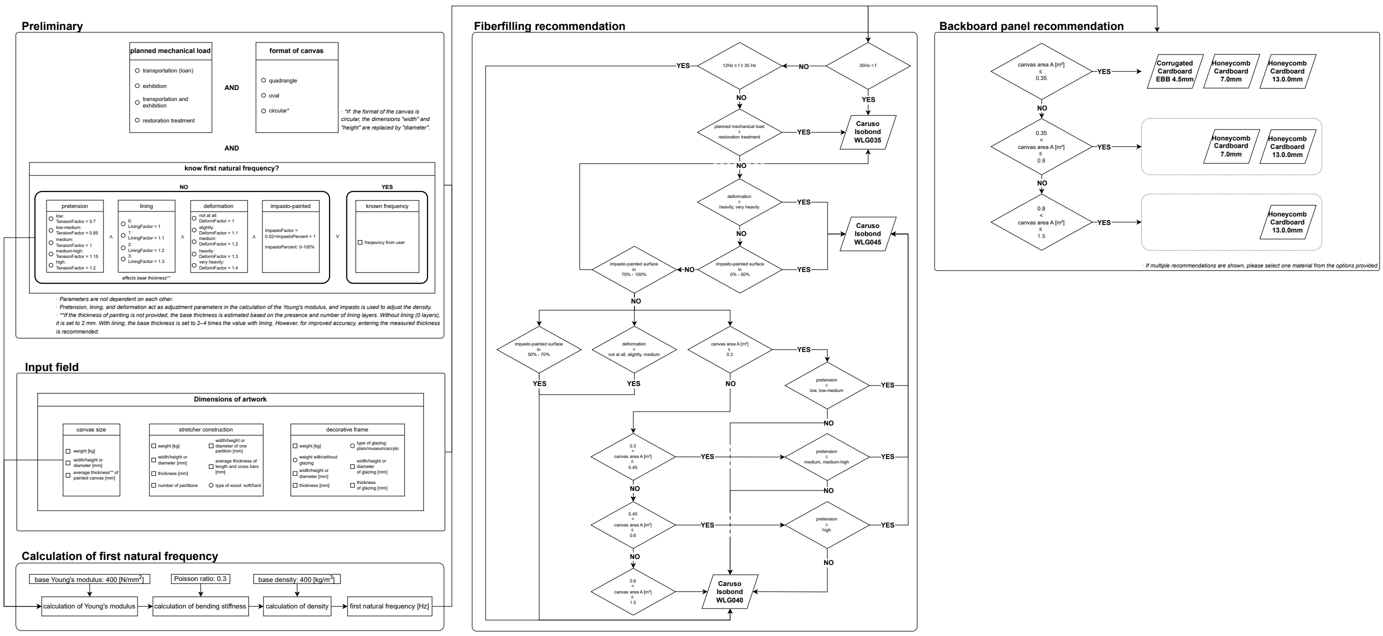
Appendix



Preliminary and calculation of first natural frequency
Preliminary
planned mechanical load
transportation
exhibition
transportation and exhibition
restoration treatment
format of cnavas
quadrangle
oval
circular*
*If the format of the canvas iscircular, the dimensions "width" and"height" are replaced by "diameter".
know first natural frequency?
yes
no
first natural frequency from user
pretension
low: TensionFactor = 0.7
low-medium: TensionFactor = 0.85
medium: TensionFactor = 1
medium-high: TensionFactor = 1.1
high: TensionFactor = 1.2
lining**
0: LiningFactor = 1
1: LiningFactor = 1.1
2: LiningFactor = 1.2
3: LiningFactor = 1.3
**If the thickness of painting is not provided, the base thickness is estimated based on the presence and number of lining layers.
Without lining (0 layers),it is set to 2 mm. With lining, the base thickness is set to 2–4 times the value with lining.
However, for improved accuracy, entering the measuredthickness is recommended.
deformation
not at all: DeformFactor = 1
slightly: DeformFactor = 1.1
medium: DeformFactor = 1.2
heavily: DeformFactor = 1.3
very heavily: DeformFactor = 1.4
ImpastoFactor = 0.02 × ImpastoPercent + 1, where ImpestoPercent in 0-100%
Parameters are not dependent on each other.
Pretension, lining, and deformation act as adjustment parameters in the calculation of the Young's modulus, and impasto is used to adjust the density.
Input field
canvas size: · weight [kg] · width/height or diameter [mm] · average thickness of painted canvas [mm]
stretcher construction: · weight [kg] · width/height or diameter [mm] · thickness [mm] · number of partitions ·width/height or diameter of one partition [mm] · average thickness of length and cross bars [mm] · type of wood: soft/hard
decorative frame: · weight [kg] · weight with/without glazing · width/height or diameter [mm] · thickness [mm] · type of glazing: plane/museum/acrylic ·width/height or diameter of glazing [mm] · thickness of glazing [mm]
calculation of first natural frequency
base Young's modulus: 400 [N/mm²]
Poisson ratio: 0.3
base density: 400 [kg/m³]
calculation of Young's modulus
calculation of bending stiffness
calculation of density
go to recommendation part



Recommendation fiberfilling and backboard panel
Fiberfilling recommendation
35Hz < f
true
false
Fiberfilling 'Caruso Isobond WLG035'
12Hz ≤ f ≤ 35Hz
Fiberfilling 'Caruso Isobond WLG040'
planned mechanical load = restoration treatment
Fiberfilling 'Caruso Isobond WLG035'
deformation = heavily, very heavily
Fiberfilling 'Caruso Isobond WLG045'
impasto-painted surface in 0% - 10%
Fiberfilling 'Caruso Isobond WLG045'
deformation = not at all, slightly, medium
Fiberfilling 'Caruso Isobond WLG040'
impasto-painted surface in 50% - 70%
Fiberfilling 'Caruso Isobond WLG040'
Fiberfilling 'Caruso Isobond WLG035'
canvas area A [m²] ≤ 0.3
pretension = low, low-medium
0.3 < canvas area A [m²] ≤ 0.45
Fiberfilling 'Caruso Isobond WLG045'
Fiberfilling 'Caruso Isobond WLG040'
pretension = medium, medium-high
0.45 < canvas area A [m²] ≤ 0.6
pretension = high
0.6 < A ≤ 1.5
Backboard panel recommendation
canvas area A [m²] ≤ 0.35
Backboard panel
· 'Corrugated Cardboard EBB 4.5mm'
· 'Honeycomb Cardboard 7.0mm'
· 'Honeycomb Cardboard 13.0mm'
0.35 < canvas area A [m²] ≤ 0.8
Backboard panel
· 'Honeycomb Cardboard 7.0mm'
· 'Honeycomb Cardboard 13.0mm'
0.8 < canvas area A [m²] ≤ 1.5
Backboard panel
· 'Honeycomb Cardboard 13.0mm'
recommended backing board construction 'fiberfilling + backboard panel'



Preliminary
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format of canvas
know first natural frequency?
Input field
Dimensions of artwork
canvas size
stretcher construction
decorative frame
Calculation of first natural frequency
calculation of Young's modulus
calculation of bending stiffness
calculation of density
first natural frequency [Hz]
Fiberfilling recommendation
Caruso Isobond WLG035
Caruso Isobond WLG045
Caruso Isobond WLG040
Backboard panel recommendation
Corrugated Cardboard EBB 4.5mm
Honeycomb Cardboard 7.0mm
Honeycomb Cardboard 13.0mm