Advances in Structural Monitoring by an Integrated Analysis of Sensor Measurements and 3D Building Model

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Abstract The use of open GIS standards offers a broad variety of potential, particularly in the field of data exchange, data storage, and interoperability. GML and CityGML are excellent examples for the ontological description of real world objects by means of an open standard whereas SensorML serves to describe measurements, sensors and measuring platforms. The use of such standards offers not only the possibility of using a common standardised language, but also the use of open service standards. The combination of spatial data and sensor standards in services and service-oriented architectures goes far beyond previous existing solutions on the market and provides a novel platform for monitoring structures. That in fact is far more than a simple data storage model. The methods and models presented in this contribution allow a direct integration of sensor data and its provision through an open standard language. In this case, all the intermediate steps at any time through an open service interface are addressed and may be made available and provided to different actors and stakeholders participating in a construction scenario. The great potential and the added value of such an information system is the permanent availability of measurement and object data and an associated integrated analysis of sensor data in combination with a finite element model (FEM). The automatic derivation of a finite element model from the 3D structure model, the visualisation of FEM, the provision of raw (measurement) data and sensor information for each time of measurement transform the platform into a

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universal tool in the field of structural monitoring. This contribution introduces the individual components, the standards used and the interaction between the components to an overall system.

Keywords Structural monitoring · SensorML · Finite Element Method · Integrated analysis · City model · Building model

1 Motivation

A main application in the field of geodesy and one of the most important tasks in engineering geodesy is the monitoring of structures. Since at the beginning site visits to pick up the measured data was mandatory. Nowadays open standards, the internet-of-things (IoT) and the OGC Sensor Web Enablement (SWE, Bermudez 2011) allow the development of web based solutions. A permanent monitoring covers the measurement of changes of various parameters such as, deflection, inclination, strain, temperature, humidity etc. The measured parameters are both at points distributed over the entire structure, as well as holistic, considering the complete structure. Especially after or even during extreme events structures can be controlled in real time by using already installed sensor networks (Boller and Staszewski 2004; Botts et al. 2006; Resch 2012; Bröring et al. 2011, 2012).

Material degradation or the change of geometric properties such as boundary conditions and system partial connectivity can largely affect the structural performance and safety. Maintaining service will be impossible without knowing and analysing the potential damage. Today structural condition assessment is the prerequisite for prediction of engineering structures remaining in service (Farrar and Worden 2007; Worden and Barton 2004). The initial step for monitoring is the periodically or permanent observation of the behaviour of a structure under external forces, e.g. wind, earthquakes, traffic etc., by measurements of heterogeneous sensors (Welsch et al. 2000, p. 45). The main important part is to analyse these measurements under consideration of the mechanical model of the structure via least-squares adjustment (Jäger 1988; Neitzel et al. 2014; Lienhart 2007; Teskey 1988). This allows further analysis of structural properties by means of statistical tests and thus a reliable assessment of its condition. The capability of real or near real time sensor data access can largely affect the performance of the information system for structural monitoring. However, the automatic process of the high sample rate sensor data is still an ongoing development for most products on the market.

Permanent monitoring systems vary in size, shape, and sensors substantially but have almost common requirements and features. Open access to the measurements and data management as well as its analysis and interpretation are key issues in a geodetic monitoring.

The use of open standards, particularly in the area of web services facilitates an excellent opportunity to provide all involved parties a uniform, standardised machine-readable format. Using the Sensor Web Enablement (SWE) standards of the Open Geospatial Consortium (OGC), all kinds of sensors, transducers and sensor data repositories can be located, accessed and used via the WWW. The combination of sensor technology, computer technology and network technology, thus offers new solutions in the field of construction site safety, industrial controls, meteorology, geophysical survey, flood monitoring, risk assessment, tracking, environmental monitoring, defence, logistics and many other applications.

A system for structural monitoring must also offer the possibility for a visual interpretation of the measured data as well as the analysis results. Besides a treatment in tables, graphs, or text form is sufficient for the representation of the measured data, the presentation of the analysis results requires the inclusion of the structure itself.

The presented approach will demonstrate how open standards such as CityGML (Gröger et al. 2012) and SensorML have to be combined in order to satisfy asset owner and asset manager needs. The proposed solution covers:

- Near real time measurement and storage of sensor data
- On-the fly analysis of measurement data
- Data exchange with stakeholders in a standardised way
- Conversion of CityGML to FEM and vice versa
- Integrated analysis of sensor data and FEM model based on CityGML standard
- CityGML extension proposal by material and time entities

It will be shown how two different standards can be harmonised and combined to fulfil an ongoing research task in the field of geodesy by applying methods and standards from the field of geoinformation science.

2 Requirements

Construction companies are demanded to guarantee for the operational capability of the structures they built. The use of sensor networks allows to monitor those structures in real-time. Without the use of sensor networks, a continuous monitoring is difficult to carry out and quite time and cost intensive. In addition to planning and performing geodetic measurements, the complete documentation, provision of data, analysis and results, captures a central position in the field of structural health monitoring (Furtner et al. 2013). Often, data have to be converted, reorganised, or specially prepared to meet all the requirements of stakeholders participating in a construction project. Thus, a structural health monitoring system will help asset owners and asset managers to minimise maintenance and observation costs by maximising the assets lifetime. An advanced tool for structural health monitoring based on an integrated analysis has to cover the following requirements:

1. **Data storage**
   The huge amount of measured sensor data has to be structured and stored in a redundant database. Moreover, the database and related interfaces should enable easy access to the stored data via web services, such as OGC's SOS (Bröring et al. 2012).
2. **Data pre-processing and preparation**
   The system should provide an analysis tool in order to detect malfunctions of sensors or to identify gross errors in the data. Furthermore, a detailed time series analysis of the sensor data should be provided, e.g. auto-correlation, cross correlation, detrending, filtering etc.
3. **Data and feature visualisation**
   An advanced system for structural health monitoring should also provide the possibility for a visual interpretation of the measured data and analysis results. Since a treatment in tables, diagrams or text form is sufficient for the representation of the measured data the visual presentation of the analysis results, requires the inclusion of the structure itself.
4. **Data aggregation and reduction**
   Asset owners and managers are mostly not interested in the huge amount of measured data. Thus, valuable filter operations, event detection algorithms, aggregation, and reduction methods are required to limit the transferred data to a feasible minimum.
5. **Integrated analysis**
   The integrated analysis via least-squares adjustment is based on a FE model that allows further analysis of structural properties by means of statistical tests and thus a reliable assessment of the current condition of the structure. The FE model is derived from existing 3D semantic object models, such as CityGML and the conversion from CityGML to FEM and vice versa is a major requirement of such a tool.

3 Integrated Analysis

To model the mechanical behaviour of a structure like a bridge, is in fact a quite challenging task. Besides its geometry many additional properties need to be taken into account, e.g. types of bearings, different materials, internal and external forces, temperature, etc. Therefore, the basic principle of an integrated analysis is demonstrated on a statically bended beam, as a simplification of the deformable deck of a bridge.

3.1 Mechanical Modelling

The deformational behaviour of statically bended beam under external forces can be described by the specialised mechanical model of the Euler-Bernoulli beam theory. This theory yields a governing equation that connects all related and influential quantities together. The governing equation is mathematically expressed as an ordinary differential equation. In order to use the specialised mechanical model, we have to ensure that the tested beam specimen fulfils the following requirements: (a) In the bent configuration, the cross sections of the beam remain plane and perpendicular to the neutral axis—the set of lines that don't extend or contract. (b) The beam is only subjected to an external pure bending moment—shear forces, axial normal forces or torques are excluded. (c) The beam consists of isotropic material which obeys Hooke's law. (d) The total length of the beam is much greater than the deflection. (e) The dead load of the beam can be neglected. Under above requirements the governing equation reads as

$$\frac{\mathrm{d}^2 u(x)}{\mathrm{d}x^2} = -\frac{M(x)}{EI}, \tag{1}$$

where u is the deflection of the beam at a position x, M the bending moment, E the Young's modulus and I the moment of inertia. The differential equation (1) describes the deformational behaviour of the beam under a bending moment and can be solved analytically. Oftentimes a mathematical exact solution for more complex structures is not found yet or very time-consuming to compute by hand. In this case, numerical methods such as finite element method are introduced (Zienkiewicz 1971). They transform partial differential equations into linear algebraic systems that can be solved with computers with known algorithms.

For a numerical example we generated a chain-like FE model with 726 elements of a four-point bending test which is illustrated in Fig. 1. The properties of the aluminium beam specimen and the forces the specimen is exposed to are listed in Table 1.

In order to include inclination and strain for each element, we approximate its deflection by a polynomial function of 5th order. The approximated solution of the differential equation (1) yields

Fig. 1 Four-point bending test

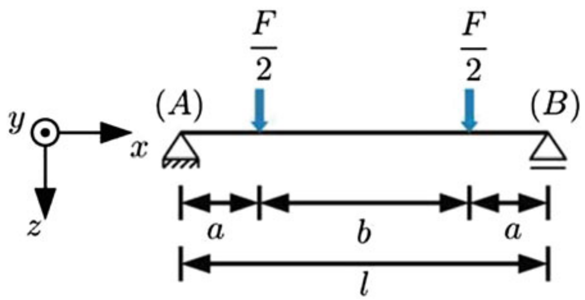


Table 1 Properties of the beam specimen

Length l	7.26 m
Width	0.20 m
Height	0.36 m
Elastic modulus	70 GPa
Force F	7,460 N
Force position a	2.42 m

$$\mathbf{u} = \mathbf{K}^{-1}\mathbf{f}. \tag{2}$$

The matrix **K** is known as stiffness matrix and the vector **f** is denoted as load vector. The vector **u** contains the displacement, inclination and strain at each node of the FE-model. The **K** matrix only depends on the number of elements of the FE-model, while the load vector **f** is a function of the parameters of the experimental setup. Therefore, the behaviour of the beam can be determined. Such a kind of problem definition is known as a forward problem.

3.2 Data Analysis

The described forward problem usually occurs during the design phase, while the engineer determines the behaviour of a structure under external forces. However, during a monitoring usually the behaviour of a structure is observed at different positions using different types of sensors. The analysis of those hybrid measurements is directly based on the solution (2) of the differential equation (1) and reads as

$$\begin{bmatrix} u_0 \\ \vdots \\ u_i \\ \vdots \\ u_N \end{bmatrix} = \begin{bmatrix} k_{00} & \cdots & k_{0j} & \cdots & k_{0N} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ k_{i0} & \cdots & k_{ij} & \cdots & k_{iN} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ k_{N0} & \cdots & k_{Nj} & \cdots & k_{NN} \end{bmatrix} \begin{bmatrix} f_0 \\ \vdots \\ f_j \\ \vdots \\ f_N \end{bmatrix}. \tag{3}$$

The functional model for a measurement u at a node position i yields

$$u_i = k_{i0}f_0 + k_{i1}f_1 + \cdots + k_{iN}f_N, \tag{4}$$

in which the load vector f_j contains the elastic modulus E

$$f_j = b_j \frac{1}{E}. \tag{5}$$

While choosing the elastic modulus E as an unknown parameter results in the functional relationship

$$u_i = \left(\sum_{j=0}^{N} k_{ij} b_j \right) X \tag{6}$$

between the measurement u at a node position i and the unknown parameter $X = 1/E$ and is known as inverse problem. The values k_{ij} and b_j are treated as error free. Furthermore, the stochastic model needs to be set up in order to take the individual stochastic properties of the different types of observations into account. Introducing more observations than unknown parameters yields an over determined equation system which can be solved via least-squares adjustment and thus allows a statistically analysis of the observations and unknown parameters.

3.3 Sensor Placement

To develop a sensor configuration best suited for the presented structure, we generated a finite element model with known boundary conditions and known constitutive law. Based on this model, we computed synthetic displacement, inclination and strain measurements for predefined measuring points. A Monte Carlo simulation (MCS) was performed to analyse the dependence of estimated parameters on the location of the measuring point as well as on the stochastic properties of the measurements. The results are depicted in Fig. 2.

As it can be seen, very accurate sensors are needed to allow a reliable estimation of the material property. Furthermore, it is obvious that displacement and strain sensors should not be located in the vicinity of the bearings, because in this area the measured value is much smaller than the assumed standard deviation of the sensors. For the position of inclination sensors the opposite is the case. The elastic modulus can be estimated best while measuring at the bearings. In addition, it can be shown that using more than 10 sensors hardly improves the accuracy of the estimated material property.

3.4 Damage Detection and Localisation

Furthermore the potential of this integrated analysis for damage detection and localisation within a slender beam due to local material degradation is presented. To simulate beam damage, we introduced for each element a separate elastic modulus. The extent of damage can be induced by a stepwise change of the elastic modulus for a predefined number of elements from 70 (undamaged) to 15 GPa (highly damaged). Starting from the 80th element of our chain-like FE model we increased

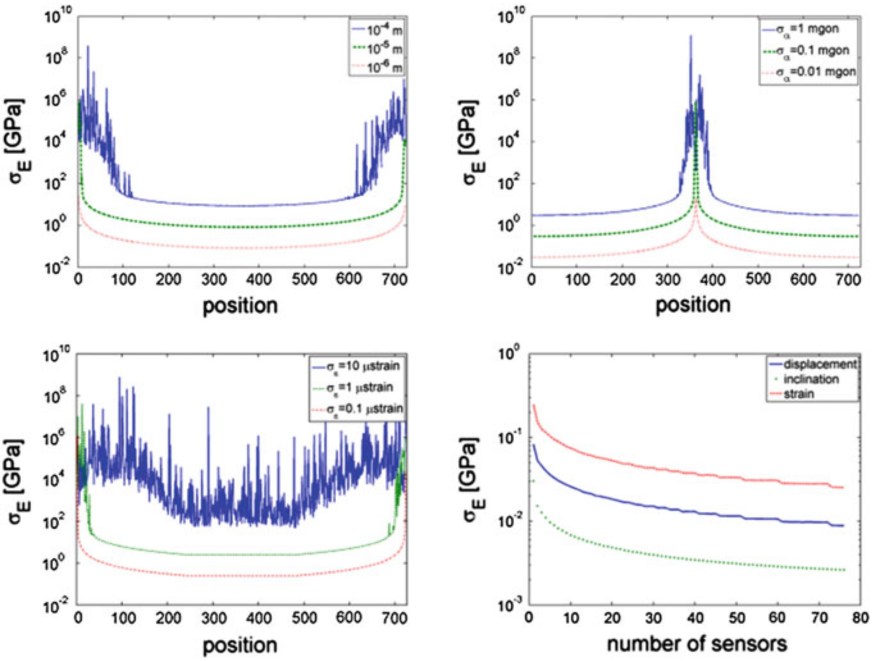


Fig. 2 Accuracy of the estimated elastic modulus σ_E depending on sensor position and accuracy of displacement (*top left*), inclination (*top right*) and strain (*bottom left*), and number of sensors (*bottom right*)

the number of damaged elements successively till the 89th element. For each simulated extent of damage, we calculated the displacement, inclination and strain of each node of the FEM. The calculated displacement and strain at node positions 70, 106 and 141 and inclination at 10 and 210 along the x-axis were used as true values for the synthetic measurements. Therefore a MCS of 1,000 experiments was performed. For each experiment we added normal distributed noise with a standard deviation of $\sigma_u = 1\,\mu\text{m}$, $\sigma_{u'} = 0.1\,\text{mgon}$ and $\sigma_{u''} = 0.5\,\mu\text{strain}$ to the true values. Based on those synthetic measurements and the functional model (6) we determined the elastic modulus for each element via least-squares adjustment in order to detect and localise the simulated damage. The results are shown in Figs. 3 and 4.

Figure 3 shows the potential of the new approach for an integrated analysis of spatially distributed hybrid measurements to detect the simulated damage. According to the chosen standard deviation of the synthetic measurement this approach is able to detect a change of the elastic modulus down to 40 GPa of two elements with a probability of 100 %. Furthermore the probability to localise this detected damage within a range of ±5 elements is ca. 55 %, as it can be seen in Fig. 4.

The presented approach for an integrated analysis based on a mechanical model of a structure is a fundamental component of an information system for structural monitoring.

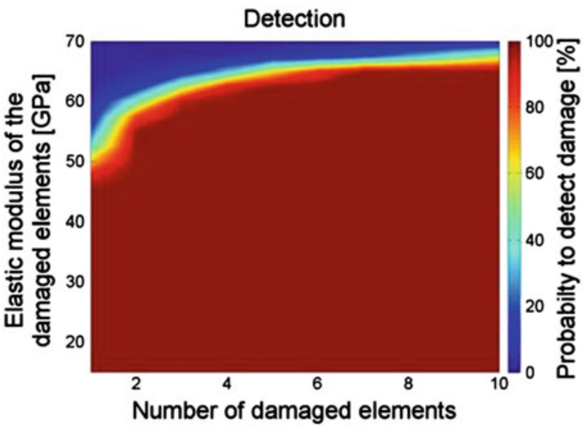


Fig. 3 Damage detection depending on material degradation (change of elastic modulus) and number of damaged elements

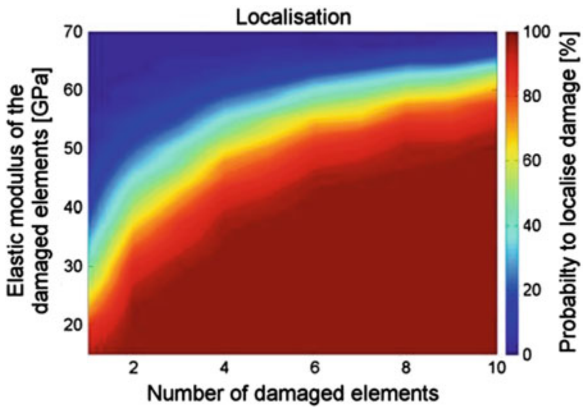


Fig. 4 Damage localisation depending on material degradation (change of elastic modulus) and number of damaged elements

4 Systems Architecture

The architecture of this system has to be designed to enable the integration of individual components in such a way that the exchange of data between all components, but also the exchange with external partners via standardised interfaces is realised. That is a crucial point with respect to the upcoming realised INSPIRE directive (2007). The exchange of spatial data will play a big role in near future. As depicted in Fig. 5 the components mainly interact with each other via services and service requests.

This allows a very flexible use of the system either as desktop version in an office or as field system on a tablet computer. Moreover, the consequent usage of OGC SWE framework for sharing observation data and WFS for sharing spatial feature data enables participants and actors involved in a construction to retrieve needed data in a standardised way. As already mentioned in Chap. Modeling and

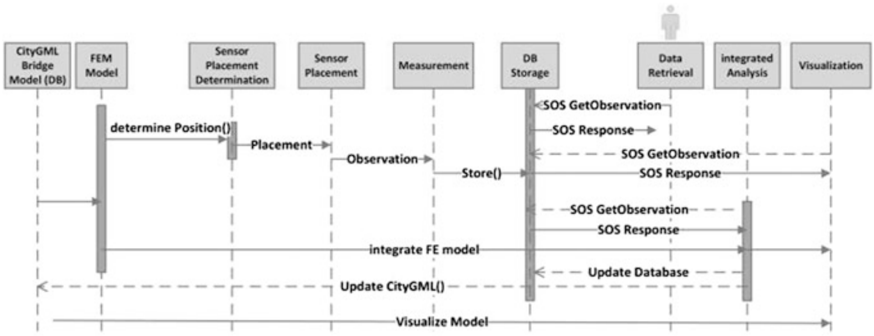


Fig. 5 Components structure and interplay between the required components

Managing Topology for 3-D Track Planning Applications the CityGML bridge model serves as a base model for required site data and for the derivation of the FE model. The bridge model is stored in the 3D CityDB either in a Oracle database (Nagel and Stadler 2008; Stadler et al. 2008) or in a PostGIS DB (Kunde 2013). Instantly this model can be used for the determination of suitable sensor positions and afterwards for placing the sensors in reality. The mapping of CityGML boundary representation onto FEM is still under development. Since we were successful for simple objects such as the beam presented in Chap. Modeling and Managing Topology for 3-D Track Planning Applications a generic tetrahedronization approach has to be developed for every type of bridge supported by CityGML. After setting up the overall sensor network the observations are directly stored into the systems database, see Chap. A Hybrid Approach Integrating 3D City Models, Remotely Sensed SAR Data and Interval-Valued Fuzzy Soft Set Based Decision Making for Post Disaster Mapping of Urban Areas. Via an SOS interface, the data can be requested and responded in a standardised way such that every following component works in a service-oriented way (Erl 2008).

As shown in Fig. 6, the measured data of the sensors are directly stored in a GIS database—based on PostGIS or by using the 52° north framework—that works also on a PostGIS or Oracle database.

Both SOS encodings explicitly enable the integration of sensor observations using CSV or XML document in the database and thus provide the measurement data to the actors in an OGC-compliant exchange format. In terms of documentation, the raw measurement data are already available for each involved actor and can be used for tests and analysis—directly on the fly. Thus, both the sensor data and the observations can be provided in a standardised way and can be prepared for an integrated analysis based on finite element models (FENICS 2014). The results of such analysis can be directly represented in 3D and by means of an update function reintegrated into the database.

The management tool will be completely developed as a browser based service. The user interface can be seen as a front end, providing access to the observed data,

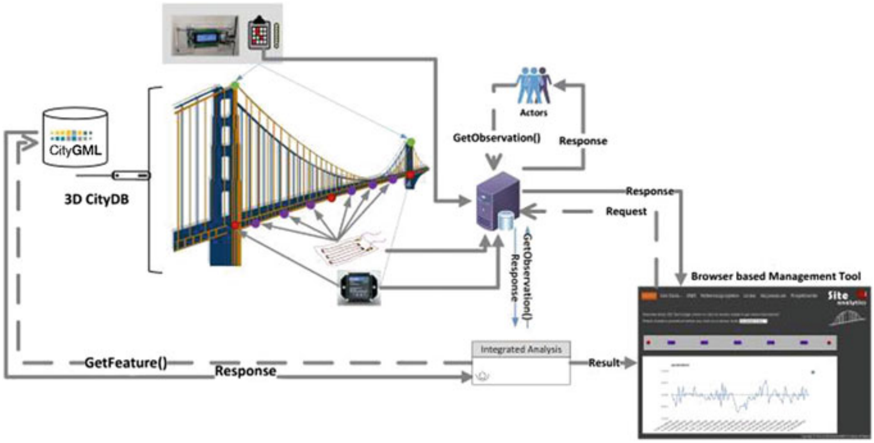


Fig. 6 Systems architecture (part of the figure are under copyright of © microstrain.com, © 3dcitydb.org)

access to analysis tools and 3D and 2D data representation. This includes a general view on the observed data as kind of a dashboard supporting different types of chart diagrams and textual representation as well as the execution of statistical analysis tools for rapid data evaluation and long-term comparison of data.

5 Extending CityGML for Use in FEM

In order to derive a numerical solution computed from FEM simulations, three main input information of the target structure have to be provided from CityGML: Initial geometry, boundary conditions and material information.

The initial geometry is used to generate finite elements by subdividing the whole structure into parts with simpler shape such as cubes, tetrahedron etc. External influences which the structure is subjected to, are described by boundary conditions, for example dead load, bearing fixations, heat transfer, loads from vehicle, wind load and more. Furthermore, the materials the structure consists of need to be known. Since that information is not part of a typical CityGML model we have to extend CityGML by using the ADE mechanism in order to support FEM analysis. Currently CityGML provides three modules that are relevant for our kind of research—the buildings module, bridge module, and tunnel module. Since material information are needed for many applications besides structural health monitoring, it should be modelled as an own module, see Fig. 7. Thus, each *_CityObject* will have different kind of Materials. As first each *_CityObject* has an *ExteriorMaterial* describing the material type of the outer shell of an urban entity. Moreover a

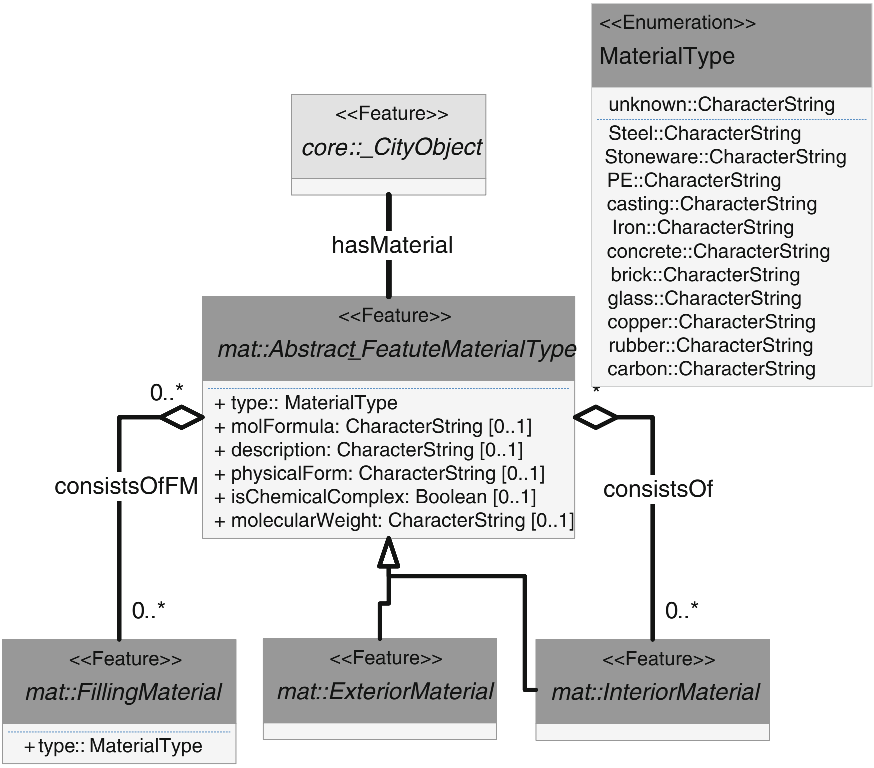
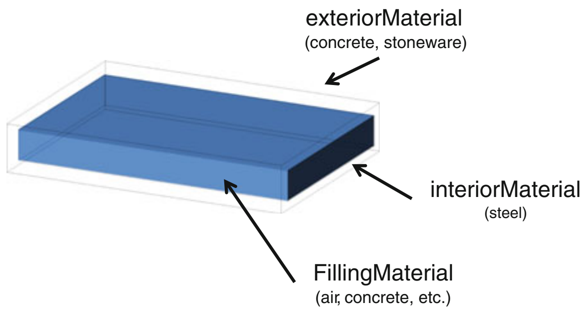


Fig. 7 Proposal for integrating material information into CityGML

Fig. 8 Material example to provide needed information for FEM



separation into *InteriorMaterial* and *FillingMaterial* is undertaken in order to describe the material of the inner shell of an entity as well as the filling material of the object itself see Fig. 8. The presented UML diagram (Fig. 7) just shows an initial approach, how to integrate material information into CityGML. Since various application nowadays also need such information for performing analysis and simulation e.g. energy and carbon dioxide calculations, bomb scenarios etc. this

Table 2 Overview about relevant DBMS for designing the overall system

Database name	MySQL	Oracle	Microsoft SQL Server Express	postgreSQL
Description	Widely used open source RDBMS	Widely used RDBMS	MS RDBMS	Based on the object RDBMS Postgres
Developer	Oracle	Oracle	Microsoft	PostgreSQL Global Development Group
License	commercial	commercial	Open Source	Open Source
Implementation language	C and C++	C and C++	C++	C
Server operating systems	Linux, OS X, FreeBSD, Solaris, Windows	AIX, Linux, OS X, HP-UX, Solaris, Windows, z/OS	Windows	Linux, OS X, HP-UX, Solaris, Unix, Windows
DB model	Relational DBMS	Relational DBMS	Relational DBMS	Relational DBMS
Supported programming	Ada, C, C#, C++, D, Eiffel, Erlang, Haskell, Java, Objective-C, OCaml, Perl, PHP, Python, Ruby, Scheme, Tcl	C, C#, C++, Clojure, Cobol, Eiffel, Erlang, Fortran, Groovy, Haskell, Java, JavaScript, Lisp, Objective C, OCaml, Perl, PHP, Python, R, Ruby, Scala, Tcl, Visual Basic	.Net, Java, PHP, Python, Ruby, Visual Basic	.Net, C, C++, Java, Perl, Python
Server-side scripts	yes	PL/SQL	Transact-SQL and.NET languages	User defined functions

will affect every module of CityGML. Thus more discussions and investigations have to be done until the integration of material information into CityGML can be stated as almost finished. This will be future work, especially for CityGML 3.0 where a special working group was formed to integrate material and texture information into the future version of CityGML.

6 DBMS and Performance Tests

The data generated by sensors are enormous and need to be stored very quickly into the database. Since enormous quantities of data is constantly being generated from sensors, […] "the spatial functionality offered by current commercial and open-source relational databases differs significantly in terms of available features, true geodetic support, spatial functions and indexing" (Ray et al. 2011). Thus, at first a revision of existing DBMS (compare Table 2) and the Pros and Cons should be taken into account followed by a performance test to ensure the thigh transaction speed. We decided to use PostgreSQL/PostGIS, since it is OpenSource, free available and widely used in GIS community.

However, the use of XML based databases is still a valid option. This is relevant for the overall decision of the design of the system, whether it can be a real-time system or not. A first rough test with a PostGIS database installed on a windows machine, using default setup parameters reveals that the DBMS is capable of handling nearly 6,000 entries per second by using 10–20 parallel working threads (cf. Fig. 9). Tuning the DBMS and allowing more parallel transactions, followed by giving more working memory, etc. should increase the number of entries per second dramatically. However, the current configuration is capable of handling a lot of low

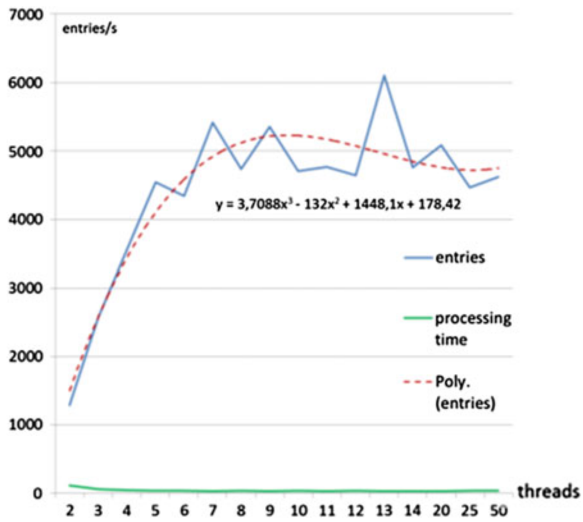


Fig. 9 Initial performance test using a standard PostGIS installation in a windows machine

frequency (max. 10 Hz) sensors, such as strain, temperature, wind speed, etc. Applying high frequency sensors such as accelerometers will dramatically reduce the number of applicable sensors due to a measurement frequency of 512 Hz.

7 Conclusions

In this contribution, new possibilities for structural monitoring, analysis and simulation are presented that are significantly based on the interoperability of systems/components. The combination of spatial data and sensor data/standards in services and service-oriented architecture provides a novel versatile platform for structural monitoring, which goes far beyond a simple data storage model. The method presented in this contribution allows direct integration of sensor data and its provision through an open standard language. The great potential of such an information system lies especially in the integrated analysis of the sensor data on the base of a finite element model (FEM). The automatic derivation of a finite element model from 3D construction model is until now only implemented for basic rectangular shapes. For complex structures new algorithms and methods needs to be developed. The visualisation of FEM—simulation results based on the construction model, the provision of raw data and sensor information for each point in time drives the platform into a universal tool in the field of structural monitoring.

References

Bermudez L (2011) OGC sensor web enablement (SWE). https://www.evernote.com/shard/s264/sh/06758c15-b4cc-44fc-8440-2d26bf858604/e9e84a61e167e53bd1bc76f339934cc2/res/996f9a2d-4b7d-4670-9b40-3ad1ff6013ae/2011_OGC_Sensor_Web_Enablement.pdf. Accessed 22 April 2014

Botts M, Percivall G, Reed C, Davidson J (2006) OGC® sensor web enablement: overview and high level architecture. In: Nittel S, Labrinidis A, Stefanidis A (Hrsg) GeoSensor networks. Springer, pp 175–190

Boller C, Staszewski WJ (2004) Structural health monitoring. In: Proceedings of the second European workshop on structural health monitoring, München, pp 7–9

Bröring A, Echterhoff J, Jirka S, Simonis I, Everding T, Stasch C, Liang S, Lemmens R (2011) New generation sensor web enablement. Sensors 11(3):2652–2699

Bröring A, Stasch C, Echterhoff J (2012) OGC® sensor observation service interface standard, OpenGIS® Implementation Standard, version 2.0. http://www.opengis.net/doc/IS/SOS/2.0. Accessed 17 June 2014

Erl T (2008) Soa: principles of service design, vol 1. Prentice Hall, Upper Saddle River

Farrar C, Worden K (2007) An introduction to structural health monitoring. Philos Trans Soc A: Math Phys Eng Sci 365(1851):303–315

FENICS (2014) http://www.fenicsproject.org. Accessed 22 Apr 2014

Furtner P, Stöger M, Schreyer M (2013) SHM DATA—management, treatment, analysis and interpretation—a solution for permanent monitoring systems. In: 6th International conference on structural health monitoring of intelligent infrastructure, Hong Kong, 9–11 Dec 2013

Gröger G, Kolbe TH, Nagel C, Häfele KH (2012) Open-GIS® city geography markup language (CityGML) encoding standard, version 2.0.0, OGC 08-007r2

INSPIRE directive (2007) Directive 2007/2/EC of the European parliament and of the council of 14 March 2007 establishing an Infrastructure for spatial information in the European community (INSPIRE). Online: http://www.eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32007L0002:EN:NOT. Accessed 22 Apr 2014

Jäger, R (1988) Analyse und Optimierung geodätischer Netze nach spektralen Kriterien und mechanischen Analogien, DGK, Reihe C, Nr. 342, München

Kunde F (2013) CityGML in PostGIS : Portierung, Anwendung und Performanz-Analyse am Beipiel der 3D City Database von Berlin, Masterarbeit am Institut für Geographie, Universität Potsdam, unveröffentlicht

Lienhart W (2007) Analysis of inhomogeneous structural monitoring data. Shaker Verlag, Aachen

Nagel C, Stadler A (2008) Die Oracle-Schnittstelle des Berliner 3D-Stadtmodells In: Clemen C (Hrsg) Entwicklerforum Geoinformationstechnik, Shaker Verlag, pp 197–221

Neitzel F, Weisbrich S, Wu CC (2014) Integration der finite-elemente-methode in die ausgleichungsrechnung zur parameteridentifikation. In: Wieser A (ed) Ingenieur-vermessung 2014, Beiträge zum 17. Internationalen Ingenieurvermessungskurs Zürich, Herbert Wichmann Verlag, pp 301–310

Ray S, Simion B, Brown AD (2011) Jackpine: a benchmark to evaluate spatial database performance. In: International conference on data engineering, IEEE

Resch B (2012) Standardisierte Geosensornetzwerke für Umweltbeobachtung in naher Echtzeit. http://www.berndresch.com/download/work/publications/resch_geosensornetzwer-ke_rt-gis_2013.pdf. Accessed 22 April 2014

Stadler A, Nagel C, König G, Kolbe TH (2008) Making interoperability persistent: a 3D geo database based on CityGML, In: Lee J, Zlatanova S (Hrsg) 3D Geo-information sciences, selected papers from the 3rd international workshop on 3D geo-information, Seoul, Korea. LNG&C Series. Springer, pp 175–192

Teskey WF (1988) Integrierte Analyse geodätischer und geotechnischer Daten sowie physikalischer Modelldaten zur Beschreibung des Deformationsverhaltens großer Erddämme unter statischer Belastung, DGK, Reihe C, Nr. 341, München

Welsch W, Heunecke O, Kuhlmann H (2000) Auswertung geodätischer Über-wachungsmessungen. In: Möser M, Müller G, Schlemmer H, Werner H (eds) Hand-buch Ingenieurgeodäsie. Herbert Wichmann Verlag, Heidelberg

Worden K, Dulieu-Barton JM (2004) An overview of intelligent fault detection in systems and structures. Struct Health Monit 3(1):85–98

Zienkiewicz OC (1971) The finite element method in engineering science. McGraw-Hill, London