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Case study for the integration of geometrical analyses for structural condition assessment in building information models

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Abstract. During its life cycle a building structure is exposed to many various external influences which could lead to changes, damages in different dimensions or signs of wear related to a decrease of functionality. Continuous monitoring and survey of the structure using conventional inspections by special trained engineers are supported by modern technology as sensor networks or laser scanning keep the costs for reconstructions as small as possible. The collected data and the applied analysis methods are able to allow a precise assessment of buildings. The integration of standard analysis processes could accelerate the evaluation process additionally. Combining the building model and the related or integrated survey data a complete basis for inspection documentation would be provided. In this article, a workflow for the modeling of data analyses, management and automated evaluation for building condition assessment linked to building information models is proposed. In a practical case study, the workflow is applied in order to obtain structural evaluations based on the processing of survey raw data. As test case an implementation shows the application of the developed concepts for a concrete beam during a three-point bending test.

1. Introduction

Building survey and monitoring is an important part of maintenance and evaluation of structures providing essential information about the structural health of buildings. In further processing and analysis steps these data enables estimations of the building condition or behaviour. This requires an extensive documentation of the survey and its related data. In the last decades the applied technologies for monitoring issues changed from manually and analogously recorded to mainly automatically managed and digital stored and linked documentations. Modern developments as sensor networks [1] unmanned aircraft systems (UAS) equipped with high resolution cameras [2] or laser scanning used for structural monitoring [3] create digital data that can be processed, analysed and evaluated. These technologies enable an efficient survey process for buildings and infrastructures that require frequent inspections. Examples are high resolution images of bridges recorded by UAS for the investigation of cracks or other visual identifiable damages [4]. Computer vision algorithms can be applied to extract 3-dimensional (3D) and georeferenced point clouds from the recorded images to represent the structure geometry in a detailed model. Placements, dimensions and shapes of deformations and damages can be detected and quantified in building related condition evaluation utilizing methods for analyzing and comparing 3D models, for example point clouds or mesh-based surfaces.

One of the increasingly discussed topics in the field of computer science in building constructions is the development of building information modeling (BIM). Next to the planning and management of buildings during their life cycle the exchange and interoperability between different disciplines is a main aspect of this topic [5]. Therefore, building specific elements are related and linked to additional data and processes. Interfaces realise a consistent data transfer between different modeling and simulation applications using the relations of building models and their metadata. This avoids a loss of information during the interaction of applications for planning or maintenance [6]. During the period of maintenance a building information model is able to be used for management, documentation and linking of monitored data derived from the processes explained previously to the related model object of the building element [7]. In [8] it is shown how external calculations or simulations based on the recorded data are additionally related. For as-built situations the model has to be created from existing plans, images or site measurements to obtain the digital representation. In current researches 3D point clouds from laser scanning or image based reconstruction for these purposes are used. The stages from laser scanning to data processing, typology identification and finally geometric and information modeling are explained in [9]. Several case studies [10] showed that the method can reach a high level of detail and demonstrated the process of model extraction from 3D point clouds.

This work deals with the building related modelling of monitoring data for structural analysis. Furthermore, a case study for the direct extraction and comparison of relevant geometries from 3D point clouds of simple building elements related to building information models is presented. A structure-from-motion method [11] is used for the reconstruction of 3D point clouds from high resolution images. The images were recorded during a three point flexural test on a reinforced concrete beam with high resolution cameras. Using the resulting 3D point clouds an algorithm for edge detection extracted the deflected beam edge for comparison with the previous state to simulate different building conditions during usage. A method for the integration and linking of the data to a building information model based on Industry Foundation Classes (IFC) was developed. Furthermore, processes for the evaluation of data are modelled and integrated. All developed applications are described and translated into general workflows.

2. Data and process modelling

The design of the model for monitoring data contains the data itself represented in a defined hierarchy, analysis operations and processes as well as the linkage to a building model and its components. In this case data means any recorded or processed values, its unit and assignment, e.g. acceleration, temperature, deformation, etc. Processes describe the transformation of data into meaningful parameters for the structural evaluation.

2.1. Data hierarchy and relations

Modelling the data structure for processing and analysis applications should represent the different levels of processed data, their relations among each other and the classification to the engineering specific context. In this case the base level is represented by raw data, which means the unprocessed values directly from a measurement or recording. Considering that even a direct output of a monitoring system could be already processed, a related model representing the system itself is necessary for an appropriate interpretation. Following the sequence of operations and processes from the raw data to an evaluation of specific parameters, each step has to keep the references to the primary data level. Thus a logic relation from the final evaluation to the underlying raw data realises a reproducibility of each intermediate level. [9] describes a similar approach for different data stages basing on each other in which the focus is set on the progress from raw data to geometrical modelling including metadata information. That can serve as a practical example for the abstract scheme.

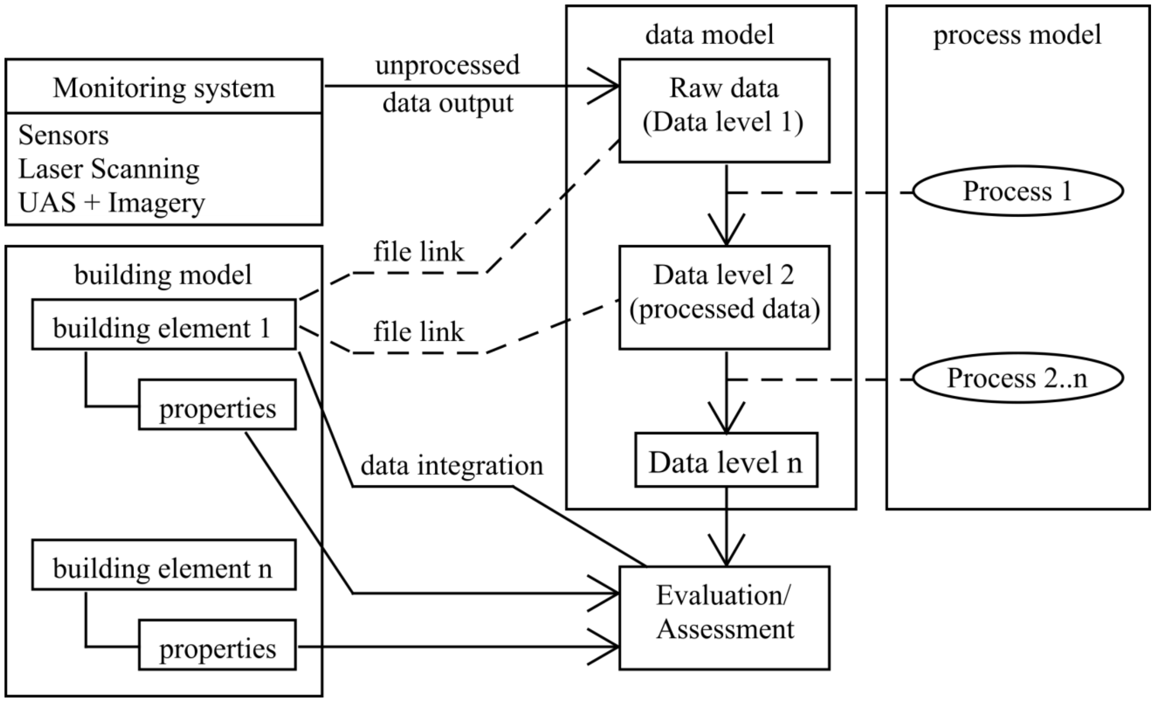

Figure 1. Relation between monitoring system producing raw data, the model for a data hierarchy related to processes in between, the linkage to a building model containing information about building element related properties and a final evaluation combining the information

Figure 1 shows the relations between data, processes and the building model. A Monitoring system giving an unprocessed output serves as source for the data model composed by a level hierarchy. The data levels are created through processes which are describing the analysis algorithms. In addition, a data level is able to be linked to or integrated in a building model and its components. For a final evaluation of the processed data also properties of these related building components could be used. Linking this topic to the fact of continuous repeated structural inspections aiming the same kind of analyses, the data model has two additional tasks. One is to control data processing in this way that the evaluations are comparable in terms of characteristics. The other one is to provide a model of the consecutive processes that can be accessed with raw data.

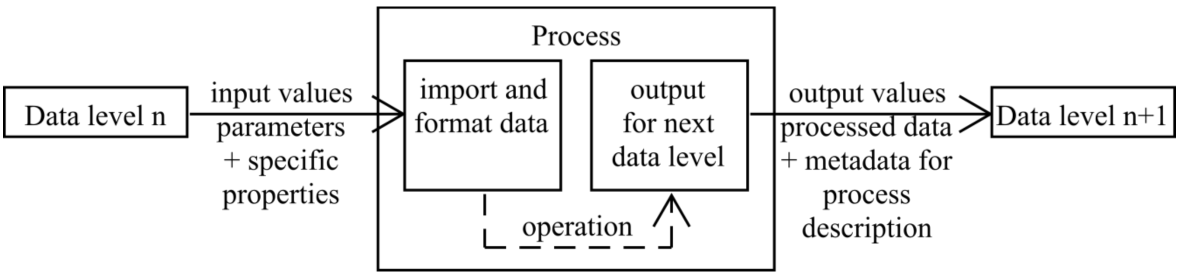

Figure 2. Detailed view on a process connecting two consecutive data levels. The data of level n is used as input for an operation that results in level n+1 adding metadata for the process description

Relations between two data levels are represented through a defined process workflow. These workflows are divided in the input data, the process itself and the output data that forms the next data level (see figure 2). The process contains either an internal model, e.g. simple processes that do not require special software, or an external model that usually is realised by an interface to additional

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software running complex operations. In this case simple processes are basic mathematical operations including vector operations as well as filtering algorithms or threshold checks.

The combination of several processes leading from one data level to the next and finally to the intended evaluation are forming an analysis workflow that can be reused with different raw data of the same characteristics. The resulting outputs are expanded with additional metadata describing the process and its parameters for the representation in the data model or the related building information model.

2.2. Representation in building information models

The building information model containing the related building elements for the recorded data has to be linked. IFC models use a global unique identifier (GUID) for the identification of building elements in relations. These identifiers constantly exist during the life time of a building element in the model. Figure 3 shows three different variants of linking additional data to a building model using the GUID as reference.

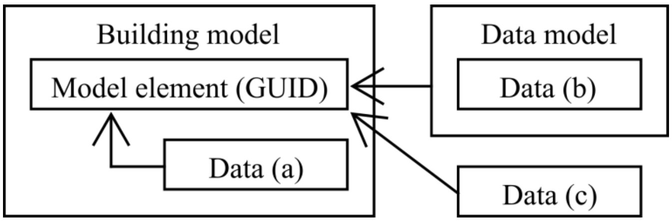

Figure 3. Variants of data linking: (a) Data is included in the model format and internally related, (b) an external data model or database is managing the data related in the building model, (c) the raw files are referenced without any container in the building model through links

On the one hand the modelled elements serve as possible input parameters, e.g. giving information about material or geometry. This requires a linking between model and data beginning from the level of raw data to ensure permanent access to the needed information. On the other hand the analysis results could link to the building model and its elements. For analysis workflows producing a big amount of data the links to the model can also be selective to avoid fast growing models which are hard to handle.

3. Implementation

For the implementation of the case study the authors created an exemplary workflow for the extraction and evaluation of deformations of a beam. During a three point flexural experiment, high resolution images covering the beam surface were acquired in each stage. Agisoft Photoscan [12] was used for the computation of precise and dense 3D point clouds from each image set.

The resulting point clouds were analysed using a MATLAB script developed by the authors identifying the beam edges for comparison. Finally an own developed JAVA application was used for the modelling of the simple operations to evaluate the deformations and to link the information to a building information model.

3.1. General concept

As the previously described applications are mostly representing external processes, the developed JAVA application is handling data and processes internally and furthermore establishes links to the building information model. Therefore, the GUID of building elements in an IFC model is used. Data can be imported from simply formatted text files and integrated in the internal semantic for measured values, e.g. acceleration data, temperature series or polygons representing building geometries. Process sequences are managed for the data evaluation in flexible objects that automatically adopt any raw data if related. A graphical view visualises the content in appropriate plots for the user. A detailed workflow scheme adapting the following case study is shown in figure 4.

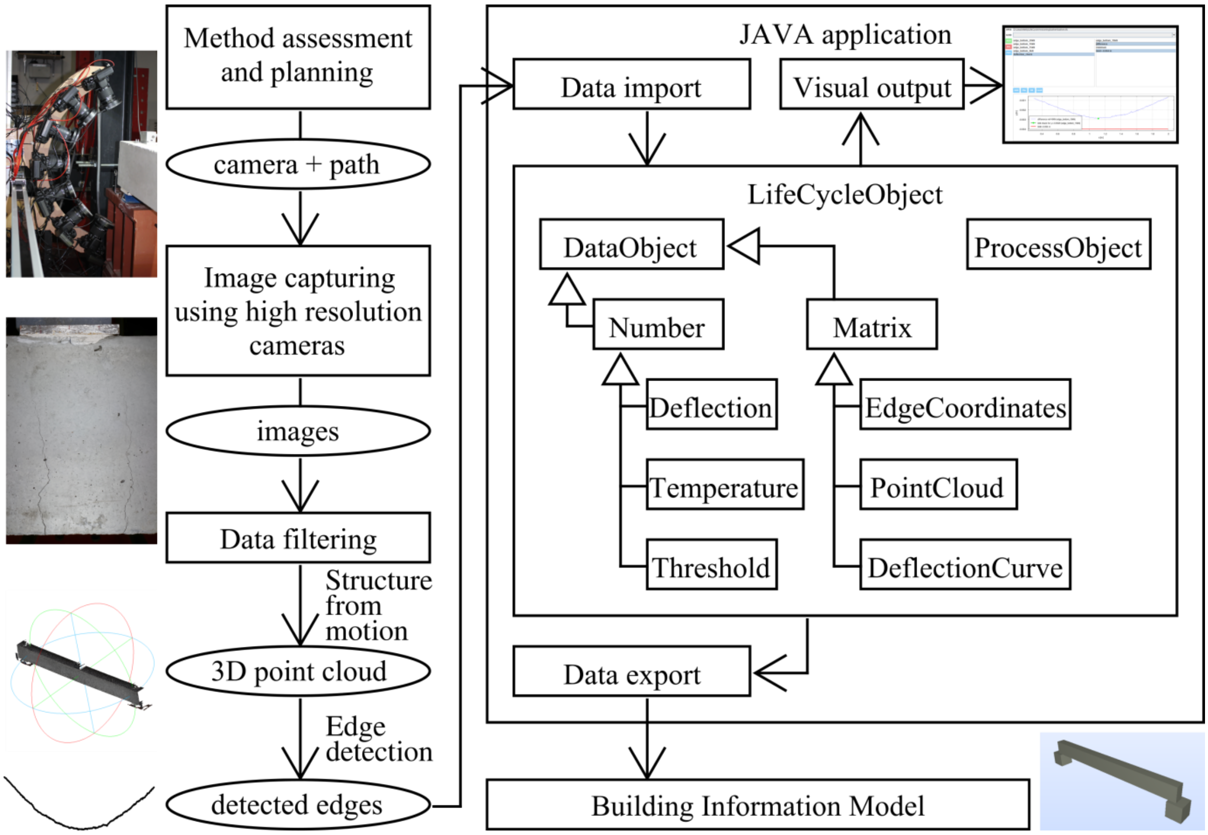

Figure 4. Workflow of the data processing from the planning of the monitoring recording to the evaluation of the deformation showing as well the general schematic as the application in the case study. An exemplary selection of subclasses of *DataObject* shows the inheritance structure in Unified Modeling Language

3.2. Data model
The data model of the JAVA classes is composed by a superior *LifeCycleObject* containing the collections of *DataObject* and *ProcessObject*. *DataObject* operates as the superclass for all data oriented classes inheriting the attributes and methods for the data itself (see figure 4), representation in other formats, derivation and possibly the implementation of a process. Implemented processes contain the descriptive algorithm for an operation, e.g. difference of two vectors, which is executed with the appropriate input. In the first sublayer the subclasses inherited from *DataObject* define the data characteristic; in the second sublayer the subclasses give the semantic assignment according to the data.

The *ProcessObject* keeps the relations between the basic raw data and the process sequence results. One time defined a workflow is able to be reused for any further analysis with the same procedure and parameters keeping the process parents exchangeable.

3.3. Linking to the building model
In the actual implementation the linkage between data model and building information model is realised by the simple GUID reference of the IFC building elements. The data model exists in a separate file next to the IFC file storing all reference information. In further developments a stronger coupling with the building model could be realised to include the extraction of metadata as additional information, e.g. geometries or material properties. As well as the complete integration of selected data into the building model. This kind of coupling is highly dependent to the format used for the

building model. In the case of IFC the format is free and standardised, other proprietary formats are not well to embed and therefore to use only with restrictions.

4. Case study: three point flexural test

For an exemplary implementation and practical use of the previously described strategy, a three point flexural test was executed at the Bauhaus-Universität Weimar. As shown in figure 5 the setting was a two point supported reinforced concrete beam with a span width of 2.0 m, a total length of 2.2 m and cross section height of 20 cm and width of 12 cm. The load application was placed at the centre of the beam and raised in steps of 2.5 kN from 0 kN to 25 kN. For each load step, images covering the beam were acquired with seven synchronized Canon EOS 100D cameras arranged in a half-circle mounted on a linear transfer track (see figure 5). 3D point clouds were reconstructed from the image sets. The 3D point clouds were then analysed in order to extract the edge geometry, which then was used as input for the deflection calculation between different loads.

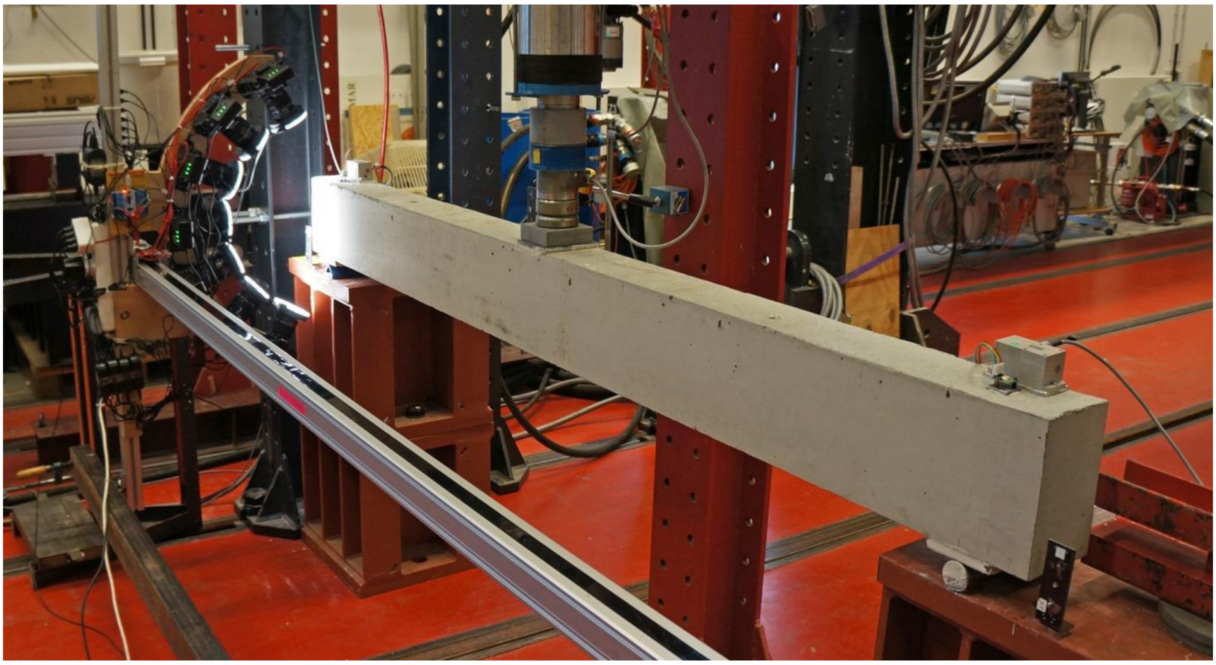

Figure 5. Experiment setting for the recording of high resolution images using cameras mounted on a movable frame during the three point flexural test

The experiment was chosen to simulate obvious deformation of structures for a clear exemplary comparison and evaluation. The test case can be adapted to similar image based inspection aims, e.g. deformation of bridge elements as large and slender piers. Especially, modern semi-integral bridges could get large temperature based deformations due to the special kind of construction. Each inspection data and analysis could be stored and managed as well as linked to a building information model with the software solutions in this study.

4.1. 3D point cloud reconstruction

In each stage of the experiment, 329 images covering three long sides of the beam were acquired automatically. Hence, in a 4.7 cm horizontal interval seven vertically aligned images covering three beam sides were acquired, ensuring a mean effective image overlap of 3.5. This means that each object point is visible in 3.5 images in average. Due to a mean camera-to-beam distance of approximately 27 cm, the reached object resolution is 0.04 mm per pixel. In order to reduce image noise as well as to obtain a large depth of field, LED-based ring flashs around the camera lenses were used. This enables the usage of low light sensitivities (e.g. ISO 100) and an aperture of f/20. Furthermore, the 42 bit raw images were enhanced and converted to 24 bit jpeg images using DXO Optics Pro [13].

For each load stage, a dense point cloud representing the beam is estimated from the corresponding set of images using Agisoft Photoscan. Three control points with measured 3D coordinates were used in order to scale the 3D model. Based on automatically detected feature points the relative orientation as well as a sparse point cloud representing the triangulated 3D feature points are estimated. After the relative orientation of the cameras is known, the dense point cloud of the object can be computed by finding correspondences for each pixel in the images. The density of this point cloud is 106 points per mm², with an absolute number of estimated points around 580 million. The estimated camera configuration and the dense point cloud are shown in figure 6. The metric dense point clouds can be exported to various established file formats, e.g. Stanford-PLY, Wavefront-OBJ or ASCII-XYZ.

(a) (b)

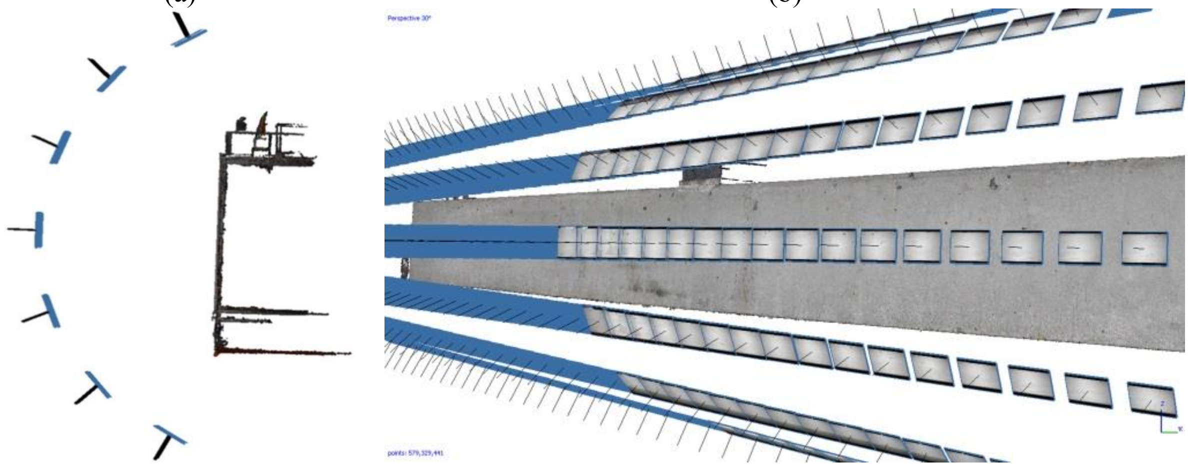

Figure 6. Reconstructed 3D point cloud showing the beam with camera positions (panels) for a single recording sequence in profile view (a) and perspective view of the front (b)

4.2. Edge detection

Based on the reconstructed 3D point cloud of a certain stage it is possible to extract the beam edges for further comparison. The authors developed a section based edge detection method from point clouds implemented in MATLAB. The script reads the point cloud file and identifies the edges of the approximately cuboid geometry by assembling the corner points of 340 equidistant sections along the longitudinal axis of the beam. A CSV file containing the positions of the cross section corners is written at the end of the process. As the cameras were not covering the backside of the beam completely the point density in this area is not high enough for reliable edge detection. A similar problem appears at the positions of the experiment equipment for the supports and the load application where the additional tools disturb the edge detection. For this reasons only the edge at the intersection of front and bottom face at the length between the two supports is considered in further analysis. In figure 7 a view on a section showing the identification of the edge points and the extracted edges for each load case of the case study are shown.

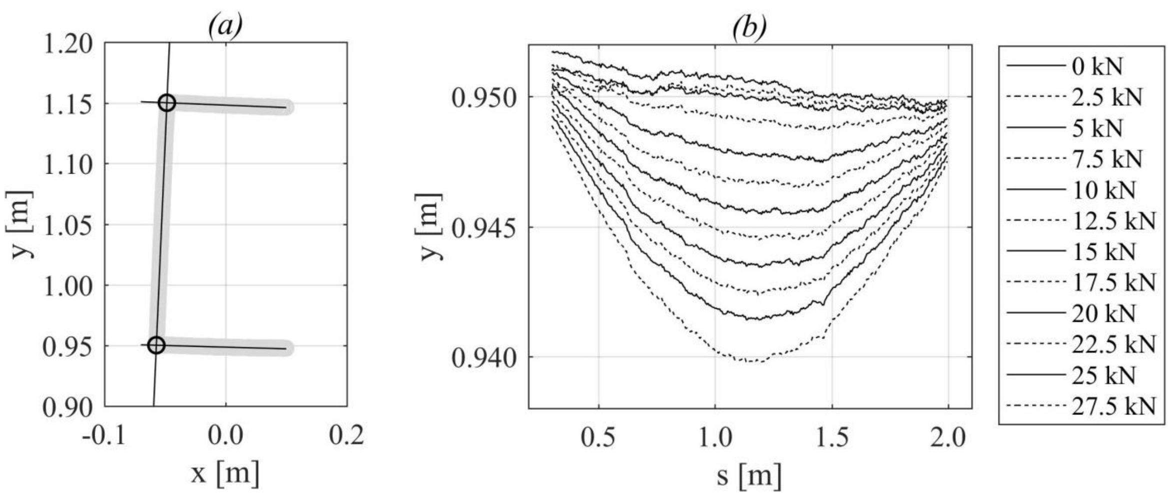

Figure 7. Identified beam edges in a selected cross section of the 3D point cloud (a) and a comparison of the assembled beam edges for each load level (b)

4.3. Data and process definition

With the aim of an automated evaluation of deformation values taking the extracted edge lines as input the authors developed a JAVA application with a graphical user interface. An IFC model of the beam with two supports was related to show the linkage between data and model. Therefore the GUID of the beam in the IFC model was chosen from the interface and set as related building element (see figure 8).

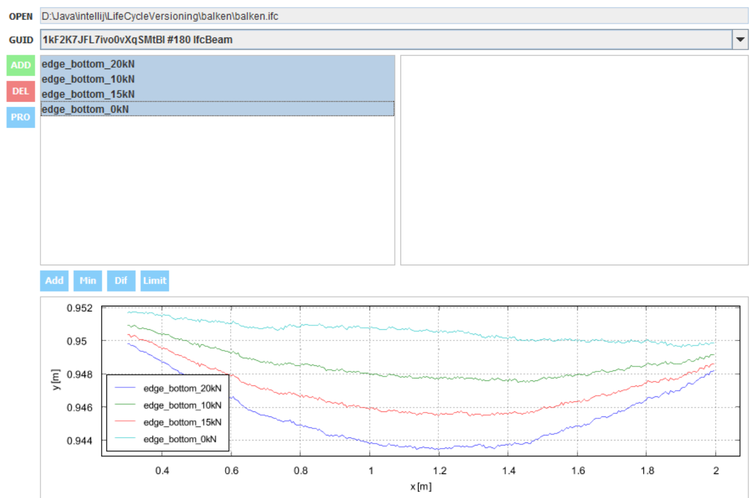

Figure 8. Screenshot from the surface of the JAVA application developed by the authors showing the selection of data assigned to an element of the IFC model (in this case edges to IfcBeam)

The CSV files of the considered beam edge for each load step were imported and automatically linked to the GUID owned by the beam. Each edge line is represented in the data model by its coordinates. By adding a process, a sequence of analysis steps could be defined. In this case the analysis steps for vector difference referring to the coordinates of the edge line from the unloaded state, the selection of the minimum of the resulting deflection curve and checking for a defined threshold of the deflection were added. Each step takes as input argument the resulting output of the previous step except the first one which considers the related edge lines as input. By adding an imported edge line to the modelled process sequence the steps are executed and the results are stored. If the several steps in the list view are selected a fast visual comparison can be done. The user interface for modelling a process and relating it to multiple data entries is shown in figure 9.

(a)

(b)

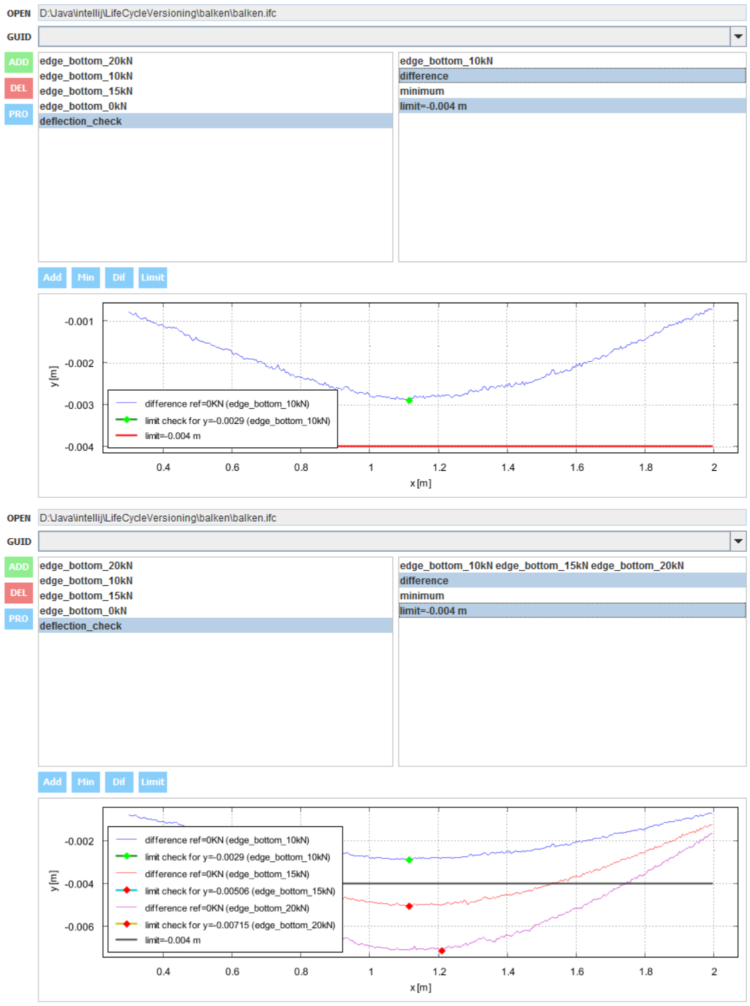

Figure 9. Screenshots from the surface of the JAVA application showing (a) the modelling of an evaluation workflow calculating the deflection curve of the beam and comparing the maximum deflection to a defined threshold value and (b) adding data from higher load steps to the modelled process

5. Conclusion

Continuous building survey for an assessment of structural conditions is necessary for an effective maintenance of critical structures, e.g. bridges. Modern technologies support these inspections and can create a big amount of heterogeneous data that has to be handled and evaluated by analysis methods. With regard to the method of BIM the collected data can be connected to a building model. Therefore a classification for data hierarchy was defined and implemented in a JAVA application developed by the authors. Additionally operations for the analysis steps were modelled. The developed workflow was tested with an exemplary three point flexural test experiment where the steps from high resolution images to point clouds and finally deformation evaluation were shown. An IFC model of the surveyed structure was connected to the data collection to link the data and processes to the appropriate building element.

The developed applications give a conceptual approach for the BIM related management of monitoring data. Prepared flexible process sequences for the automatic replication of analyses give the advantage of fast and effective assessment of the data. Taking additional properties from linked building information models extends the scope of such data evaluations. However, the flexibility of the data structure and consequently the variety of possibly processable data is strictly related to the implemented data model due to the needs of semantic assignments of data objects. Also the linkage to the building model is to improve in terms of multiple relations or a representation of relations also in the IFC file. Future works could improve these drawbacks using open standards also for storing the additional inspection data file.

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