



Full Length Article



HeXA: Haptic-enhanced eXtended reality framework for material-informed Architectural design

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ARTICLE INFO

Keywords:

Early-design stage
 Material-informed
 Sketch-based modeling
 Extended reality
 Haptic feedback

ABSTRACT

Traditional architectural design processes are caught in sequential and isolated planning workflows, starting with pen-and-paper sketching, digitizing, visualizing for stakeholders, and refining. Only after the basic design has been established, structural engineers get involved and modify the structure, such that the design withstands all external loads. This segregated approach is driven by knowledge barriers associated with structural analysis and by lengthy feedback loops regarding structural design decisions involving finite element simulations. This paper presents research on a novel collaborative and digital design framework, labeled as HeXA, that lowers this knowledge barrier and enables all stakeholders to actively participate in structural design decisions. HeXA couples architecture, structural and material mechanics, computer science and graphics, as well as robotics in six modules: (1) a sketching interface for architectural design, (2) a geometric modeling module that translates the sketch to finite element meshes, (3) a material modeling module that predicts the mechanical properties of sustainable bio-composites, (4) a structural analysis module that assesses the mechanical performance using finite element simulations, and (5) an extended reality environment's immersive visualization that is enhanced by (6) structural haptic feedback provided by a collaborative robot. This allows users to touch and push the envisioned structure in a virtual environment and experience realistic structural deformations provided by the robot and its arm in real-time while resulting stress fields are mapped onto the virtual structure. This way, architectural and structural design processes – particularly at the crucial early design stage – become collaborative, interactive, accessible, and responsive as demonstrated in the paper based on two use cases in theater stage design and building architecture.

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<https://doi.org/10.1016/j.job.2025.112707>

Received 23 October 2024; Received in revised form 17 April 2025; Accepted 17 April 2025

Available online 10 May 2025

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1. Introduction

Formfinding processes in Architecture, Engineering, and Construction (AEC) are inherently complex, requiring expert knowledge across multiple disciplines. A traditional workflow is predominantly sequential: it starts with pen and paper sketching of the architectural design, followed by digitization, refinement, and visualizations for clients and stakeholders. Domain planning (structural design, building services, ...) is typically introduced only in subsequent stages [1]. This way, many AEC workflows promote silo-thinking, induce lengthy feedback loops, risk information loss or design flaws, and may ultimately lead to suboptimal designs [2] with high costs [3].

Structural design is one of the key domains for AEC design. On the one hand, the structural design ensures that the envisioned structure safely resists loads (own weight, wind, earthquake, ...) and maintains its serviceability (e.g., by keeping deformations of structural elements in check). On the other hand, it also involves the selection of adequate materials for all structural elements and thus serves as a key lever for reducing the structure's environmental footprint and promoting sustainable materials. While it is well-recognized that structure plays an indispensable role in any architecture [4], aspects of structural design are often ignored during the early design and only performed once the basic design has already been established by the architect [5]. This oversight is particularly problematic, as informed decision-making during the early stages of design has a high impact down the line [6].

The main reason for this disregard is that grasping the structural mechanics and accurately predicting the impact of design choices can be complex and challenging. Structural engineers typically rely on finite-element-based structural analysis (finite element (FE) modeling), which requires input of the design geometry, along with appropriate loading and support conditions, and the results have to be visualized and interpreted carefully. This process requires both knowledge and time. Architects often struggle to comprehend the structural limitations of their designed structures, causing frustration by engineers [7] and ultimately leading to non-collaborative design workflows. The knowledge barrier is even more difficult to overcome by other stakeholders without an engineering background. This way, the structural design is, more often than not, done by the structural engineer alone with little creativity or ambition for innovative solutions, the main source of frustration by the architect [7].

In order to overcome the traditional sequential design workflow and collaboratively engage architects and structural engineers (as well as other domain experts), several integrative approaches have been introduced in the last two decades, catalyzed by digital transformation. Material-informed design approaches [8], Building Information Modeling (BIM) [9], and integration of digital sketching with finite element-based structural analysis in 2D [10–12] and 3D [13,14] allow for a more collaborative workflow and overcome some of the downsides of the sequential design approach.

While all these approaches allow for a more collaborative workflow, they provide very little to overcome the knowledge barrier involved in structural engineering. Herein, we present a workflow that tackles the challenge of overcoming knowledge barriers and making structural engineering considerations comprehensible to all involved partners of an AEC project. Even further, we aim to allow all partners to participate in the structural design from the very beginning, i.e., starting from the first sketch of the structure. To bridge the knowledge gap, we aim to provide interactive visualization with haptic feedback on the structure's deformations. In more detail, the users shall be able to physically interact with their designs in real-time, feeling the mechanical responses of the designed geometry and selected materials. We therefore rely on elements of XR.²

While VR and sketching have already been successfully merged [17–20], the novelty of the herein presented design framework is the integration of haptic structural feedback. This way, we can offer all project partners a collaborative and immersive experience not only of spaces, materiality, and aesthetics but also of the structural response and load-bearing capacity within a virtual representation of their creations. We expect that this capability will empower designers to gain hands-on experience by seeing and feeling the mechanical response for each combination of geometry, structure, and material. By highlighting the weakest links in the design, this approach could enable immediate improvements early in the design phase. Moreover, adding the sense of touch to VR with haptic simulation expands the perception of a design beyond visual representation making the experience more tangible and interactive. Haptic feedback not only improves task performance and presence in VR [21] but also facilitates the transfer of virtual experiences into the physical world [22]. It may particularly raise awareness of the fundamental role materials play in a built design, offering benefits aimed at addressing global challenges in AEC, like the adoption of sustainable building materials and the implementation of circular economy practices.

The structural haptic feedback is provided by a collaborative robot [23] in an XR environment. The designer is then able to approach the structure in VR, extending his hand, and applying a force (which might be amplified for large structures such as bridges) to the robot's arm. The robot arm then mimics the structural response by allowing a deformation according to the simulated structural response. With the haptic sensations, the user will get simultaneous visual feedback to not only feel but see the stress state the material has to endure in each location. Our objective is to take a substantial leap forward by integrating advanced haptic feedback technology for better final designs. Through this innovation, users shall be able to physically interact with their designs in real-time, feeling the mechanical responses of different materials and designs as they perform structural analysis on a sketched geometry.

To elaborate on this idea, we herein present a HeXA, a framework that unifies research areas such as computer graphics, architectural sciences, building construction, and structural and material mechanics. These disciplines are represented through

² XR encompasses immersive technologies [15] that span from fully virtual environments (VR) to combinations of digital and real world, which either overlay digital content onto the physical environment (augmented reality (AR)) or a computer-generated environment with elements of the real environment (mixed reality (MR)) [16].

six interconnected modules: sketching, geometric modeling, material modeling, structural analysis, extended reality, and haptic feedback. The paper builds up on a previously developed integrative design framework [14] that allows for material-informed design and is equipped with structural analysis feedback. We herein extend this framework by including structural haptic feedback in XR.

The remainder of the paper is structured as follows: Related works for this framework and its respective modules are discussed in Section 2, followed by a detailed description of the tool itself in Section 3. To proof the concept of HeXA, the workflow is then used to tackle two different design scenarios in Section 4. Potentials and limitations of the design frameworks are further discussed in Section 5, and the paper concludes in Section 6.

2. Background and related works

2.1. Integrative design frameworks for AEC

The integration of structural haptic feedback with architectural design in XR is the novelty of this paper. Design frameworks that aim at integrating different domains in early AEC design already exist and mainly combine sketching with one or several of the following modules: geometric modeling, XR, and structural analysis. BIM models are a well-established example of such interdisciplinary approaches. They digitally represent the physical and functional characteristics of buildings, enabling collaboration, analysis, and simulation throughout their lifecycle, but do not focus specifically on early design stages when designs are sketched only very roughly. HeXA addresses precisely this gap by enabling designers to test structural behavior before a detailed model exists, using a haptic and visual interface rather than a fully parametric BIM environment. Moreover, broad adoption of BIM, is often constrained by interoperability issues, skepticism about its impact on creativity, and the added time required for coordination [24–28]. Design workflows that target these shortcomings typically provide a centralized digital sketching application at its core which is then translated, using geometric reconstruction and beautification methods to suitable geometries to engage with domain expert feedback. Several of those approaches combine 2D sketching with structural analysis [10–12]. To allow for a more realistic 3D structural analysis approach, an artificial intelligence method has been successfully implemented [13]. XR and sketching have already been successfully merged [17–20] and have shown their potential for providing collaborative and immersive design experiences and for fostering a more integrated workflow [29,30]. Material-informed design approaches for early-stage architectural design, despite their potential to significantly reduce the carbon footprint of buildings and structures, are still underutilized. One approach that combines material modeling with sketching, geometric reconstruction, and structural analysis of the meshed geometry has been very recently merged and successfully applied to theater stage wall design projects [14] and is the basis for the present paper.

2.2. Sketching

Several commercial and open-source applications are available for digital sketching in two dimensions (2D). 3D sketching, however, is a subject of ongoing research. In VR context, the use of six degrees of freedom (DoF) tracked devices is well established (Ramsier [31] provides an overview of VR sketching/painting/sculpting applications.) However, this approach harbors another challenge: the lack of tactile feedback for sketching. Arora et al. [32] have shown that accurate drawing in 3D greatly benefits from tactile feedback. Müller et al. [33] address this issue by using a phantom device as available at the time of their research, finding positive effects of tactile feedback on user experience. Drey et al. [34] proposed a design tool for 3D VR sketching with a hybrid stylus-on-tablet and six DoF tracked pen interaction, using a tracked stylus and drawing tablet device to provide both six DoF and the tactile feedback of stylus-on-surface contact.

To use 2D input devices (pen-on-tablet), several suggested techniques rely on a proxy surface (e.g. planes or freeform surfaces) in 3D. This surface, to which we refer as a drawing canvas, is then used to project the 2D strokes onto [35–37]. To define the position and orientation of the drawing canvas in 3D, some techniques use device tracking (e.g. tracking the tablet) [33], hand tracking [38], or just a separate user interface (UI) interaction.

In the context of AR interactions, Xin et al. [39] propose a handheld AR system for 3D sketching using stylus input and marker tracking. Arora et al. [40] describe a technique for combining 2D and 3D sketching for in-situ design. In a preliminary step, the designer defines a drawing canvas as a patch surface fitted to multiple freeform 3D mid-air sketch lines created via a six DoF motion-tracked pen. Subsequently, sketching onto the tablet surface projects the sketched lines on the predefined drawing canvas. Yee et al. [41], Berging et al. [42], Paczkowski et al. [43] and Wacker et al. [44] provide further examples of sketching within a context using AR techniques.

2.3. Geometric modeling

Several surfacing methods in the literature are aimed at reconstructing geometries from 3D sketches created within state-of-the-art interfaces. Some of the methods relate to surfacing *Curve Networks*, while others address *Stroke Cloud* surfacing methods. Curve networks basically refer to a set of sparse, designer-drawn, well-connected curves that depict a compact and descriptive representation of 3D shapes. CASSIE [17] is an example of a sketch-based modeling interface that progressively transforms mid-air sketch strokes into patched 3D curve networks. Behind the background, it adopts the method by Zou et al. [45] to achieve a triangulation of multiple, non-planar 3D polygons forming the boundaries of the patches in the network. In terms of methods for

surfacing stroke clouds, SurfaceBrush [20] converts coarse VR drawings of varying widths and ribbon-like 3D brush strokes into user-intended manifold free-form 3D surfaces. Their specialized surfacing algorithm, coupled with their sketching interface, works by converting raw designer-drawn strokes into a user-intended manifold 3D surface by matching edge sequences along input stroke polylines. Another recent work addressing the same problem is done by Yu et al. [46] where their method transforms sparse 3D stroke clouds into piecewise-smooth surfaces using iterative segmentation and optimization of smooth patches to fit their surrounding strokes.

Furthermore, a variety of methods are applicable to point sets or point clouds derived from 3D sketches, e.g., point sets obtained from 3D stroke polyline vertices or point clouds formed by a dense set of points sampled along the 3D stroke ribbons. An exemplar work was done by Huang et al. [47], where they introduced an algorithm named VIPSS which reconstructs implicit surfaces from un-oriented point sets sampled from a set of unstructured 3D curves using quadratic optimization.

Besides the methods addressing surface mesh reconstruction mentioned above, there have been several methods that, in preparation for various physical simulations, address the translation of such surface meshes to volume meshes, in other words, tetrahedralizing the resultant triangular meshes. The seminal work TetGen by Hang [48], introduced a method that produces precise constrained Delaunay tetrahedralizations that enforce the inclusion of input faces in the mesh. The method generates tetrahedral meshes suitable for numerical methods, such as FE analysis. Following this work, Hu et al. [49] introduced TetWild, a fast and robust tetrahedral meshing tool that produces high-quality outputs. It requires no complex user-controlled input and comes with pre-set general parameters, in contrast to existing methods like TetGen [48] or CGALmesh [50], which often require specific parameters or flags because they are backed by multiple algorithms for different cases.

2.4. Material and structural modeling

The models which link microstructural features to macroscopic mechanical material properties are the focus of the modeling campaign. This way, users can quickly change material compositions, such as the amount, nature, or orientation distribution of fibers when dealing with fiber-reinforced composite materials. Two state-of-the-art multiscale modeling approaches have emerged successfully for providing such structure–property relations.

Numerical approaches, most importantly FE approaches in the context of computational material modeling [51] discretize the material into small elements. Thus, they allow for resolving even complex microstructures in great detail and provide typically very accurate mechanical predictions. They also enable the incorporation of material nonlinearities (fracture, cracking, debonding, plasticity) at microscales. FE material models, however, are often very expensive [52], and thus of limited interest for our design framework in which computational immediacy is crucial.

Analytical micromechanics models in the framework of continuum micromechanics [53], on the other hand, overcome this drawback. They can be tailored for predicting linear elastic properties for materials with rather complex hierarchical microstructures [54–56], albeit with simplified representations involving ellipsoidal constituents. The low computational cost of this analytical homogenization approach motivates the incorporation into the design framework, as described in more detail in Section 3.4.

Our design framework targets complex three-dimensional structures and aims at overcoming the need to isolate one-dimensional (columns, beams) or two-dimensional elements (walls, plates, shells). Analytical methods for structural analysis, such as Bernoulli beam theory or Kirchhoff plate theory, are therefore out of reach. Hence, a classical finite element approach [57] is used herein, as it is typically done in engineering practice.

2.5. Haptics in XR

Haptic feedback allows users to touch and interact with virtual objects as if they were real. The addition of haptics to XR environments heightens immersion, enriching user experience by providing tactile sensations [58]. There are passive and active (motorized) haptic solutions. Passive haptics employs simple object similar in shape to its virtual counterpart and placed within the real workspace in a position of the virtual object to enable the haptic interaction with it [59]. They can provide realistic and manipulation-friendly haptic feedback [60] and significantly enhance the realism of VR [61]. However, passive haptics have issues with synchronization between virtual and real worlds and scalability due to the necessity of having props in various shapes and different positions as required by the simulation.

In contrast, encountered-type haptic devices (ETHDs) provide haptic sensations by placing a haptic representation of an object at the desired location using a robotic device [62,63]. ETHDs can be semi-stationary, as robotic arms on fixed platforms [64,65], however, they suffer from a general problem of the limited interaction range. That makes them unsuitable for the large-area haptic applications. For a more extensive overview of ETHDs, we refer to the surveys by Mercado et al. [66] and Bouzbib et al. [67].

Some researchers suggested grounding robotic haptic devices on the user's body to guarantee haptic availability anywhere the user moves [68–70]. However, the body-grounded devices potentially might impact the user's experience due to added weight, unintended counter-forces, and, in some cases, the bulkiness of the device. Quadcopters have been employed to create an all-rounded interactive volume [71], but they are limited in terms of supported weight and forces.

Recently, mobile robots have gained attention. VR setups with cleaning robots carrying physical objects as ETHD showed results comparable to passive haptic feedback at room-scale [72,73]. Their systems suffer from late haptics availability due to the slow movement of the robots or accidental collisions with the user. Employment of a larger mobile platform for grounding robotic haptic devices allows for rendering stronger forces while enabling users to freely navigate the environment and experience haptics at

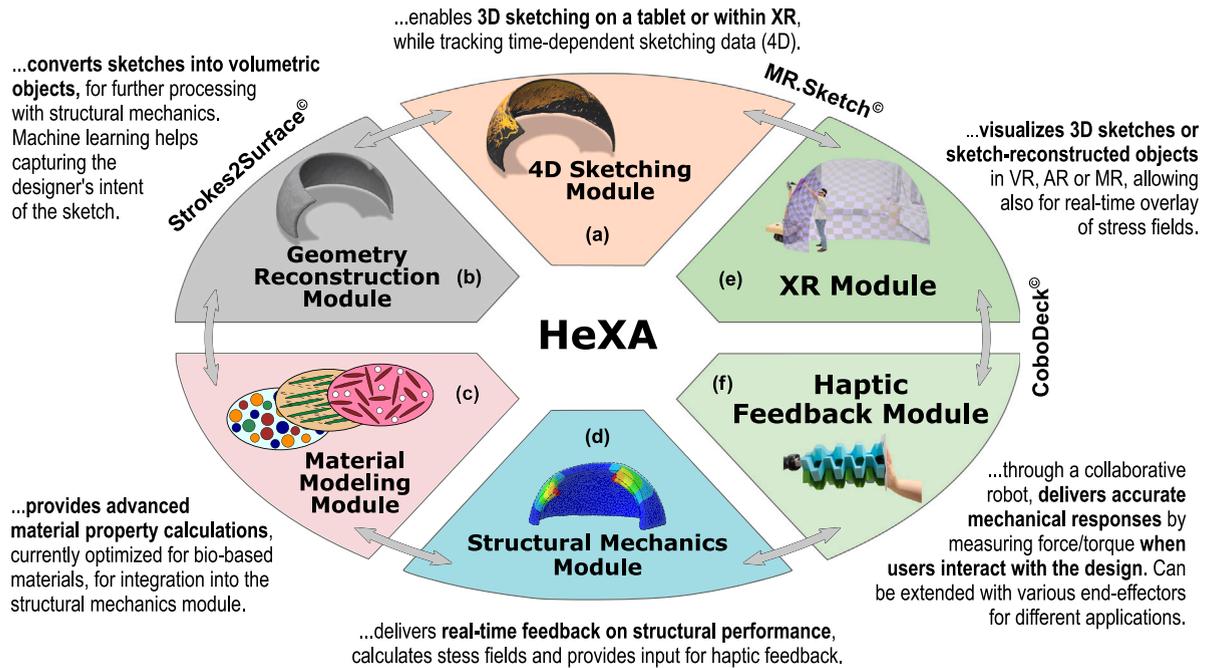


Fig. 1. Overview of the HeXA design framework and its six modules.

desired locations [74,75]. Nevertheless, within the design context, it might be not enough to present an object, but there is a need to simulate its various static and more importantly dynamic properties.

While different haptic feedback devices focus on simulating properties like shape, size, and texture, certain mechanical aspects, such as stiffness, remain relatively unexplored. Pseudo-haptic techniques [76] leverage visual dominance over haptics to manipulate the users' perception and convey a sense of softness. However, there exists a threshold for consistency in pseudo-stiffness methods in VR, limiting their applicability to certain levels of flexibility [77]. In wearable haptic devices, some works address variable stiffness haptic rendering [78–80] but are often limited in scale to single-finger interaction, potentially affecting user immersion. Largilliere et al. [81] proposed a device for soft object haptic rendering with stiffness control, but it lacks support for full-hand interaction and real-time stiffness adjustments. Our framework interactively simulates deformation and offers perspectives for addressing these challenges.

3. Proposal for HeXA framework

3.1. Overview

The development of the herein proposed HeXA framework is rooted in interdisciplinary collaboration, a key aspect of our ongoing SFB research project [82], which aims to bridge the gap between various fields such as architectural design, computer graphics, and material and structural mechanics. HeXA represents one of our efforts to integrate research advancements from these fields into a unified, modular framework for enhanced architectural design processes. Several applications have emerged from these research fields, each addressing different aspects of the design workflow. For example, *MR.Sketch* [83] has proven to be a valuable 3D sketching platform for rapid, intuitive design exploration, while a new *Strokes2Surface* pipeline [84] recovers curve networks from such sketches, improving geometry reconstruction, and additionally converting them into volumetric models for mechanics simulations. Similarly, *multiscale material models* [56,85] have provided advanced methods for calculating mechanical properties of bio-based materials, and *CoboDeck* [23] has enabled haptic feedback through collaborative robotics.

The HeXA framework seeks to integrate these more or less independent systems, trying to create a comprehensive, connected workflow. As a result, the framework consists of six interconnected modules, as depicted in Fig. 1. It builds on our previous work [14] that introduced an integrative design framework for architectural structures, beginning with a (a) 4D sketching interface as an architectural form-finding tool for designers, and a point-cloud based (b) geometric modeling module for reconstructing these sketches. Material choices, vital for load-bearing elements, were offered by a database from the (c) multiscale material modeling module, particularly focusing on biocomposites. A (d) structural analysis module, using finite element calculations is then adopted to determine stresses and displacements. These four modules are revisited herein, improved, and updated.

To lower the knowledge barrier for early-stage design decision-making, two new modules are incorporated. An (e) XR module offers an immersive, interactive environment for designers and stakeholders where they can explore and interact with the design

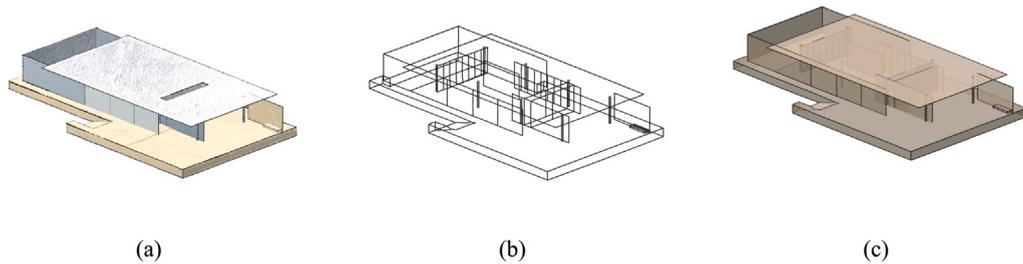


Fig. 2. (a) Input sketch of Barcelona pavilion, (b) its corresponding recovered curve network, and (c) the final reconstructed geometry by Strokes2Surface pipeline, as in [84]. Input sketch: Philipp Stauss.

at a lifelike scale, and (f) a haptic feedback module that adds a tangible dimension to the design experience. This haptic module, augmented by a collaborative mobile robot [23] allows all stakeholders to physically engage with the sketched design — applying forces, sensing realistic deformations, and visually observing the resulting stress states in the structure. These new additions in the modular framework and the corresponding updates and links in the previously existing other four modules are described next.

3.2. 4D sketching interface

A recently developed MR sketching application [83] is at the core of the HEXA workflow. The application adopts a portable pen-on-tablet approach, mirroring the tactile experience of traditional sketching with pen and paper. This setup not only captures the essence of holding a stylus and the resistance of a drawing surface but also leverages familiar stroke motions for intuitive use. To place the strokes in 3D, we use 2D to 3D projective sketching, as established in related research [86]. To assist the designer in accurately perceiving and interpreting the spatial configuration of the drawing canvases, two different canvas visualizations are created. The first adopts a semi-transparent grid, allowing the user to determine which elements are in front of and which are behind the drawing canvas and also assists in scaling the sketch. The second visualization renders the intersection lines of the canvas. This allows for a deliberate and accurate alignment of the sketch lines. Both visualizations can be combined and both interact with any objects. Additionally, we developed a novel technique of viewport-attached drawing canvases, which simplifies the process by removing the need for manual canvas adjustments during the sketching process.

This module allows the design to sketch the envisioned geometry of the structure intuitively and quickly and is intended to work as a hub for all other modules. We note that some of the required links in between the modules are not seamlessly integrated yet, as discussed in more detail in Section 5. The sketching module is already directly linked to the XR module. Designs can not only be visualized in VR, but also three distinct MR sketching interactions can be performed, as discussed in Section 3.6. The sketching module also offers the possibility to select different materials from a catalog, including some pre-defined biocomposites, and assign it to individual strokes. Moreover, users can adjust the thickness of the strokes using a slider that ranges from 0.01 m to 1.00 m, allowing for precise control over the strokes' width. This information along with temporal data of sketch and a set of geometry-related and stylus-related metadata (camera's extrinsic parameters, canvas transformation, stylus pressure, tilt, twist, etc.) are linked to the geometric modeling module and thus to the structural modeling, facilitating data-driven sketch-analysis.

3.3. Geometric modeling module

After completing the concept design phase with sketching, the digital modeling stage ensues, requiring the translation of the sketch into a geometry that can be leveraged in downstream structural analysis. In contrast to the geometry reconstruction method used in our previous works [14,87], where ray tracing was utilized to generate point clouds from 3D sketches for feeding into the pre-trained Points2Surf model [88] to reconstruct mesh geometries, we now adopt a more advanced pipeline tailored to architectural design sketches. To this end, instead of using existing point cloud reconstruction methods trained on common 3D benchmarks consisting of generic 3D shapes, we use Strokes2Surface [84]. This pipeline recovers curve networks from design sketches, which are then surfaced resulting in output geometry. Beyond capturing the design intent more accurately and reconstructing artifact-free geometries, the underlying recovered curve network representation, composed of curve segments and surface patches, offers a main advantage to the method used in our previous work. It results in an output geometry consisting of several meshes corresponding to individual patches in the curve network, rather than outputting a single mesh for the whole, as is in existing point cloud reconstruction methods. This is quite beneficial for architectural design use cases since it eliminates the need for manual segmentation of the geometry as each patch could represent an architectural element, e.g., a roof or a wall (see Fig. 2).

For maximum flexibility, we adopt 3D volumetric meshes, which – unlike 1D or 2D simplifications like beam or shell models – provide a more general approach, capable of handling complex geometries with higher fidelity when necessary. Therefore, it is required to translate the reconstructed surface mesh geometry into such an analysis-ready volume mesh. To this end, we leverage the obtained curve network representation and first extrude each surface patch by the mean thickness values of the original strokes used to draw its boundary curves, thereby solidifying each patch. This is followed by constrained tetrahedralization using the TetWild engine [49], transforming each patch's surface mesh into a volumetric one. Carrying out this process for every patch in the curve

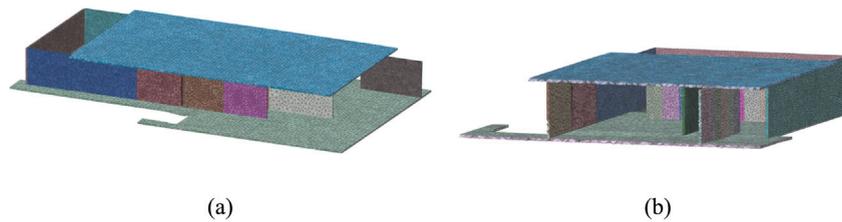


Fig. 3. Tetrahedralized volume mesh obtained after extrusion of the reconstructed surface mesh geometry in Fig. 2 with individual geometry parts rendered in unique colors: axonometric view of (a) the whole pavilion, and (b) a cross-section to reveal the interior walls.

network results in a volume mesh of the intended architectural object, providing direct access to the volumetric representation of the individual segments of the intended geometry (see Fig. 3). The presence of a curve network here introduces flexibility in downstream simulations, as individual segments corresponding to different elements can be selectively included or excluded from the analysis. This in turn allows users to explore different layout configurations, optimizing for the desired physical response of the model.

3.4. Multiscale material modeling module

The HeXA framework focuses on plant fiber-reinforced biocomposite materials, while not excluding traditional construction materials such as steel or concrete (see Section 5 for more context). Biocomposites are gaining popularity as a sustainable alternative to conventional building materials [89]. However, standardized material property databases for these materials are still lacking, largely due to the significant variability in matrix and fiber types, dosage, and production processes. This variability results in a wide range of possible mechanical properties and, in contrast to steel or concrete, to highly anisotropic material behavior. Therefore, sophisticated and reliable models, such as the multiscale material model we incorporated here, are crucial for accurately predicting their behavior. The multiscale material module is designed to feed calculated mechanical properties, such as stiffness and elastic limits, directly into the structural analysis module. This integration allows us to predict how changes in material composition – such as fiber orientation or volume fractions – will affect the macro-properties of the design. As demonstrated in the proof of concept, such changes can have a significant impact on structural performance. The module and its updates are revisited in the following paragraphs.

We build upon a recently developed micromechanics approach [56,85], which resolves the microstructure of any possible plant fiber-reinforced biocomposite across four observation scales. Thereby, we exploit that all biocomposites share a common microstructural morphology, all the way down to the nanoscopic scale where the universal building blocks of plants, namely cellulose (with characteristic chain-like structure), amorphous hemicellulose, and amorphous lignin are envisioned. At the microscale, we consider that the cellulose form so called microfibrils which are embedded in a porous hemicellulose–lignin matrix, and that the microfibrils are inclined at an angle (the so called microfibril angle) with the direction of the fiber. The microfibril-matrix composite then constitutes the cell wall which contains lumen pores and finally, several of these cells are considered to represent one plant fiber which reinforces the polymeric matrix on the largest observation scale.

Physico-chemical fiber properties (cellulose content, microfibril angle, etc.) vary between different plant species, geography, harvesting time, and many more [90]. Fiber orientation (distribution), fiber length (distribution), fiber volume, and fiber interface characteristics (in terms of interface compliances) depend on the composite mix design, the composite production method, and potential fiber treatment. All these variations can be considered in the micromechanical model by adjusting the morphometric properties such as volume fractions, orientations, and interface parameters. This way, the micromechanics model is capable of dealing with any biocomposite and can predict the elastic stiffness and the elastic limit by means of continuum micromechanics homogenization, as discussed next.

Homogenization of the elastic stiffness tensor of plant fibers is performed by consecutive “upscaling” of the known and intrinsic stiffness of the plant constituents using self consistent and Mori–Tanaka schemes, as detailed in [56]. In the final step, the previously homogenized anisotropic plant fiber stiffness, together with the isotropic polymer stiffness obtained from polymer databases, and with estimated interface compliance parameters to assess the interface weakness between fiber and matrix, are homogenized to yield the biocomposite stiffness [85]. Thereby, a matrix inclusion-problem with spring-type interfaces is encountered and solved according to [91]. This way, we end up with the sought 3D stiffness tensor of the biocomposite which can then be used in the structural simulation module.

As for predicting the macroscopic elastic limit of biocomposites, two modes of microscopic failure are taken into account.

- Tensile cellulose failure at the nanoscale is initiated when the uniaxial tensile stress in a crystalline cellulose chain reaches its tensile strength of 2.3 GPa [92]. This approach proved very successful in predicting the fiber strength [56].
- Failure of the polymeric matrix is considered by means of a Drucker–Prager type failure criterion, which proved suitable for describing failure of polypropylene [93].

To evaluate the two failure criteria, elastic macrostresses are downscaled, in a linear fashion, to average stresses of the polymer matrix and to average stresses of the crystalline cellulose, respectively, to check whether a microscopic failure occurs.

The biocomposite is then considered as linear elastic-ideal plastic material with von Mises yield criterion, an idealization of the observed progressive softening [94]. This approach navigates a delicate balance between the pursuit of incorporating a realistic constitutive material behavior and the necessity of constraining computational expenses. Stiffness and elastic limit, obtained from micromechanics multiscale modeling, are then handed to the structural modeling module, that comes next in the HeXA design workflow.

3.5. Structural modeling module

As in our previous work [14], the FE method is employed to analyze and assess the mechanical performance of the sketch-reconstructed geometries. The mechanical properties of various biocomposite materials are derived from the multi-scale material model (Section 3.4). Materials can be selected and the proper material behavior is allocated to the corresponding structural elements. The FE analysis focuses on linear elastic material models for computational immediacy. However, non-linear behavior, like plasticity and viscosity can be selected and pre-calculated for desired points of interest or specific loading scenarios.

In addition to geometry and material properties, boundary conditions and external loads have to be defined. Users can either specify the locations for boundary conditions and loads manually or have them automatically determined. Fixed displacements at the base of the sketched structure will then be generated, and a grid will be assigned at each of the surfaces of the sketched structure. The grid distance depends on the size of the surface and is typically 2 m for large structures. Grid points are also assigned to all edges and corners. Normalized loads perpendicular to the surface are then applied.

Upon user request, pre-calculations of the designed structure are performed. Then, the finite element model is evaluated separately for unit loading at all of the grid positions. Computation times are kept in check by relying on linear tetrahedral elements. However, selecting a higher-order shape function for these elements is possible and may enhance accuracy. In areas between the grid points, the field variables (such as displacement and stress) are interpolated linearly to ensure smooth feedback if the user decides to touch the VR object at locations other than the predefined grid points. Relying on the adopted linear elasticity, the realistic deformation fields of the structure are obtained by multiplying the actual user-applied (and typically amplified) force by the calculated deformation field referring to the unit load, as explained in more detail in the haptics module in Section 3.7.

Should the analysis reveal excessive displacements or stresses surpassing material strengths, designers can intervene by either modifying the structure, such as altering its geometry or adding supports, or by choosing stronger, stiffer materials, e.g., by adding more fibers to the biocomposite. The analysis outputs include but are not limited to the 3D nodal displacements, stress and strain fields, and the degree of utilization, all of which can be visualized in the XR module, described next.

3.6. XR module

The XR module allows for visualizing and manipulating sketches, visualizing the sketch-reconstructed object (resulting from the geometric modeling module), and for visualizing simulation results (resulting from structural modeling). It thus supports decision-making about architectural design in full-scale immersive VR/AR visualization [95].

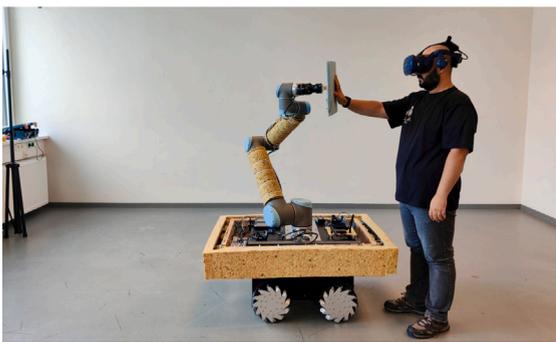
In our sketching application, MR.Sketch, three distinct MR sketching interactions are implemented. The viewport-affixed drawing canvas is available in AR mode. In this mode, the camera position is adjusted via six DoF inside-out tracking using the built-in light direction and ranging (LiDAR) scanner of the tablet device. Drawing canvas visualizations and control are still available in this mode. The LiDAR scanner also enables spatial mapping and meshing of the geometry in the physical environment. In this second mode, the geometry of the scanned physical environment provides the surface for sketching. This allows the designer to draw directly over physical objects such as existing buildings. Akin to the tangible UI paradigm, physical objects can be used as drawing guides. The third sketching mode forgoes device pose tracking and enables more traditional, touch gesture-based camera and drawing canvas manipulation in a pure virtual sketching environment. However, it is possible to switch between sketching modes at any time during the creation of a sketch.

Sketch-reconstructed objects are presented seamlessly in a VR showcase application that uses realistic lighting and rendering, see Fig. 4. It thus enables the observation of sketches under different conditions and in multiple environments. To enhance the sketching experience in XR, our platform offers designers a range of interactive capabilities, empowering them with more flexibility and precision in refining their sketches while facilitating easier evaluation and enhancement. Using control sliders and buttons in the UI, designers can seamlessly manipulate the virtual model by rotating, translating, or scaling it to gain comprehensive insights into every aspect. This functionality is also useful during presentations to clients or stakeholders. For instance, a designer can efficiently scale down and rotate a sketch, offering an overview of the model. They can then seamlessly return it to full scale, allowing users to immerse themselves in the virtual model, providing a tangible sense of being within the designed structure. This eliminates the need for costly physical mockups.

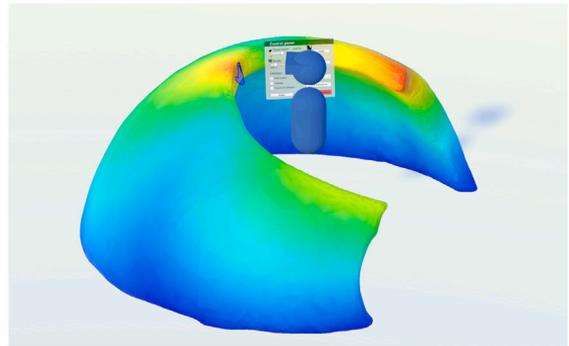
Moving on from sketches to structural modeling results, designers can interact with various components of the structure within the VE, observing the results of their actions in real-time. The overlay visualization enables them to locate the weaknesses in the structure and refine the design or choice of material to strengthen the structural integrity. In addition, the virtual UI provides a possibility to scale up the applied force, freeze the deformation, and enable displacement or stresses visualization overlay, identifying the points of potential risk. This makes the experience truly interactive and informative but does not change the simulation. Therefore, within the VE, users can thoroughly and comfortably examine and refine the designed structure by touch. This is further supported by structural haptics, as explained in the next section.



Fig. 4. Immediate immersive visualization of a 3D sketched theater stage wall in XR: Comparing model-scale and full-scale sketch. Input sketch: Ingrid Erb.



(a)



(b)

Fig. 5. Immersive haptic feedback system Cobodeck: (a) A user touching a plate-prop presented by the robot in the real world, and (b) the user represented through an avatar in the VE touching a theater stage wall and exploring the resulting stress field XR module.

3.7. Haptic feedback

The HeXA framework not only enables users to visualize their designs in XR but also offers the possibility of physically interacting with the structures to gain a deeper understanding of how they deform under real-world loads. To achieve this, we developed and incorporated Cobodeck [23], a mobile robotic platform that offers prop-based encountered-type haptic feedback and forms the core of the haptic interaction module, see Fig. 5.

Cobodeck is a large-scale interactive haptic system that allows users to freely walk around, wearing VR goggles, explore a large virtual space, and interact with virtual objects in an intuitive manner. The robot consists of an omnidirectional mobile platform to which a robotic arm is attached. The robot with the robotic arm moves in real space according to the user's actions. Whenever the user approaches the structure in the virtual environment the robot presents a physical prop (e.g., a plate) to the user in the real environment (see Fig. 5(a)) that matches the position and orientation of a corresponding virtual object (see Fig. 5(b)). The interaction with a virtual structure happens in a natural way using bare hands, without being aware of the robot's real-world operation. To enhance the haptic experience and move beyond simply presenting a rigid, flat prop to the user, there are several ways to achieve more dynamic, realistic haptic feedback. One such approach is the use of different end-effectors, such as origami tube end-effectors [96] or shape changing devices like Shiftly [97], whose potential is further discussed in Section 5.

To provide the targeted structural haptic feedback upon loading by the user, first, the force applied by the user has to be quantified. Hence, the robot arm is equipped with Robotiq FT-300 force-torque sensor, measuring the user-applied force in real-time, as visualized in Fig. 6. The measured force F is then multiplied by the previously defined unit force to give the displacement corresponding to the user's actual force, which is a valid approach within the assumptions of linear elasticity. Since the user's actions alone often cannot simulate the full magnitude of real-world forces, the system allows for dynamic adjustment of force intensity

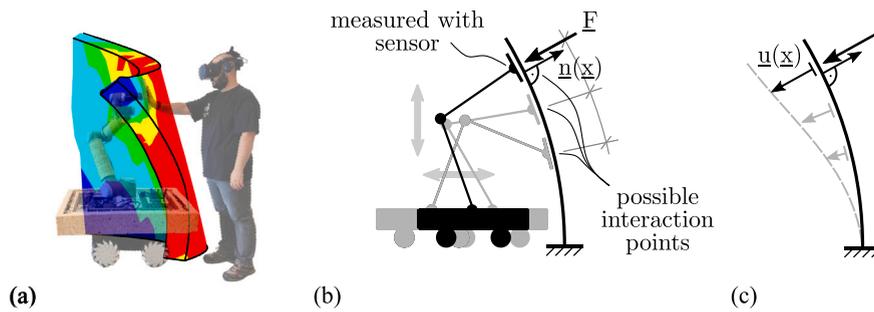


Fig. 6. (a) A user interacting with a physical plate-prop presented by the robot in the real world, while simultaneously viewing the deformation of the virtual wall and corresponding stress fields in VR. (b) A simplified 2D schematic showing the user's applied force, which is measured through a force-torque sensor. (c) The resulting displacement upon loading by the user is mimicked through the retracting robot arm.

through the UI as shown in the proof of concept. The user has the option to amplify the applied force or scale down the designed object, effectively enabling the user to wield a Godzilla-like strong force.³

Realistic structural deformations from the applied force, together with the position and orientation of the robot and its arm, are obtained from the pre-calculated deformation field provided by the structural modeling module (Section 3.5). It relies on mechanical properties from the material modeling module (Section 3.4) and the tetrahedralized mesh from the geometric modeling module (Section 3.3). Based on the calculated deformation at the interaction point, the robot arm reacts by retracting or resisting accordingly, providing a more authentic sense of how the structure would behave under real-world conditions.

4. Proof of concept

The use of two distinct case studies allows us to demonstrate the practical application and versatility of the HeXA framework across different architectural contexts. These cases have been carefully selected to showcase how the framework works at different scales and with various types of architectural elements.

The first use case focuses on a single, yet geometrically complex architectural element — a curved theater stage wall. This scenario allows us to test the framework in a controlled manner, from sketching to structural haptic feedback, in order to assess structural integrity. By focusing on a fixed geometry, we can highlight how the HeXA framework operates, efficiently integrating sketching, material and structural modeling, and haptic feedback within a streamlined design environment.

In contrast, the second use case features a real-world architectural project, the iconic Barcelona Pavilion [98]. Known for its clear definition of architectural elements – slabs, walls, and roofs – and its relatively small scale, the pavilion makes an ideal candidate for exploring the potential of the HeXA framework. The distinct definitions of these elements enable the reconstruction algorithm to automatically differentiate between them. Further, this use case allows us to focus on elements with different properties, such as load-bearing versus non-load-bearing components, while also experimenting with novel bio-materials. Additionally, the structure of the pavilion, characterized by relatively few supports, enables us to analyze the structural integrity, reveal weaknesses, and propose feasible, material-informed design solutions already in the early design phases.

4.1. Use case 1: Theater stage wall

Use Case 1 features a curved wall, echoing a theater stage design from our earlier research [14]. The HeXA workflow starts with the designer sketching the structure in the sketching tool (see Section 3.2) using a stylus and tablet, see Fig. 7(a). Geometric reconstruction then translates the strokes into volume meshes discretized with linear tetrahedral elements, see Fig. 7(b). Thereby, timestamps and other metadata captured during sketching enhance the reconstruction algorithm (see Section 3.3 for details), allowing for a clear distinction between stroke styles. The resulting geometry exhibits sharp edges, just as the designer intends. The structure has a length of $L = 7.40$ m, a height at the highest point of $H_1 = 3.80$ m, a height at the lowest point of $H_2 = 2.00$ m, and a width of $B = 0.25$ m.

A biocomposite material, consisting of 10% (by volume) uniformly distributed flax fibers mixed with a polypropylene (PP) matrix and porosified (50% pores) to reduce weight, is selected from the designer. Micromechanics material modeling (see Section 3.4) immediately provides mechanical properties of the composite: an elastic modulus of 1.93 GPa, a Poisson's ratio of 0.140, a density of 511 kg/m³, and an isotropic elastic limit of 40.83 MPa. After material selection, structural analysis according to Section 3.5 is performed. Therefore, the designer selects suitable boundary conditions and loads first. As for the theater stage wall, fixed displacements at the bottom end of the wall are enforced and the dead weight of the structure is considered. Then, the user may

³ The term 'Godzilla-like strong force' refers to the iconic Japanese pop culture figure Godzilla, known for its immense size and strength. In this context, the analogy emphasizes the amplified force users can exert in the VE, highlighting the exaggerated, yet playful nature of interacting with large architectural structures in an XR setting.

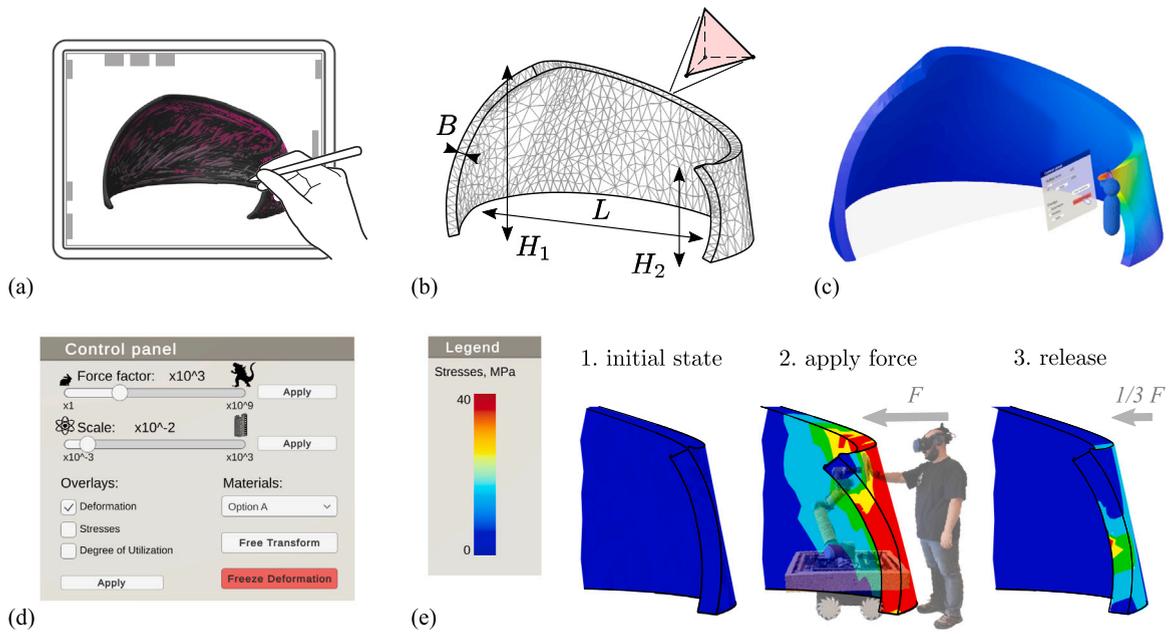


Fig. 7. (a) 3D sketching using stylus and tablet in the sketching interface, (b) geometrically reconstructed tetrahedral mesh, (c) visualization of the geometry in XR allows for user interactions, (d) control panel with sliders for scaling the model itself and the applied force, and (e) a scheme for showing the real-time feedback of the robot and the calculated stress field in accordance to the applied force. Input sketch: Ingrid Erb.

define locations at which interactions in XR are possible, or otherwise, these positions are automatically assigned at the edges of the structure and in a grid with a spacing of two meters in between. Finite element simulations are then performed, utilizing the tetrahedralized mesh, the predicted material properties, and the defined boundary conditions and loads. Notably, for each interaction point, a separate calculation is performed. At each interaction point, a unit force of one is applied orthogonally to the surface.

The structure itself and the results of the structural analysis are then explorable in XR (Section 3.6) enhanced with haptic feedback (Section 3.7). The setup allows the user to freely walk around or inside the structure, scale and rotate it to their liking. Moreover, the user can touch and feel the structure, see Fig. 7(c), with the robot's arm moving to any point of possible interaction (determined by the moving hand of the user). If the user decides to push against the wall, the robot arm will react such that the user experiences a realistic structural response to the applied force in real-time. The applied force is measured with a force–torque sensor integrated into the robotic arm, and the results from the finite element simulations (which refer to a unit load) are multiplied by the pushing force. Notably, if the position of the applied force is different from the predefined interaction points, then the actual deformation field for this point is obtained by linear interpolation in between the finite element results of neighboring interaction points. Moreover, the force typically applied by a user is too small to significantly deform the structure. To enrich this experience and allow for meaningful interaction, users can amplify the applied force, thus being able to effectively mimic Godzilla-like power. This feature can be selected through a control panel, depicted in Fig. 7(d), which further enables the exploration of the structural response for several different previously defined materials.

The haptic feedback is complemented by visualization effects. The representation of stresses (Fig. 7(e)) shows the response of a user pushing on the top right edge of the structure toward the outside. Upon applying the force, the robot arm will respond and the initially unloaded (blue) wall will show large (von Mises) equivalent stresses in red color. Then, after releasing two-thirds of the applied force, the stresses will reduce significantly and the robot arm will move back. Instead of stress fields or deformation fields, a degree of utilization may be visualized (see the options in the control panel), and the corresponding color legend will pop up. When showing the stress field or the utilization, any areas at risk of failing are highlighted in red. This indicates that the elastic limits (determined by the micromechanics model) have been exceeded, and the structure is at risk of collapse.

4.2. Use case 2: Barcelona pavilion

After presenting the HeXA workflow in Use Case 1, we now shift our focus to the benefits it offers in design as we examine the structural integrity of a building inspired by the iconic Barcelona Pavilion, initially introduced in previous works [84,99]. The sketched design, visualized in Fig. 8(a) is approximately 30.0 m in length, 11.0 m in width, and 3.0 m in height. All walls and the roof should be as thin as possible and are assumed to be 15 cm thick. Initially, the analysis focuses on the load-bearing elements as specified by the designer. These walls are highlighted in red in Fig. 8(a) to distinguish them from non-load-bearing elements, such as the envisioned transparent sections akin to glass walls, which are omitted from the initial model. Geometry reconstruction is performed such that the individual parts of the structure (each wall element) and the roof are separated, enabling the designer

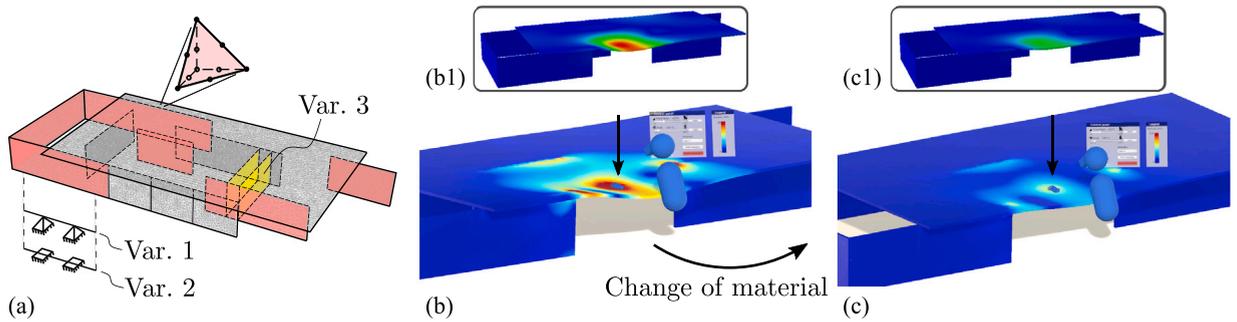


Fig. 8. (a) The reconstructed version of a sketch resembling the Barcelona Pavilion, as in [84,99]: red walls are solid walls, all other walls are transparent elements, not intended to contribute to the load bearing. (b) Deformation of the structure and its stress field under a vertical force applied by the user in XR showing large vertical deflections. (c) Reduced deformations due to changing to a stiffer biocomposite material. Subfigures (b1) and (c1) additionally show the corresponding displacement field overlays for better visualization of the overall deformation.

Table 1
Selected materials for use case 2 and their mechanical properties.

Material	Ref.	used in	Mechanical properties ^a	Notes
Flax-PLA (isotrop)	[100]	Fig. 8(b), Fig. 9(a–c)	$E = 3.67 \text{ GPa}$, $\nu = 0.23$, $\rho = 1292 \text{ kg/m}^3$, $\sigma_{ult} = 59 \text{ MPa}$	Weak interfaces, random distribution of fibers
Flax-PLA (transversal isotrop)	[100]	Fig. 8(c)	$E_{\text{plane}} = 8.35 \text{ GPa}$, $E_{\perp} = 4.50 \text{ GPa}$, $G_{\text{plane}} = 3.26 \text{ GPa}$, $G_{\perp} = 2.01 \text{ GPa}$, $\nu = 0.28$, $\rho = 1292 \text{ kg/m}^3$, $\sigma_{ult} = 146 \text{ MPa}$	Strong interfaces, preferred fiber orientation in plane direction
Holocellulose-PMMA (isotrop)	[101]	Fig. 9(c)	$E = 11.79 \text{ GPa}$, $\nu = 0.27$, $\rho = 1302 \text{ kg/m}^3$	Transparent biocomposite ^b

^a Obtained from the multiscale material modeling module.

^b Lignin-modified and polymer-infiltrated cellulose-based material offering optical clarity and mechanical strength.

to easily include or exclude them during structural analysis. Due to the slender nature, geometry reconstruction is performed using quadratic tetrahedral elements, thereby enhancing the accuracy of the finite element analysis.

An isotropic flax-poly lactide acid (PLA) biocomposite is selected and the results of the multiscale material model are documented in Table 1. As for the boundary conditions, we initially consider hinged connections (Variation 1) between walls and foundations, as it is commonly done in structural engineering. Structural analysis is performed, again for unit point loads orthogonal to all surfaces, along the edges, and also on the structural elements themselves.

The designer (or the team of designers) now switches to the interactive XR environment, and aims at intuitively examining the structural response of the design. In order to touch the roof, the structure is scaled down. Pushing on the roof at different locations (using adequate force amplification) and seeing the color-coded stress fields in real-time to identify potentially weak zones is very intuitive and also accessible to non-experts in structural engineering. Initial tests with the chosen flax-PLA composite reveal limitations under vertically applied forces, with the structure exhibiting excessive stress and deformation beyond the material’s capabilities, as shown in Fig. 8(b). A subsequent iteration, leveraging a transversally isotropic version of the flax-PLA material with fibers oriented within the plane of the roof (see Table 1 for more details), significantly mitigates these issues. This new material-informed design successfully withstands the applied forces, demonstrating tolerable vertical deformations and stresses within acceptable limits, depicted in Fig. 8(c).

Next, the user interactively explores the structure’s lateral behavior by applying localized forces at various positions in XR. This allows for an intuitive understanding of where the design may lack stiffness or require additional bracing, as demonstrated in the following variation. The user initially applies an amplified force in the direction of the pavilion’s longer dimension, aligning with most supporting walls. In this orientation, the structure exhibits significant stiffness; virtually no displacement is observed, and stress levels remain minimal. Conversely, when an amplified force is applied orthogonally to this direction, i.e., along the structure’s shorter dimension, the structure displays markedly less stiffness. Even a minor force is sufficient to cause substantial lateral deformations, leading to the pavilion’s collapses in a manner reminiscent of a house of cards, as illustrated in Fig. 9(a).

To address this, the connectivity hinge-type bearings at the bottom are replaced by fixed ones (Variation 2). It is worth noting that such a restraint requires complex and thus rather expensive joints between walls and the foundation and also between walls and the roof, and that actual structural behavior would likely fall between a hinged and fixed bearing, contingent upon the implementation of structural connectors or fasteners in construction. After re-evaluating the structural response using finite element calculations, the user notes that the structure behaves much stiffer under the same force, necessitating a significant increase in force by a factor of 20, to induce the same deformation as with hinged supports (Variation 1), see Fig. 9(b). This difference is due to the additional bending resistance provided by the fixed supports, which substantially increases the lateral stiffness of the structure. Even in early design phases, such changes in support assumptions can have a significant impact on perceived structural behavior and material

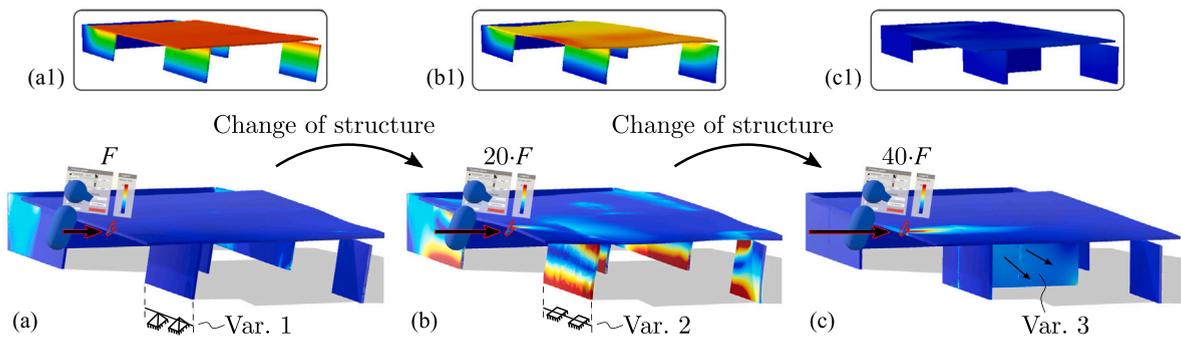


Fig. 9. Design optimization regarding the structural integrity when applying horizontal forces: (a) Initial vulnerability mimicking a house of cards, (b) enhanced resilience through rigid connectivity at base, walls, and roof interfaces, and (c) introduction of “shear walls” for efficient horizontal load distribution to the foundation. Subfigures (a1), (b1), and (c1) additionally show the corresponding displacement fields, in contrast to the stress field overlays shown in (a), (b), and (c).

demands. However, while this adjustment allows the structure to withstand greater forces, it introduces excessive (material) stresses, which exceed the biocomposite strength.

Seeking a better design, the user decides to re-purpose two of the transparent wall elements, highlighted in yellow in Fig. 8(a) as load-bearing parts of the structure (Variation 3). A novel transparent biocomposite may qualify as material for fulfilling both mechanical stability and optical transparency (see Table 1 for the micromechanics-based simulation results of such a composite). This is achieved by selectively removing lignin, which is primarily responsible for light absorption, and impregnating the remaining cellulose scaffold with a refractive-index-matched polymer. The preserved cellulose framework ensures the necessary structural integrity of the composite material [101,102]. These parts now act as “shear walls”, effectively channeling horizontal forces directly into the foundation, thereby preventing any significant deformation and stresses.

These considerations and the explored iterations are typically done by experienced structural engineers and are thus inaccessible to other stakeholders. Providing an XR framework in which the implication of (even little) design changes are tangible, helps designers to come up with structurally sound buildings already during the earliest stages of the design process. In contrast, if these analyzes are performed at later stages where the design may already be set in stone, as it is common practice in traditional AEC planning processes, additional unappealing support structures (such as diagonal bracings) would have to be put in place. The collaborative and interactive HeXA framework has herein shown its full potential, by rather relying on a creative material-informed solution that explores the possibilities of novel materials, such as transparent biocomposites.

5. Discussion

5.1. Contrast to existing design frameworks

Compared to existing digital design frameworks, HeXA is the first to incorporate structural haptic feedback in XR, thus creating a virtual space for all project partners (independent of their background) to interactively work on the structural design together with functional and esthetical design aspects. While many design frameworks provide a centralized digital sketching application at its core and combine it with XR elements [17–20], the additional inclusion of (at least coarse-level) structural analysis has only been explored by a couple of authors [10–13]. Notably, unlike earlier design frameworks that combine 2D sketching with structural analysis [10–12], HeXA supports 3D geometry from the outset of sketching. Compared to BIM, our approach aims at providing a digital playground to explore structural design and thus inherently fosters creative solutions rather than conservative and unimaginative designs, a criticism often mentioned in BIM workflows [26,28]. HeXA links all involved domains (architecture, structural engineering, computer science, robotics) further to material science by incorporating a multiscale material model into the framework. Consequently, it paves the way for material-informed structural design and this way follows earlier material-based design approaches [8]. These frameworks often also include production or fabrication aspects in their design [103], or link the design process to automatic additive manufacturing [104]. Given the large dimensions of typical architectural use cases, such a task would be unfeasible for current 3D printing setups.

5.2. Limitations

The design framework is not yet fully integrated and automated. Direct integration of the six modules into a single user-friendly system is beyond the scope of this paper. In the future, we plan to streamline the workflow to boost the user experience by integrating geometric, material, and structural modeling into the sketching tool with suitable graphical user interfaces. This requires porting some of the developed code (material modeling, geometric modeling, FE analysis) into the Unity Engine, which the sketching tool and the XR framework rely on.

Several challenges currently exist in the integration of the HeXA framework, largely due to the manual nature of specific workflow steps. While data transfer between modules is still manual and the entire processing chain – from sketching to material assignment and preliminary structural evaluation – takes notable time, these limitations are acknowledged and accepted within the context of our objectives.

The sketching tool, requiring explicitly defined and closed boundary lines, currently limits some aspects of design freedom. Addressing this constraint will be essential to fully harnessing the creative potential of users during early-stage design explorations.

Although automatic generation of structural connections and the simplification of 3D meshes into lower-dimensional representations (e.g., beam, truss, or membrane elements) remain technically challenging, our main aim is not full automation or complete simplification. Our framework does not intend to compete directly with comprehensive BIM models or detailed structural analysis tools. Instead, the core strength and primary objective of our approach lie in enhancing the early design phase by facilitating collaboration and delivering a novel, interactive design experience. Currently, only concentrated point loads are implemented for interactive robotic feedback. While expanding load types to include more realistic scenarios (such as distributed wind or seismic loads) is technically feasible, it has not been prioritized yet. It is important to distinguish between engineering loads (like wind loads, seismic loads, and other complex loading scenarios), which can be easily applied within a finite element simulation, and the point load applied by the user, where the robotic arm provides feedback. This user-applied point load serves solely to allow designers to haptically explore the stiffness and strength of structures. Since we can only physically explore loads through our hands, there is no practical need to extend this type of loading.

Our future work will thus primarily emphasize extending our concept and refining user interfaces to support creative and collaborative design processes, rather than striving for perfect or fully automated structural analysis solutions.

Currently, the robot allows a single user to interact with the designed structure in XR. Providing multi-user interaction in XR with multiple robots would improve the collaborative nature of the approach and will be tackled in future research, particularly focusing on safety aspects regarding robot-to-user collisions. The current setup is further limited by the robot's maximum vertical reach of approximately 2 m, and its motion is deliberately restricted in real time if the user moves too quickly, in order to prevent potential collisions. In addition, the robotic arm and end-effector does not yet allow the haptic rendering of small-scale geometric or material features. As discussed in Section 5.3, alternative end-effectors may address this limitation and expand the system's ability to convey detailed haptic feedback.

Another limitation of the current setup is the cost of the collaborative robot, and the space required to safely operate it. While stationary haptic feedback devices [64,65,105] could mitigate this disadvantage by reducing the need for a mobile platform, they would also limit the immersive experience by restricting the user's ability to freely walk around and explore large-scale designs in VR.

The potential benefits of the proposed design framework have not yet been studied systematically. Clearly, the selection of two use cases cannot cover all aspects of early-stage AEC design. Rather, these examples serve as proof-of-concept demonstrations to illustrate the current capabilities of the HeXA framework. Future work will thus expand on the use cases by introducing the framework to architectural and civil engineering students in joint ventures. This naturally leads to a broader outlook on the framework's potentials, which are discussed in the following section.

5.3. Potentials

To further expand the applicability of HeXA, different *end-effectors* can be mounted to the robot's arm. Inspired by the origami-based props that are becoming more popular [106,107] for their simplicity and different capabilities [108–110], we developed and evaluated two custom end-effectors.

An innovative origami zipper flower tube end-effector [96] can be mounted on a robotic gripper of our robotic arm. Controlling the fingers of the gripper, the origami tube contracts or expands, see Fig. 10(a). This provides not only a reliable mode of positioning the touch panel, but may also act as stiffness-adapting end-effector based on the geometry of the origami. It thus allows immediate stiffness response unlike solutions relying on path planners [96].

To enhance the user experience and haptically render various shapes and surfaces with a single end-effector, a custom-made origami-inspired shape-display named "Shiftly" has been developed [97,111]. Rather than swapping out physical props to match the desired shape, Shiftly is crafted as a triangular prism with three curved origami patterns made from dense paper. Each surface is independently actuated by a stepper motor, and curved folding creates a shape with a reasonable amount of stiffness for haptic interaction (Fig. 10(b)). This allows Shiftly to render flat and rounded surfaces, as well as various angled edges.

While originally designed with biocomposites with largely varying microstructures and thus largely varying mechanical properties in mind, HeXA is flexible to host *other materials*. Similar analytical micromechanics multiscale models have been developed for other construction materials, including traditional concrete [112], recycled concrete [113], and bricks [55,114]. More straightforwardly, a material with more standardized material properties (such as wood or steel) can be incorporated by providing a material catalog within the sketching tool from which user can select their preferences.

Another, so far unexplored potential of the approach is the use of HeXA in *education*. We envision that its interactive, hands-on learning environment in XR – featuring immediate visual and haptic feedback – supports a more intuitive understanding of structural behavior in early-stage designs. This may help architecture and engineering students better grasp the spatial and structural logic of complex 3D systems, especially in cases where load-bearing behavior is not readily apparent from visual inspection alone. While formal studies have not yet been conducted, we see strong potential for HeXA to serve as an educational tool that bridges abstract analysis with experiential learning. For example, when students interact with virtual models such as the "Barcelona Pavilion" or the

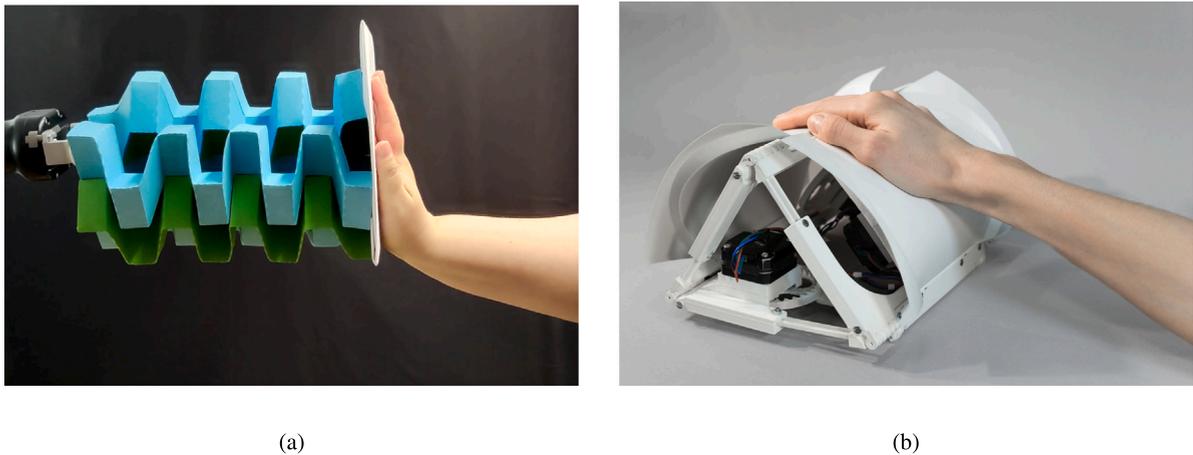


Fig. 10. (a) Origami zipper flower tube acts as a haptic end-effector controlled via a robot's gripper [96]. (b) Shape display Shiftly can replicate curved surfaces to allow the user to touch curved objects in VR.

“Theater Stage Wall,” they physically experience structural deformation and simultaneously visualize stress fields, greatly improving their comprehension of structural behaviors, load distribution, and integrity.

Additionally, the framework allows students to experiment practically with various materials within the XR environment. By switching between materials like biocomposites, students directly observe how different material properties influence structural performance under identical loading conditions. Furthermore, HeXA promotes multidisciplinary collaboration, enabling students from architecture, structural engineering, and material science to engage in joint explorations. This collaborative setting helps architecture students understand engineering constraints while giving engineering students insights into architectural design intentions. Thus, the HeXA framework fosters integrated, creative, and informed design thinking from early education stages.

Beyond education, the HeXA framework may also support collaboration among stakeholders with different technical backgrounds. Its visual and haptic feedback allows users to jointly explore how structural behavior responds to changes in geometry or material, even without deep engineering knowledge. This can help architects and non-technical participants better understand design constraints, while engineers can respond directly to spatial and aesthetic goals. By making structural effects visible and tangible in real time, HeXA encourages earlier alignment between disciplines and therefore supports more inclusive, creative decision-making.

The HeXA concept may also show its benefits when dealing with *kinetic architecture*, where parts of buildings can move and adapt according to user needs [115]. In this context, the haptic feedback provided by the robot in XR may be used to allow the user to experience the process of space transformations in an immersive way, facilitating design decisions and optimization loops.

Further noteworthy capabilities of HeXA are the possibility to render *any* designed geometry into 3D tetrahedral meshes used in finite element simulations. The approach is thus not limited to certain structural elements such as trusses, columns, or slabs such as many previous efforts [10–12], and even works for organic structures. Nevertheless, the automatic reduction of FE meshes for such 1D or 2D elements is already achievable using the latest version of the geometric modeling module and thus helps to mitigate the computational costs of large structures.

6. Conclusions and outlook

The key achievements of this work include the implementation of interactive structural haptic feedback using a collaborative robot embedded in an XR environment, enabling users to physically experience structural responses in real time. The proposed workflow bridges the gap from initial sketching to early structural assessments by integrating, for the first time, a multiscale material model for biocomposites into an interactive, haptic-enabled design workflow. The capabilities of the HeXA framework were validated through two use cases — a curved theater stage wall and a reconstruction of the Barcelona Pavilion. Compared to traditional sequential AEC planning processes, HeXA integrates several crucial aspects of structural and material engineering into the earliest stages of the design process, making it an asset that complies with global AEC challenges such as sustainability and resource efficiency.

Most importantly, the framework addresses the major knowledge barriers associated with structural engineering by creating a virtual playground of the designed structure in XR with realistic haptic feedback of the structural stiffness. The stage designer in our first use case could experiment with different materials for the stage walls or adapt the geometries to their liking, so the walls could be engaged within the play and by actors. HeXA mitigates the need for laborious iteration cycles typical in conventional workflows. It empowers designers to see their design in 3D and gain immediate hands-on experience while freely walking around, virtually exploring and interacting with it, and seeing and feeling the mechanical response for any combination of geometry, structure, and material. Consequently, technical and non-technical members of the project can explore the design and its structural response creatively and collaboratively and, independent of their expertise, participate in the decision-making process. This is illustrated in

the pavilion use case: the lack of lateral bracing in the original design was identified and made physically perceptible through haptic XR. Users could feel the structural difference with their own hands — interacting directly with the virtual model to experience how the structure responds with or without bracing. To reconcile the design intent of visually ‘lightweight’ wall segments with the need for stability, novel biocomposite materials offering both transparency and stiffness were explored from the earliest stages of the design process.

While the current HeXA framework shows considerable promise, further development is required to rigorously quantify its benefits through user studies in both real-world and educational contexts, especially with more complex use cases. In educational settings in particular, the integration of haptic structural feedback offers a unique opportunity: it enables users to develop an intuitive understanding of structural behavior — a challenge that has traditionally posed a significant hurdle for students in AEC. Further development of the framework will target the automation and integration of its six modules, enhancing structural analysis capabilities, incorporating more diverse load types, and enabling multi-user interaction for collaborative design processes.

List of abbreviations

AEC	Architecture, Engineering, and Construction
AR	augmented reality
BIM	Building Information Modeling
DoF	degrees of freedom
ETHD	encountered-type haptic device
FE	finite element
HeXA	Haptic-enhanced eXtended reality framework for material-informed Architectural design
LiDAR	light direction and ranging
MR	mixed reality
PLA	polylactide acid
PMMA	polymethyl methacrylate
PP	polypropylene
UI	user interface
VE	virtual environment
VR	virtual reality
XR	extended reality

CRedit authorship contribution statement

Valentin Senk: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Conceptualization. **Mohammad Ghazanfari:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Conceptualization. **Sherwin Rasoulzadeh:** Writing – original draft, Visualization, Software, Resources, Methodology. **Khrystyna Vasylevska:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Methodology. **Balint Istvan Kovacs:** Writing – original draft, Software. **Soroosh Mortezaipoor:** Software, Resources. **Emanuel Vonach:** Software. **Iva Kovacic:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Josef Füssl:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Hannes Kaufmann:** Supervision, Funding acquisition. **Markus Königsberger:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was funded in whole or in part by the Austrian Science Fund (FWF) [10.55776/F77, 10.55776/Y1093]. For open access purposes, the authors have applied a CC BY public copyright license to any accepted manuscript version arising from this submission. The funding of the Horizon Europe Project “AI-TranspWood” (Project ID 101138191) is also gratefully acknowledged.

The authors thank all partners within the SFB project “Advanced Computational Design” [10.55776/F77], particularly Michael Wimmer for judiciously guiding the project and initiating inter-disciplinary collaborations. The authors would also like to thank Kiumars Sharifmoghaddam, Georg Nawratil, and Tobias Batik for their work on the origami designs. Special thanks to Peter Ferschin and Ingrid Erb for their contributions to the development of the sketching tool, and to Ingrid Erb and Philipp Stauss for their input sketch designs. Their expertise and insights have significantly enriched this project.

Data availability

Data will be made available on request.

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