Processing 3D Point Clouds of Historical Timber Structures for Analysing their Structural Behaviour pressed for Time

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Fast assessment of the condition of historical timber structures is important in case of sudden damage or while renovation work. In angled and complex timber constructions, surveying with tachymeter is time consuming and requires additional manual work in post-processing, for a structural modelling of the wooden beams and their joints. Visual analysis is subjective and does not allow further quantitative evaluation. Thus, an automated method is required. The technology of 3D laser scanning has evolved significantly in recent years and allows the measurement of several hundred thousand points per second. Thus, point clouds covering an entire timber construction can be recorded quickly from multiple scanning positions. However, manual modelling of beams from point clouds is still a work-intensive task.

Developments in automated geometric modelling from point clouds are driven forward with the goal of overcoming the bottleneck in manual modelling. Developed methods for triangulated mesh generation or parametric modelling (e.g. “Non-uniform rational B-Splines” (NURBS) or simple geometric solids) are finding their way into more and more applications for thin walled or solid structures. Geometric fact-finding and modelling in historical timber constructions requires at least information about the axis and dimensions of wooden beams to be obtained. For a subsequent structural analysis, it is important to correctly locate the woodworking joints on the beams and determine their structural characteristics. The requirements for a reliable structural assessment – e.g. in terms of geometric accuracy, completeness of the geometric model as well as beam and joint characteristics – need to be discussed for different levels of detail (e.g. ideal straight or curved rectangular beams, deformations, cracks and other damages on beams).

While an elaboration with current manual methods for geometric and structural assessment takes weeks, our vision is to develop a method for a highly automated assessment within some hours respectively a few days. A fast, automated structural assessment also enables monitoring of existing structures with respect to progressive structural failure in the future.

Key words:
Point clouds; beams; automated geometric modelling; structural modelling; historical timber structures

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INTRODUCTION

For a better understanding of historical timber structures, on how they were designed and built by the carpenters and how they have deformed and changed over the years, geometric information about beams and woodworking joints must be collected on site for a later analysis [Eßer et al. 2016]. Depending on the requirements, this information can be visually captured by the person in the building, sketched on paper or digitally measured. The geometric reconstruction of the object of interest, in whatever medium and format, can then be considered for an analysis of the timber structure. In recent decades, numerical modelling and visualization techniques have proved universally applicable to the digital documentation and archiving of cultural heritage objects [Pieraccini et al. 2001; Levoy et al.

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2001; Ikeuchi et al. 2001; Remondino 2011]. The logical next step is the extraction [Macher et al. 2015] and modelling [Barazzetti 2016] of individual components which have already been investigated for some applications in the “Building Information Modelling” (BIM) context. Solutions for non-standardized or deformed components, such as wooden beams in historical roof structures, are still a main research topic for applications in digital heritage conservation.

The modelling of geometric entities (e.g. wooden beams) can be based on points, lines, and faces measured on objects surface by surveying methods, including tachymetry and 3D laser scanning. In comparison to the single point measurements with a tachymeter, the laser scanning technology allows recording of hundreds of thousands points per second, resulting in a dense point cloud. Data is typically acquired at multiple scan positions, registered in a common coordinate system and in this way aligned to a complete model of the timber construction. Such a model consists of millions of individual points on objects, which are visible from the different scan positions (see Fig. 1).

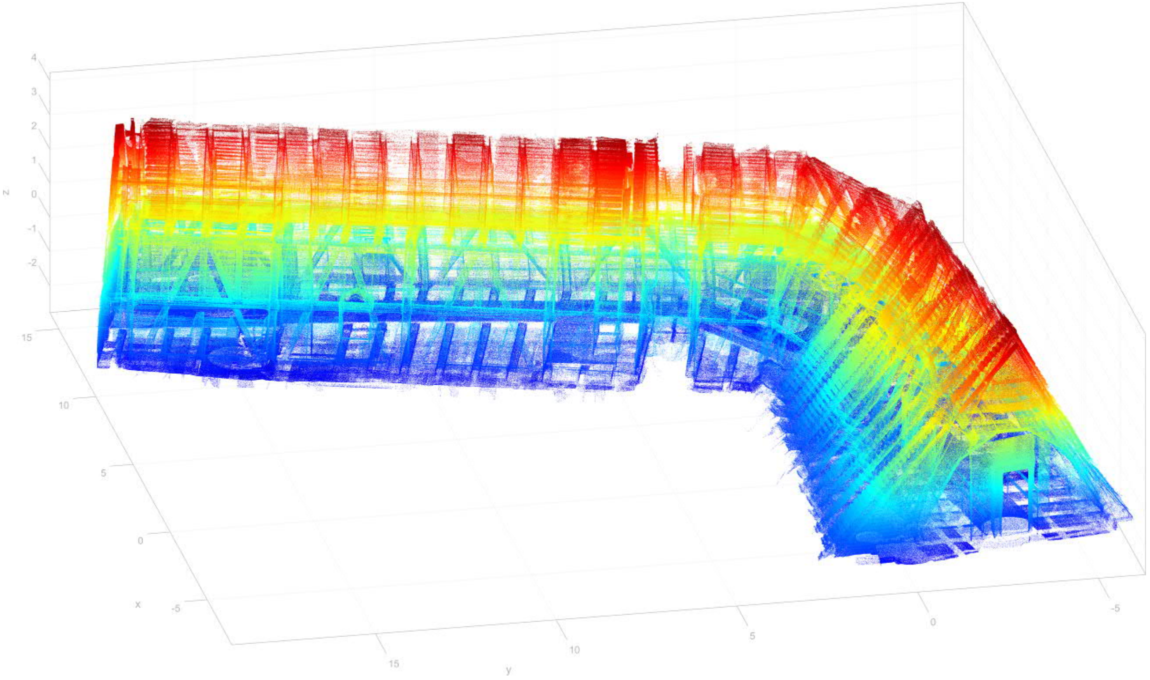

Fig. 1. Large point cloud of a complex roof construction of the Amalienburg in the Vienna Hofburg

The structural modelling is based on the geometric reconstruction and includes an analysis of the flow of forces, displacements, overstressing on structural members and joints.

The current state of the art for fact finding (i.e. geometric modelling) in timber structures and subsequent structural assessment consists of several manual tasks including:

a) Manual acquisition of information about the timber structure and geometric survey.

b) Manual modelling of 2D slices of the timber structure

c) Manual generation of an adequate structural systems in structural engineering software (FEM)

d) Prediction of the mode and risk of structural failure

The time required to complete the structural analysis is – depending on the size of the construction – usually several weeks to months. Based on recent developments in the automated geometric modelling from 3D point clouds, the following vision for a timesaving assessment of timber structures emerged:

a) Acquisition of point geometry with a 3D laser scanner

b) Automated transformation of points into geometrical elements like planar or curved surfaces.

c) Highly automated transformation of planes into cross sections, beam axis and mid-planes in terms of structural modelling

d) Modelling of joints between main structural elements.

e) Integration of joint characteristics based on manual observations

f) Structural analysis including predictions of risk and mode of structural failure

Due to risk of imminent collapse, the structural analysis of historical timber constructions may have to be performed under heavy time pressure. Thus, the aim of this development is a complete workflow for the analysis of large and complex timber structures within some hours or days.

Geometric modelling of complex structures from point clouds

The geometric reconstruction of objects scanned with terrestrial laser scanners, and more generally described by point clouds [Otepka et al. 2013] has been a major research topic in the recent years. While countless publications in the field of Cultural Heritage and Archaeology cover the topic of modelling individual objects in high detail, the main focus of the building industry in terms of “(Heritage) Building Information Modelling” (HBIM) lies on a complete modelling of complex structures.

Individual wooden beams were measured, modelled and used for deformation analysis by Gordon et al. [2004] and Cabaleiro et al. [2017]. This proofs the feasibility of the data acquisition method and its integration in structural analysis. However, concentrating on one beam leaves out the task of 3D modelling of an extensive set of beams, partially overlapping, and especially connected to each other in different types of joints.

For the geometric modelling of complex structures in the building and construction industry, methods have been developed for specific applications, like the identification of piping installations or indoor structures. Virtanen et al. [2018] present a method for modelling of indoor scenes. They describe the state of automation and the considerable manual effort to obtain clean results. Indoor scenes typically include objects of different type, i.e. relevant objects that shall be modelled and temporary models not of interest in scene reconstruction. In more controlled, but still complex, environments, like industrial sites, the reconstruction of piping installations was investigated earlier by Rabbani et al. [2007], but obtaining complete models is still challenging [Qiu et al. 2014]. In industrial installations connecting elements between pipes are typically challenging to detect, because they can be small. In timber constructions the joints between individual elements are challenging, because they are naturally occluding each other.

Structural analysis of complex buildings has been investigated by Castellazzi et al. [2015] and Gonizzi Barsanti and Guidi [2017]. Both publications propose a workflow for computation of finite element models from 3D point clouds. The derived models are then used for the structural evaluation.

A structural analysis of metal frame structures was carried out by Cabaleiro et al. [2014] by modelling the connections and the entire frame from 3D point clouds. The work uses the detection of sharp edges of the metal frame with Hough transform of the points in the point cloud. The detected edges are the basis for a 2D structural modelling. Yet, the thickness of the metal plates has to be measured manually.

Parametric modelling of cuboid wooden beams from point clouds in timber structures is shown in Yang et al. [2017] and Pöchtrager et al. [2018]. In the latter paper a roof construction with more than 400 beams was modelled automatically, which would still require manual editing to achieve a complete 3D model. We build on this work and propagate it to structural analysis.

Bassier et al. [2016] have already taken first steps into the development of a complete modelling workflow from point clouds, including geometric modelling of beams in with a triangulated mesh and subsequent structural analysis with “finite element method” (FEM). Their approach does not require the identification of individual beams. While this is an advantage for 3D geometric modelling, it was only shown for a smaller dataset (section of rafters). It furthermore does not allow modelling the individual beams and their joints.

Strategies for structural modelling

In general, three strategies for structural modelling in the context of historical timber structures are available respective applicable depending on the type of requested results for 3D, 2D and 1D modelling

3D modelling implies perfect view from all sides for the definition of the volumetric representation, knowledge about fitting of neighbouring members in the interior, the definition of contact areas between members and high computational costs. The material specification should be as accurate as possible to catch local structural effects.

If historical timber structures are already enriched respective strengthened by thin walled steel cross sections, a more abstracted strategy of structural 2D modelling in terms of plane elements with usually small member thickness would be possible. This approach could be based on the definition of the shape for the single planes only by edges and manual completion by the thickness. In principle, such engineered thin walled cross sections could also be handled by 1D modelling, but with no possibility for the assessment of local stability like buckling.

1D modelling saves both computational costs and costs for structural modelling by idealisation respective densification to simpler structural elements like beams or plates. The global structural behaviour could be addressed quite well, local reasons for possible failure mechanisms have to be matched by mechanical simplifications. Anyway, this approach is perfect for a quick assessment of the structure and identification of critical, highly stressed domains especially in the cases stressed in time.

Characterization of historical timber structures

The beam-like structure usually consists of either straight beams with minor geometrical imperfections of the beam axis due to growth irregularities or dedicated curved beans. Such curved beams directly are taken from grown trees like subsections of the trunk in combination with branches or are prefabricated from short boards with appropriate curved shaping of the longitudinal edges and assembly in a staggered manner by nails to rectangular cross sections (= construction system of Philibert de l’Orme; see [Erler 2013]).

The cross sections of single members usually are rectangularity shaped with dimensions following the architectural demands or the needs from structural loading. Sometimes, sharp edges are missing in order to exploit the maximum structural cross section from an existing circular stem. If the dimensions of cross sections are varying, substructures may be assembled either with respect to the mid-plane of the structure or with respect to the plane of one side view as it was typical for old half-timbered houses. This time, the single beam axes as theoretical centre-line of each beam are no longer connected by points of intersection but have to be linked otherwise for interoperability in global structure. Possibly, over time, beams with initial perfect prismatic geometry at the time of chipping may start with rotation of the cross section along the beam axis due to shrinkage and local fibre deviation during the time of growing. The stability of the initial perfect rectangular cross section may also be corrupted by tensile cracks perpendicular to the grain due to the reduction of the moisture content and therefore shrinkage within the side faces of the cross section sometimes leading to cupping of the cross section.

Single members are implemented with a length as long as possible in order to avoid labour intensive connections usually also being the bottleneck with respect to the overall load carrying behaviour. The type of the connection usually was chosen with respect to the characteristic domination internal forces, the acceptability of the effects by net cross section in terms of stress peaks or stress concentrations and the impact of local stiffness on the global structural displacements.

At the beginning of the construction work, the members are trimmed and fitted together on the ground according to the initial geometrical concept of the structure usually still without any constraints in terms of forces. Only after implementation on site, these prefabricated substructures start taking loads from self-weight or external loads like dead load, snow or wind and change their initial shape due to either elongation by normal forces, significant bending due to bending moments or relative displacements of neighbouring cross sections connected with joints. If members are overstressed, the course of the beam axis may become disrupted, hopefully not being responsible and therefore the starting point for global structural failure.

Requirements for a reliable structural assessment

The structural model of a historical timber construction should at least consist of connected beam elements following the initial geometrical layout, which is definitely not that of the geometrical survey by 3D laser scan. The observable course of the beam axis is the compilation of the initial geometry enriched by the field of displacements due to manifold reasons. The strategy for reconstruction of the early stage of geometry cannot be standardized. One way could be to fit the deformed structure back to the supposed architectural framework and idealized entities usually given in terms of cones or planes for rafters or tie beams. The connected structural elements like struts have to be adopted as well in line with the assumption of initial stress less and therefore not deformed structural elements.

Another way might allow starting with the deformed structure, if the displacements o not have impact on the global structural behaviour, as it is the case for issues like stability. After calculation of the field of displacements, this field will be subtracted from the observed geometry, if it is affine to the observed on with respect to quality and quantity. Anyway, the strategy of best fitting to global geometrical entities like planes or cones is not appropriate for the reconstruction of the initial geometrical stage of the construction. The mechanical characterisation of the members could also be affected by local irregularities like cracks, fissures or degradation of the material possibly due to too long impact of moisture and fungal decay. Additional documentation by photos could help to identify those irregularities, which also could lead to increased global system displacements.

The next decisive step of structural modelling is the adequate setting of connections in between the structural elements and to the ground respective adjacent supporting elements likes walls, columns or abutments.in opposition to modern connection systems, traditional carpentry connection systems exhibit explicit nonlinear structural behaviour. This procedure can either be manually implemented or supported by libraries in structural engineering software for software supported generation of substructures.

Once, the structure is working with self-weight, it is time for the application of external loading like wind, snow or live load. Such loads usually are not applied to the directly loaded elements like battens on roofs or wooden boards on top of flooring systems, but concentrated on the underlying structural elements like rafters or tie beams.

The final verification against structural (= buckling) and failure of materials respective connections is organized within load combinations, which should be representative for realistic loading scenarios. The calculation software should also be capable to catch intermediate changes of the structural system caused by local failure of substructures or connections.

MATERIALS AND METHODS

Methods for collection and interpretation of geometrical input data

The proposed method for geometric modelling of the timber structures is based on a dense point cloud recorded by a 3D laser scanner. On the surface of wooden elements, the point density should be 1-2 points per cm² to represent all details like cracks and other damages on the wood as well.

The workflow for geometric modelling – developed in Pöchtrager et al. [2018] – uses a point cloud segmentation based on the normal vectors of the points. Extracted planar segments of the point cloud are used to identify the side faces of the wooden beams. Matching adjacent side faces are brought together to form the geometric entity of a beam. Many of the used wooden beams have rectangular cross sections, which mean the modelling methodology needs to look for adjacent side faces that are orthogonal to each other and share a common longitudinal axis. Additional rules for the beam modelling are needed for non-rectangular cross sections. Purlins with arbitrary shaped polygonal cross sections – possibly with more than four side faces – are typically used in trusses like *Liegender Stuhl*. (see Fig. 2).

If all side faces of a beam are captured by the laser scanner and extracted in the segmentation step, an accurate parametric modelling is achieved by minimizing the squared distances of the side faces to the measured points on the beam. The least squares fitting of the model is robust against small damages and cracks on the beam, but it might be affected by large (systematic) deviations of the beam from the expected geometry. A further challenge in the modelling is the determination of the correct dimension of the wooden beams for which not all side faces were recorded by the laser scanner (e.g. only two or three sides). In this respect, assumptions about the beam cross section need to be made. The dimensions of side faces can also be computed from the edge points along the beams in the laser scan. For beams with arbitrary cross section and more than four side faces, the local coordinate system should be linked to one of the dominating side faces respective edges. The shape of the cross section should then be specified by a closed polygon, which can correctly be interpreted by the engineering software Dlubal DICKQ [Dlubal 2007].

Curved beams can be handled either by connecting short linear beam sections with rigid joints along the curved axis, or by direct modelling of the curved beam axis based on the curved side faces. Depending on the degree of curvature a differentiation between initially curved beams (e.g. de l’Orme) and those deformed over time is possible.

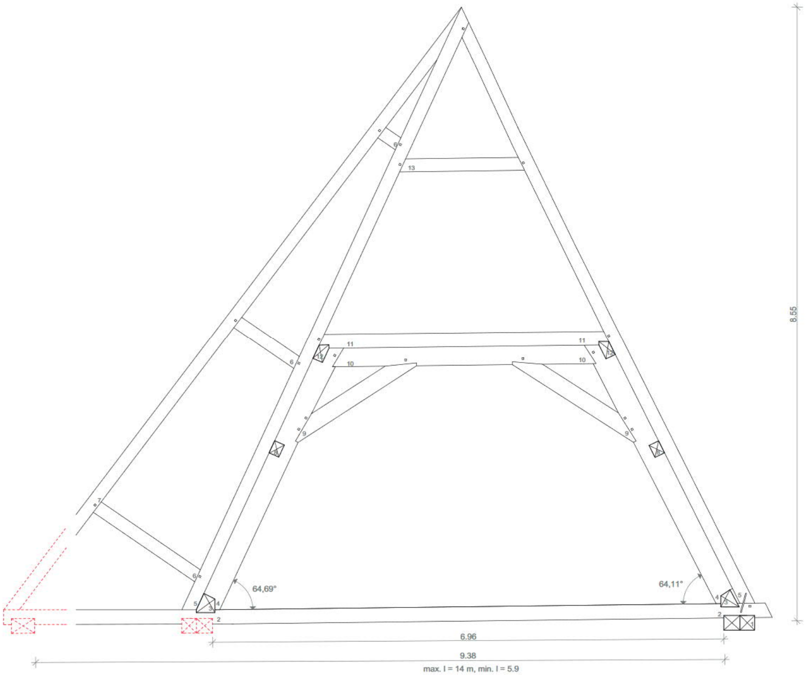

Fig. 2. Cross section of rafters in the Amalienburg
(© A. Domej, N. Hamader, and B. Kapsammer, all TU Wien, 2015)

Advanced methods for post-processing of geometrical data

After the geometric modelling of the wooden beam elements is finished, a further processing and analysis is needed on the functionality of the beams and their woodworking joints.

Detection and classification of woodworking joints:

The general goal is an automated detection and modelling of joint elements (= rigid beam-like coupling elements) based on the geometry of neighbouring beam elements. The joint is simply modelled as shortest connecting line between two beam axes. One solution for an automated joint modelling would be to find all connecting vectors between beams with a specified maximum length (e.g. 0.2 m).

In a later step, based on a joint classification characteristics can be assigned to the individual joints. For a reliable determination of joint characteristics, a manual documentation of representative joints in the timber structure is required. Subsequent to the manual documentation the joint characteristics can be automatically assigned to all similar joints based on a regular occurrence, with respect to the structural performance (= setting of hinge definitions and slip curves), following the rules of traditional carpenter design procedures. Additionally, typical geometrical pattern near expected joints, on the surface of beam elements, indicate the characteristics of a joint and can be used for validation.

Handling missing beams:

In some areas of the geometric model, beams are still (partially) disconnected from the structural system. This can either be because of deficiencies in the data acquisition with the 3D laser scanner, or in the segmentation and modelling process. The problems that come with the quality of the scan data are mostly in scan shadow areas and related to the inhomogeneity of the point density. Besides that, the generalization in the parametric modelling of the beams also leads to missing connections. This might occur for highly deformed beams. Especially in historical timber structures, however, parts may already be missing or connections may have been loosened over the time.

In general, it is better to be more generous in the automated detection of woodworking joints, as they can be easily removed or deactivated later in the structural assessment.

Fitting of deformed geometry to the original shape

The original shape is the starting point for the structural assessment. The differences between deformed and original shape are represented in the field of displacements, calculated by the structural engineering software.

Assessment of the original shape of e.g. a roofing structure should not be accomplished by best fitting planes, but has to be connected to basic architectural geometrical entities like planes, arches, domes…, which themselves must be attached to points of the original construction without stress or constraints, as it was prefabricated on the ground. At this stage, architects could also contribute with their expertise in conceptional geometrical design of building structures at that time and possibly even today without software support by CAD systems. Addition with the negative sign of the field of displacements, even calculated with the already deformed and documented system as quasi-initial geometry, could provide indications on the global original shape of the structure.

At this stage, architects could also contribute with their expertise in conceptional geometrical design of building structures at that time and possibly even today without software support by CAD systems.

Data exchange

A proper data format is required to provide simple and error-free data exchange between consecutive work steps in different software packages. Especially the step from geometric modelling to structural analysis requires attention, also because this is the interface between the disciplines of geometry and engineering. The “Industry foundation classes” (IFC) define a standard file format for data exchange in the building industries and are therefore a major component in the collaborative working in the “building information modelling” (BIM) context. To cover a large variety of scenarios for data exchange, the current schema versions in widespread use – IFC 2x3 and IFC 4 – provide the following subsets (buildingSMART 2019):

- IFC2x3 Coordination view – for architecture and technical building services
- IFC2x3 Structural analysis view – for structural design
- IFC2x3 FM handover view – for facility management

To differentiate between two main use cases the IFC2x3 Coordinate view has been divided into:

- IFC4 Reference view – for reference models that are not edited by the user
- IFC4 Design transfer view – for modifying the element geometry after import

The IFC standard can be represented in various file formats, like the ASCII STEP file, the XML file, ifcXML, and the zip-compressed ifcZIP. Within the developed workflow STEP (Standard for the Exchange of Product Model Data, [ISO 10303-21 2016]) files are used to exchange model information (e.g. geometric and structural information) between the processing tools. The STEP files transfer physical properties of the components in the timber structure and their functional interaction. For beam-like structures, the beam axis with its specification about the path between the two end points, the dimensions and in certain cases the varying orientation of the cross section must be modelled. Besides the geometry of the beam the used material needs to be stored, as well as and the geometries and characteristics of the joints.

It is not only important to uniquely define a data structure for exchange of data, also the quality of the data should, eventually, be propagated to allow estimating, how this is affecting the output of the structural analysis. This topic is treated in the USIBD specifications on accuracy and difference between acquired and represented data [USIBD 2019a; USIBD 2019b].

Model enhancement for structural analysis

The 3D model has to be further processed, before start of the iterative calculation due to nonlinearities on the level of structural behaviour or connections, issues not supported by 3D-laser scanning have to be handled. Support devices with kinematic constraints have to be supplemented and external loading from standards in addition to the self-weight of the members have to be applied and compiled to realistic load combinations for the final approval. Even the solver of the structural engineering software needs support by special settings in order to guarantee correct results.

Due to numerous nonlinearities, the numerical model needs validation by observable geometrical items like deformations, relative displacements respective rotations of neighbouring cross sections) on site. It would be helpful, if these features would already be part of the preliminary survey on site if still possible.

RESULTS AND DISCUSSIONS

In order to test the capabilities for a complete analysis and to identify the gaps in the processing, several tests were carried out, which are discussed in the following.

Stages of software development for the geometrical procedures

In the first step, a small section of the point cloud of the Amalienburg roof was cut out and the modelling of the beams with a rectangular cross-section was performed with the following settings:

Table 1. Parameters for geometric modelling

Parameter	Value
Minimum width of the beam	0.10 m
Maximum width of the beam	0.25 m
Maximum deviation from orthogonal side faces	± 0.1 rad (~ 11.45 °)
Maximum joint length	0.15 m

A typical challenge in tachymetric and laser scanning surveying, both are line-of-sight methods, are areas not visible from the chosen stand points. Increasing the number of stand points solves this problem at the cost of larger on-site time only partly, because inaccessible areas may remain. Such occluded beams or their back-faces need to be completed either based on assumptions (e.g. constant cross section) or by manual measurements and modelling. In the presented modelling results, the beams are extended to their woodworking joints, with user-guidance. The user selects two beams with a common connection point, which are extended if the length of the connecting vector is shorter than the maximum accepted joint length. The extension of the beams to their full length is to some extent additionally validated by points of the point cloud. Fig. 3 shows the transformation from the point cloud to the geometric modelled beams. The dimension of the beams and the geometry of the joint vector form the basis for the structural analysis.

The quality and weakness of the modelling can be analysed in Fig 4. The cloud-to-mesh distance shows that the beams are modelled very well and objects that are not of interest – like the roof tiling or electrical installations – are not considered. Those elements are shown in red colour, as their distance to the modelled beams is larger than 0.03 m. Yet, a major weak point is the modelling of strongly deformed beams and beams that do not have a rectangular cross-section. Fig. 4 shows that some beams have not been modelled well on the edges and that the lower purlin, which has five non-orthogonal side faces, has not been modelled at all. The next development steps in geometric modelling would therefore be the integration of non-planar side surfaces (e.g. with polygonal axis) as well as the modelling of beams with arbitrary polygons as cross sections. Additional detection and modelling of large cracks caused by shrinkage or overstressing and other damages on the wood is necessary for an accurate structural analysis.

Another field of application besides modelling timber structures could be the geometric reconstruction of thin walled cross sections in metal frame constructions. In comparison to the wooden beams, which are filtered within the point cloud based on a minimum and maximum width, the detection and filtering of metal frame components might need to integrate the following aspects in the modelling process:

- Clearly different reflectance properties of the surface than for wood.
- Metal sheets are usually too thin for accurate estimation of the thickness from 3D laser scanning
- Additional shadowing scenarios due to chords or flanges of the metal frame components

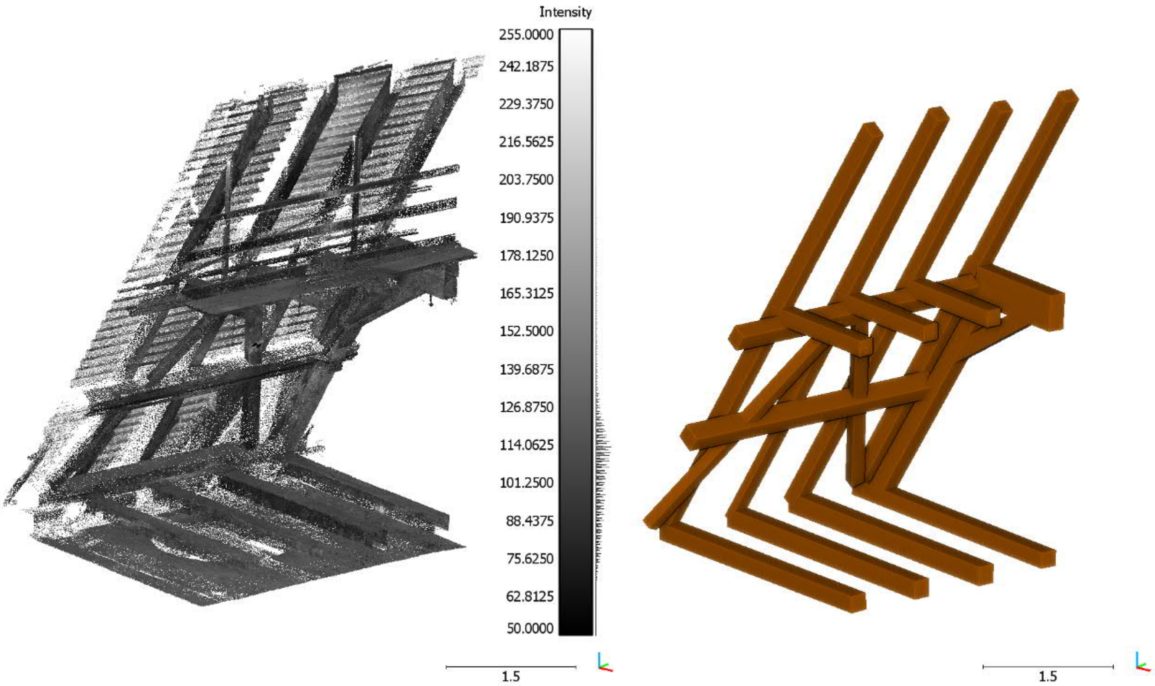

Fig. 3. Point cloud of a section of a roof structure (l) and the modelled beams with rectangular cross section (r)

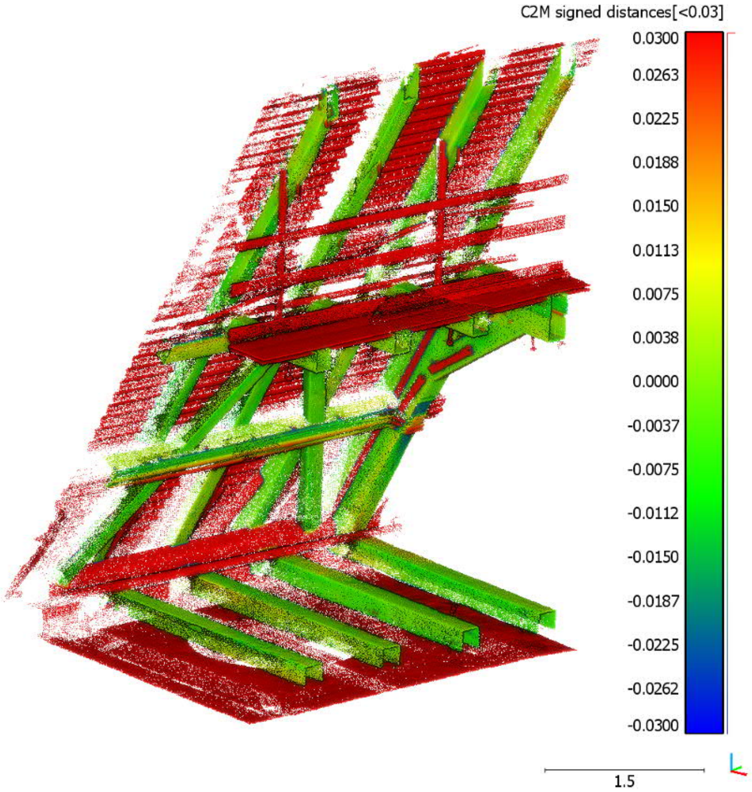

Fig. 4. Cloud-to-mesh distance showing the quality of modelled components as well as unmodelled areas

Stages of development within structural engineering software

To proceed with the structural modelling, the geometrical entities like coordinates of the nodes at the beam-ends, the spatial orientation of the cross section e.g. in terms of rotation angles and the width respective height have to be unpacked from the STEP file and enriched. Material specific parameters can already be taken from libraries containing strength and stiffness values according to harmonized European product standard EN 338 [Austrian Standards 2016, ÖNORM EN 338:2016 06 01] for solid wood, which only have to be assigned to the beam elements. Without any detailed investigations, the strength class C24, representative for medium range quality of solid timber e.g. from spruce, could be assigned as very first and uncomplicated approach [Steiger and Arnold 2009]. Sometimes it is convenient, to establish several material profiles for sake of better possibility of filtering complex structures.

At this stage, the beam elements are still rigidly connected without any settings for realistic mechanical behaviour e.g. as step joint. Today, the definition of adequate setting of nonlinear diagrams for each component of the internal forces or moments still has to be performed manually. Only by selection of some short rigid connection elements or ends of beams, this complex setting could also be software supported by predefined settings for typical connections from libraries. However, the knowledge about correct structural modelling of these special types of hinges, either on the level of beam theory or more advanced sub-modelling by local integration of 2D or 3D formulation, is still work in progress and a challenging issue of timber research.

For sake of final reporting, the documentation of consistent chains of approvals against failure could again be software supported, as it is already realized for similar issues of modern timber design. Updates of such generated reports could be automated with progressive refinement of the structural model.

Experience with structural modelling of even big and complex real structures

Before the background of very fast scanning devices and collecting big geometrical data from complex timber structures, the chance of adequate structural modelling and realisation of reliable results has to be discussed as well. At that time, such buildings usually have been designed from experience without support of structural software. Due to the sensitivity of the global structural behaviour to the stiffness characteristic of the joints, assessment of the load carrying behaviour is impossible without structural modelling. Nevertheless, the use of engineering software enables both a quick check of the system and profound parameter studies for an estimation of the most realistic structural behaviour. The investigations about the impressive timber roof structure of the “Spanish Winter Riding School” (SRS Vienna) as part of the Imperial Palace in Vienna (= Hofburg), has demonstrated (Fig. 5), that even big structures with a characteristic of 23.600 beam elements, about 13.650 knots, therefore about 82.000 equations could satisfactorily be handled with good results by a laptop with quad core and the only need of 5 GB memory despite of numerous iterations because of the nonlinear structural behaviour of the carpenter connections. Following, the bottleneck for an accurate assessment is not 3D scanning of lack of adequate tools for structural assessment, but the time lack due to manual translation of points into abstract beam axis and cross sections.

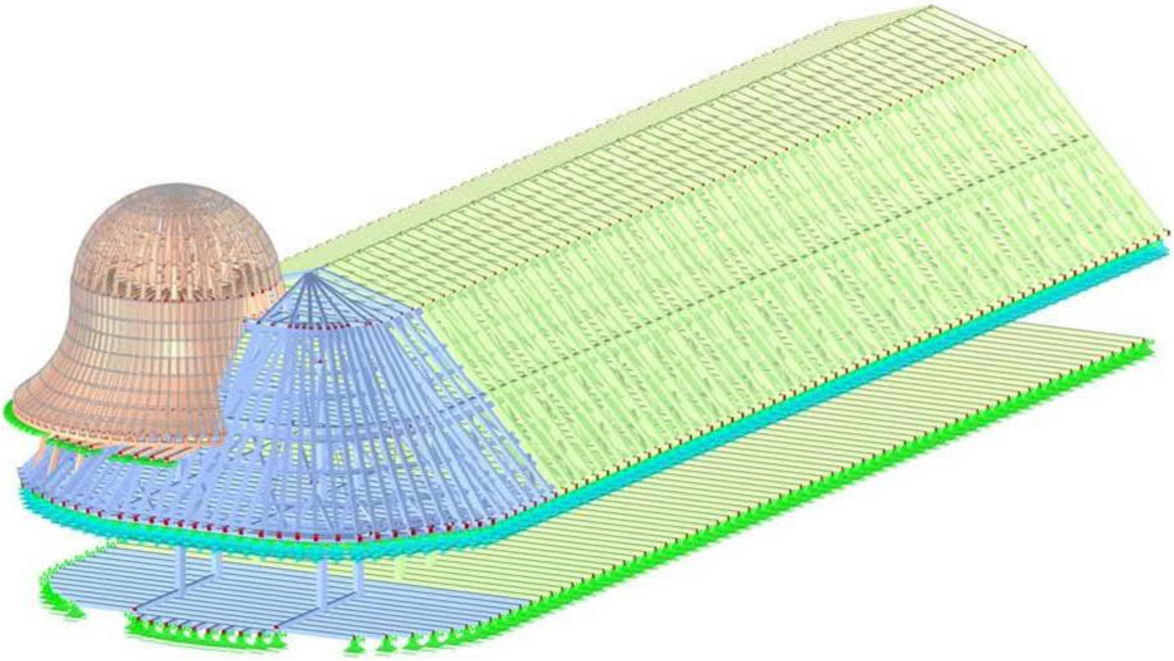

Fig. 5a. Structural model (SRS Vienna)

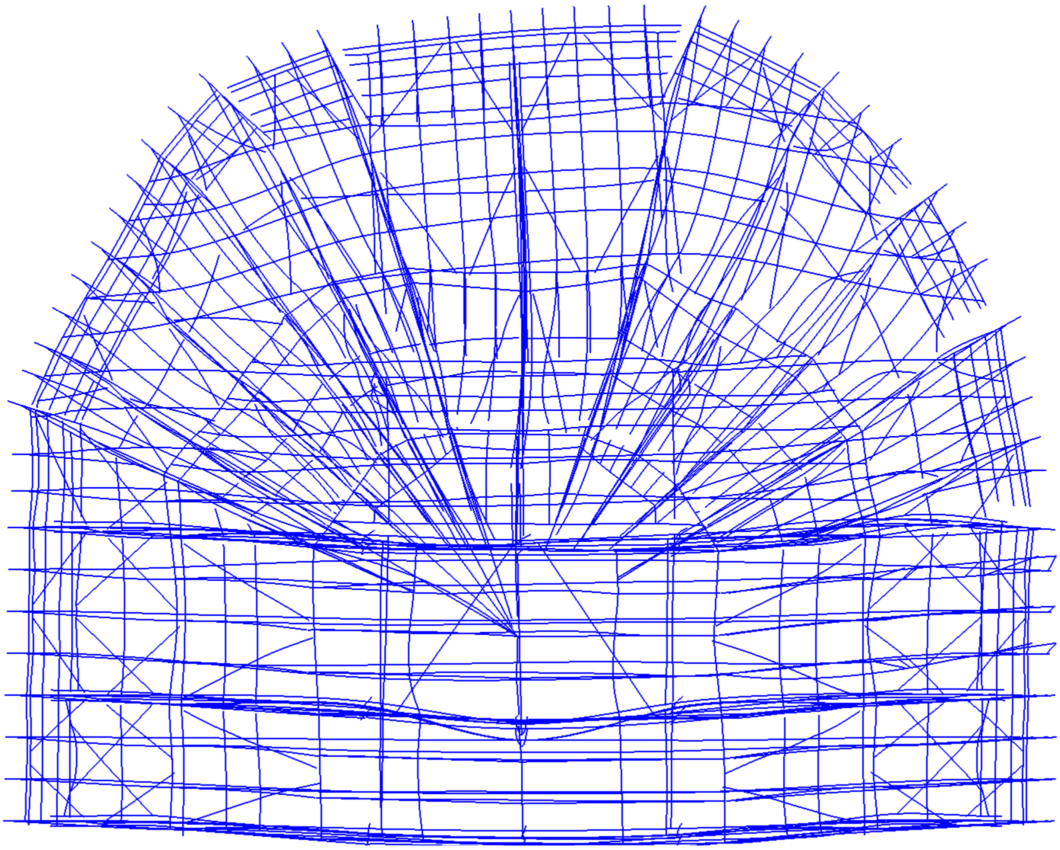

Fig. 5b. Field of displacements with gapping due to realistic realisation of the construction (SRS Vienna)

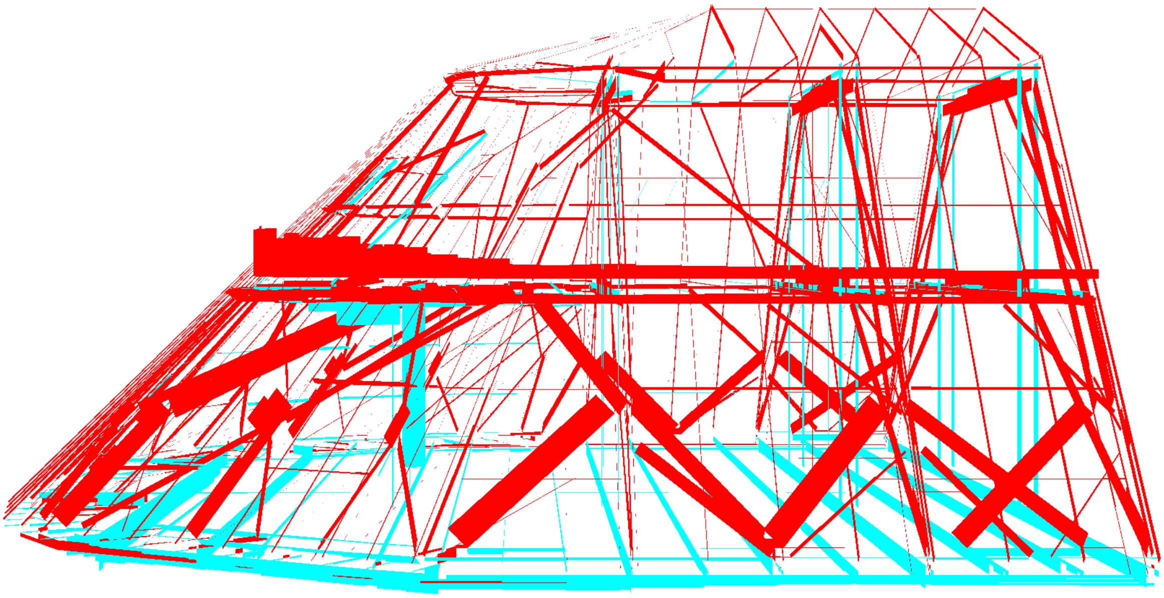

Fig. 5c. Complex distribution of normal forces in the apsis with blue=tensile and red=compression (SRS Vienna).

CONCLUSIONS

The recent developments in automated point cloud processing and the modelling of geometrical building components are important to speed up the process of preparatory geometric fact finding for adequate structural elements. Due to the high degree of automation and a clearly defined workflow starting from the raw point cloud, the process of the geometric modelling is transparent and reproducible and human error can be significantly reduced. The proposed workflow can be the basis for a fast and reliable structural assessment of huge and complex historical timber constructions, with some manual steps and issues still to be resolved.

While in the presented results only beams with straight axes and rectangular cross-section were modelled, an extension of the existing method for the representation of curved beam axes is crucial. Curvature of beams appears either due to deformation from external loading or from the original design as curved wooden beam. The second major extension refers to the modelling of beams with arbitrary polygons in the cross-section. For this purpose, the set of rules for the modelling of beams from the side faces must be adapted and extended.

Future perspectives of this work are the integration into BIM applications including the assignment of IDs to each member (beams and joints) for later identification or generation of the corresponding analytical models.

The combination of fast scanning devices with fast translation into a structural system could also be implemented for monitoring of existing structures with respect to potential progressive structural failure. The focus for decision-making could be based either on identification of excessive local relative displacements or also with respect to the structural behaviour of key members.

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