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EARTHQUAKE EARLY WARNING AND RAPID RESPONSE SYSTEM BASED ON SMART SEISMIC AND MONITORING SENSORS EMBEDDED IN A COMMUNICATION PLATFORM AND COUPLED WITH BIM MODELS

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Abstract

This paper describes the concept of an innovative, interdisciplinary, user-oriented earthquake warning and rapid response system coupled with a structural health monitoring system (SHM), capable to detect structural damages in real time. The novel system is based on interconnected decentralized seismic and structural health monitoring sensors. It is developed and will be exemplarily applied on critical infrastructures in Lower Rhine Region, in particular on a road bridge and within a chemical industrial facility. A communication network is responsible to exchange information between sensors and forward warnings and status reports about infrastructures' health condition to the concerned recipients (e.g., facility operators, local authorities). Safety measures such as emergency shutdowns are activated to mitigate structural damages and damage propagation. Local monitoring systems of the infrastructures are integrated in BIM models. The visualization of sensor data and the graphic representation of the detected damages provide spatial content to sensors data and serve as a useful and effective tool for the decision-making processes after an earthquake in the region under consideration.

Keywords: early warning and response system, interconnected sensor systems, seismic structural damage detection via SHM, integration SHM in BIM

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1 INTRODUCTION

Germany's seismicity in general is characterized as low or moderate. However, there are seismic events of moderate to strong ground motions with damage potential (Tailfingen 1978 $M_w = 5.7$, Roermond 1992 $M_w = 5.9$). These events arouse attention because the exposed regions are densely populated, highly industrialized and have an extended network of critical infrastructures. These infrastructures were mainly designed according to currently outdated or none seismic provisions. The early warning and rapid response system combined with local health monitoring systems can act supplementary as an additional arrow in the quiver of earthquake engineering to reduce the seismic risk, especially for critical infrastructures.

This contribution describes the conception and the progress of the works, that had been performed in the framework of the German nationally funded research project "ROBUST". Fundamental element of the novel system is the automated interaction of smart seismic or structural sensors and sensor systems, which are capable not only to record motions or strains, but also to process the recordings decentral and to forward the results of the assessment. In the past decades, the breakthrough in software and hardware development of sensors and techniques for data processing enabled the extended and low-cost use of a remarkable number of seismic and monitoring sensors [1]. Reliable earthquake early warning systems (EEWS) were developed all over the world and especially in seismic prone areas as Japan, California and Mexico [2]. Simultaneously, engineering diagnostics is an emerging field concerning health assessment of civil engineer's structures. Post-earthquake damage detection through sensor systems is a research topic of increasing interest. Acknowledging the developments in both directions (SHM and EWS), the examined system tries to incorporate and extend their advantages and provide a useful tool for the protection of critical infrastructures [3]. The examined system is going to be applied in Lower Rhine Region. A road bridge and a chemical industrial facility are selected as benchmark structures. The innovative system consists of four basic components: (i) the seismic sensors network, (ii) the local monitoring systems for the critical infrastructures, (iii) the communication infrastructure and (iv) the integration of the sensor data in BIM models of the monitored critical infrastructure.

Regarding the first component, namely the seismic network, the existing sparse regional network is being extended by new smart seismic sensors. To this end, an algorithm has been developed, aiming at the optimization of the location of the new sensors such, that while accounting for the geophysical conditions, reliable information on earthquakes relevant for the infrastructures can be obtained and communicated to maximize the lead time while, at the same time, to minimize the risk of false alarms. The novel sensors, developed by the German Research Center for Geosciences (GFZ), are capable to evaluate the intensity of the ground motion in real time and to send out messages via the developed communication network to the operators of critical infrastructures or local authorities (civil protection), before the arrival of the destructive seismic waves to the structures of interest. The information on a detected earthquake triggers also the local monitoring systems.

The flow of the seismic incidence information takes place through a communication network, which consists of several decentralized nodes. Every seismic sensor and every monitored infrastructure correspond to a communication node, which is responsible to send and receive the appropriate information. Synchronously, the same communication infrastructure, under development by Fraunhofer Institute for Open Communication (FOKUS), will provide warnings regarding the expected damages to the concerned parties (local authorities, operators of critical infrastructures). This allows the recipients to trigger safety measures. The kind and the intensity of the measures depend on the expected damages of the detected ground motion and can be updated relying on the most current measured data. After the assessment of the seismic performance of the monitored structures, health reports will be sent to interested actors.

The local health monitoring systems consist of a number of sensors (accelerators, velocity recorders, displacement transducers, strain gauges, thermometers etc.) and data acquisition devices. The sensors are placed in appropriate positions to record effectively the response of the structure or components and to detect particular damage indicators. The definition of the damage indicators depends on the geometry, dynamic properties and seismic risk of the various components of the monitored infrastructures. In “almost” real time, the measurements from the monitoring sensors are evaluated either decentral and locally by smart data acquisition systems or remotely at a central site by linked computers. The results of the damage identification are integrated in two steps in the communication platform. Right after the earthquake, very basic information is forwarded (e.g., whether a bridge is accessible or not or if parts of the facility are severely damaged). Gradually, more detailed information based on a refined interpretation of the sensors’ recordings will be communicated to the clients, including a graphical representation of the damages.

One of the fundamental objectives and an innovative part of the project is the graphic representation of the damage distribution of the monitored infrastructures right after an earthquake. This is possible because of the integration of the SHM system in 3D BIM models. Necessary precondition is the coupling of the sensor data with the graphic objects representing the real sensors in BIM models. For this purpose, the Desite MD software was selected. It provides the opportunity to link databases containing sensor measurements with an imported BIM model. Responsible for the development of the monitoring systems, the damage detection techniques and the integration of the sensor data in BIM models are the Center for Wind and Earthquake Engineering (CWE) of RWTH Aachen University and Wölfel Engineering GmbH.

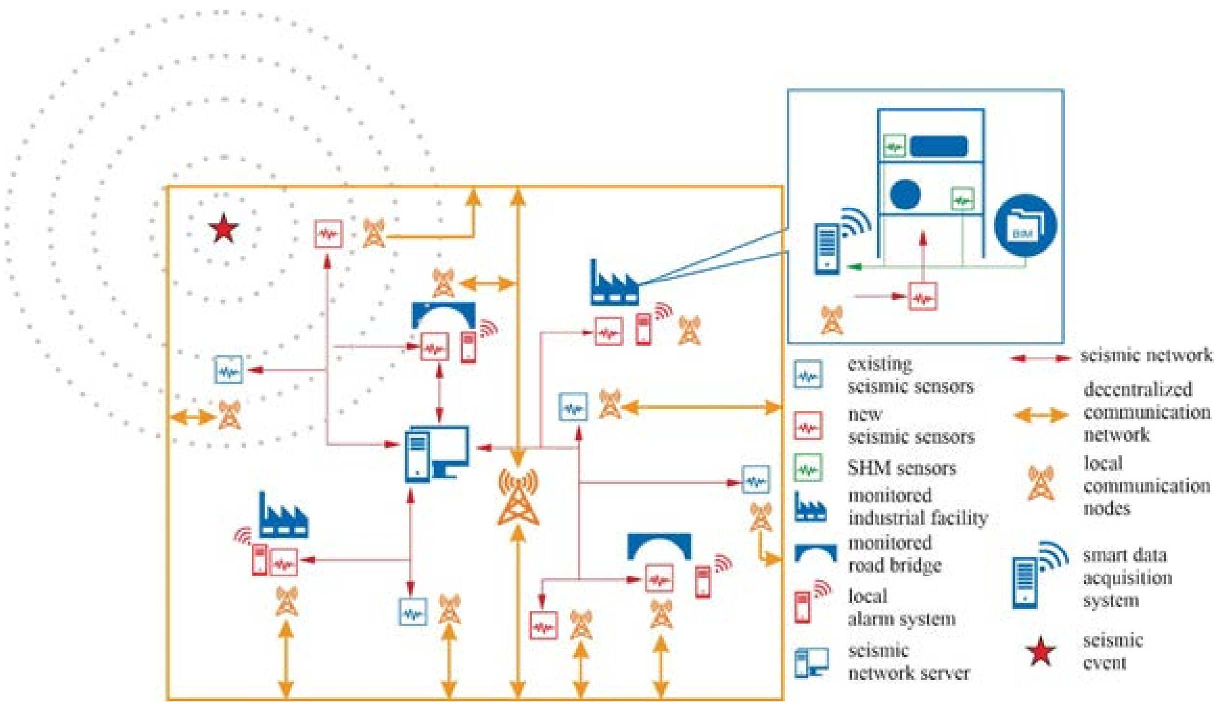

Figure 1: Earthquake early warning and rapid response system

2 EARTHQUAKE EARLY WARNING AND RAPID RESPONSE SYSTEM

2.1 General Information

The Lower Rhine Embayment in Western Germany is one of the most important areas of earthquake recurrence north of the Alps, facing a moderate level of seismic hazard in European context, but a significant level of risk due to a high population density and a large number of critical industrial infrastructures. As the seismic faults are directly crossing the study area, the lead time, i.e. the time between the onset of an earthquake and the arrival of the destructive seismic waves is in the order of a few seconds at most for events in the Lower Rhine Embayment. In this context, the project aims at designing a user-oriented hybrid earthquake early warning (EEW) and rapid response system where regional seismic monitoring is combined with smart, on-site sensors, resulting in the implementation of decentralized early warning procedures.

2.2 Seismic scenarios for the area of interest

One of the tasks of this project deals with finding an optimal regional seismic network arrangement given the known seismicity in the area. The optimization approach used here requires a representative sample of relevant seismic recordings. In the design of an EEW network, it is critical that all potential and known earthquake sources in the area are considered. Due to the sparsity of significant earthquake recordings in the region, stochastic simulations of scenario earthquakes were performed using the finite-source ground motion simulation code EXSIM [4] and the known seismicity in the area [5]. Overall, over 700 realistic scenario earthquakes were considered (for their location see Figure 2). This approach is ideally suited for the purposes of our study, as our emphasis is not on the simulation of the complete wavefield for given scenario earthquakes, but rather on the generation of a large set of spectra for hypothetical sources located according to a seismic catalog.

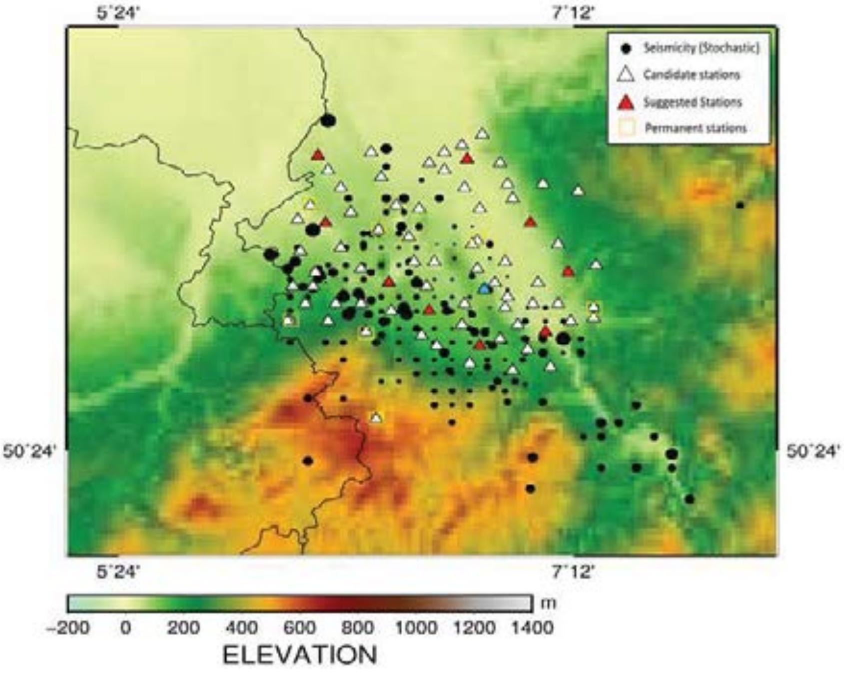

Figure 2: The Lower Rhine Embayment, Germany. The potential network is represented by candidate stations (white triangles) and suggested installations sites (red triangles) together with the existing permanent stations (yellow squares). The blue triangle represents the target site. The simulated scenario earthquakes are represented by black dots with diameter proportional to earthquake magnitude.

2.3 Optimal densification for real time assessment and early warning

The possible station locations were considered by public buildings (municipalities, schools etc) in the Lower Rhine Embayment. For each location, stochastic seismograms were computed for all scenario earthquakes resulting in a database consisting of more than 30,000 traces representing ground acceleration. An important aspect of an EEW system's performance is its ability to give not only timely, but also reliable warnings with respect to the shaking that needs to be expected at the target site. For our study site, a threshold of 0.02 g was selected, as such events can be considered as potentially damaging. The optimal network is the one that can give the correct level warning (i.e., correct level of expected ground motion at the target site) at a sufficiently long lead time for the highest number of scenario earthquakes.

To quantify this network quality, we use the cost function developed by Oth et al [6]. For finding the optimal station locations, a microgenetic algorithm was used. Such algorithms are a specific subset of genetic algorithms (GAs), which are guided search techniques based on evolutionary principles to find optimal models with respect to a given objective function (i.e., cost function). By minimizing the cost function, a comparison of the best earthquake early warning system design can be performed and the potential usefulness of existing and additional stations in the region is considered (see Figure 1). As indicated by the red triangles, by adding nine stations to the existing network, such optimal design will allow strong ground-motions with respect to the target site to be detected most quickly and most reliably.

2.4 Rapid response system

An earthquake early warning system can reduce the seismic risk on critical infrastructure more effectively, if combined with a response system. The term response system includes all automated measures that can be taken immediately after the detection of the first earthquake waves within the lead time. Structural damages are not the only threat especially for critical infrastructures. Accidents or side effects due to a seismic event such as fire or more rarely explosions or dispersion of toxic substances can have even more harmful consequences than the mechanical damages directly induced by the ground motion [7]. Possible countermeasures to limit damages and prevent domino effects that can be performed in range of seconds are emergency shutdown of gas lines, activating backups, safe stop of lifts or other equipment, interruption of medical operations, access prevention in road bridges or tunnels [7]. Within the ROBUST project, the production process of the chosen industrial facility is not interrupted automatically. The warning for a coming seismic incidence and the damage prediction is forwarded to the facility operators, who are responsible to trigger appropriate measures. Regarding the bridge, the access can be interrupted by a traffic light, in case an earthquake with damage potential is detected. Depending on “almost” real time assessment from the local monitoring system of the bridge, the access restriction will be recalled or it will remain for all or some kind of vehicles.

3 COMMUNICATION NETWORK

Essential part of the developed system is the decentralized communication network. It enables the interaction between seismic sensors and local monitoring sensor systems and is responsible to forward warning messages and structural health status reports to subscribed recipients (user oriented). Each user has access to different level and kind of information depending on his involvement. As users can be considered facility managers, local authorities, civil protection or rescue teams. From the communication infrastructure point of view, all the participants are divided into two categories: (i) sensors and (ii) actors. Sensors “produce” information and actors “consume” information. The nodes are spatially distributed and one node corresponds to each seismic sensor. At the monitored infrastructures one node is responsible for the seismic sensor and for the controller of the local monitoring system. Predefined subscriptions specify the flow of information between the nodes. At the idle period, the platform is responsible to control, which devices are connected, their health status and the plausibility of the measurements of the sensors. The administrators of each subsystem are informed through automated messages about the health status of the whole sensor infrastructure.

When a ground motion, which exceeds a predefined threshold of acceleration, is detected by the seismic network, the communication node of the corresponding seismic sensor forwards the information to the subscribed recipients to trigger the monitoring system to measure with a higher sampling ratio, in order to obtain detailed information for the response of the structures during the seismic event. If a seismic event with damage potential is detected by the seismic network, messages, graded indicative lamp systems or smart traffic lights will inform the corresponding users about the upcoming event. No emergency shutdowns or other measures are triggered directly by the communication platform. During the seismic event, the sensor signals are continuously evaluated with regard to exceedance of values indicating damages. Right after the earthquake, the health status of the infrastructures, is evaluated based on the recording of the monitoring system and sent via the communication infrastructure to the concerned subscribers. The first report includes a rapid assessment of the performance of the structure (e.g. partial or total collapse of the infrastructure, risk for fire or explosion, operational status of a bridge). After a few minutes, a second more precise health status report is delivered. It contains information about the detection of damages and their spatial distribution. The second health status report includes information about the operability of the infrastructure and a graphic 3D representation of the structural damages.

4 STRUCTURAL HEALTH MONITORING OF CRITICAL FACILITIES

4.1 Critical Infrastructures

Critical infrastructures, according to German Federal Office for Civil Protection and Disaster Assistance, are organizations and facilities with crucial significance for the state community, the failure or impairment of which would result in lasting difficulties in supply chain, significant threats for the public security or other dramatic consequences [8]. Although buildings are considered to be the most vulnerable component of the urban built environment to seismic hazard, the resilience of complex systems like transport and utility networks, gas and electric network systems, health care system, power plants and selected industrial facilities is even more critical, as they have an extreme socio-economic impact and can affect the regional prosperity [9]. Although the seismic code provisions in Germany are constantly improving [10] and seismicity of the Lower Rhine Embayment was investigated in detail the recent years [11], an important part of the critical infrastructure was designed with lower seismic actions or without any seismic code provisions. According to [11], in this region there are 51 electricity supply substations, 108 hospitals, about 1500 industrial facilities, 4 industrial chemical parks and 8 road and railway bridges over Rhine.

Interdependencies between complex systems may result in rapid damage propagation. Therefore, there is a demand for interconnected monitoring systems, that can detect damages and provide this information to crisis management centers. Appropriate safety measures to prevent or mitigate damages can be triggered effectively, only if sufficient information is available within a short time. Awareness of the structural health status of critical nodes of the transport network, such as bridges, is beneficial for the definition the optimal routes for rescue teams and ambulances (interaction health care system – transport network). Chemical industries are an important component of the infrastructure in Lower Rhine. The main threat after an earthquake in chemical industries with hazardous processes is the risk of accidental scenarios such as fire, explosion or dispersion of toxic substances due to loss of containment. Immediate countermeasures must be triggered to limit the consequences of such events in terms of fatalities, environment pollution and repair cost [12].

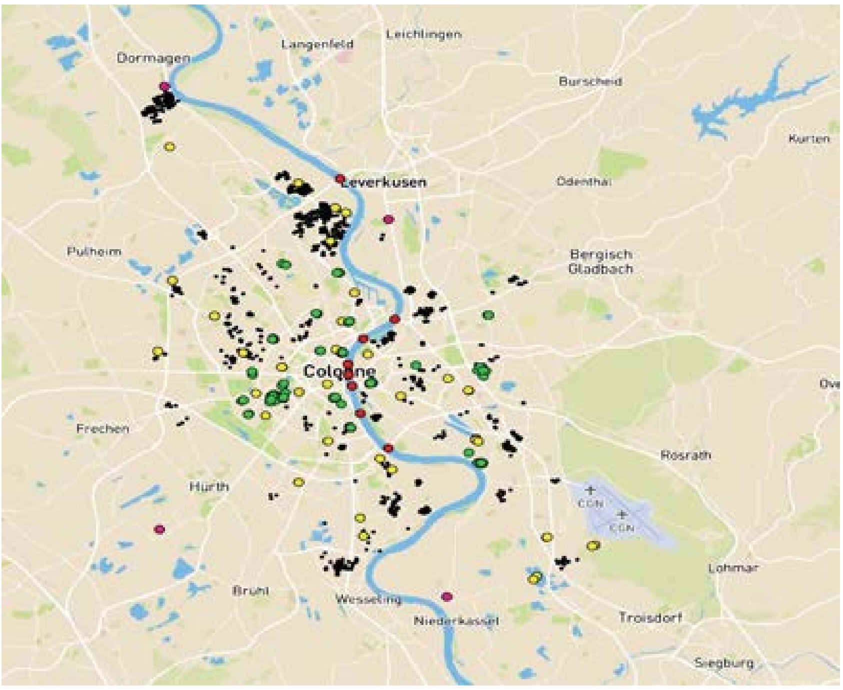

Figure 3: Distribution of critical infrastructures in Lower Rhine Region: electricity substations (yellow circles), hospitals (green circles), road & railway bridges over Rhine (red circles), industrial facilities (black circles), chemical industry parks (purple circles) [11]

4.2 Implementation of health structural monitoring system on demonstration facilities

Taking into consideration the distribution of critical infrastructures in Lower Rhine Region, an industrial facility (chemical industry) and a road bridge are selected as case studies for the installation of the local SHM systems. For both infrastructures, a probabilistic earthquake risk analysis is carried out, to define the seismic hazard. The vulnerability curves of different elements and components are defined based on the corresponding literature [13][26][27][28]. The most susceptible components are prioritized, their possible failure modes and the position of the expected damages is investigated in detail. Especially for the industrial facilities, the influence of non-structural components should be taken into account. Storage tanks, vertical and horizontal vessels, processing equipment, pumps and pipping systems are connected with each other and structural damages on one process unit can generate a multiplicity of accident chains due to mutual interactions [14]. After the basic identification of the facilities, suggestions for further damage prevention or damage limitation will be provided and discussed with the facility operators [12]. The damage scenarios determined by simulations will be communicated to the operators and may be used for improving emergency actions and prevention of cascade effects. For this purpose, appropriate damage indicators and assessment methods, providing necessary information about the global performance of the structure or local failures of critical component will be implemented. Structural damages can result in a loss of stiffness, indicated by changes in natural frequency, mode shapes or modal shape curvature. For the monitored bridge, the critical indicators are aiming at the condition of the superstructure (global response, local damages) and at the bearings (critical movement of the superstructure) [29][30]. Regarding the industrial facilities, peak floor acceleration (PFA), interstorey drift ratio (SDR), residual SDR, response of connections or strains in critical locations, for example elbow or tee connections of pipelines can be used as damage indicators [15] [16]. The number and the kind of the selected sensors (accelerators, velocity and displacement transducers, strain gauges etc.) depends on the chosen indicators and are structure specific.

Immediate damage detection and quantification, especially for critical infrastructures, is essential to minimize their operation interruption due to shut down time. Traditionally, engineering inspections and nonlinear analyses are necessary to evaluate the capacity of the structures after seismic events. This may last weeks or months, accompanied with an important economic cost due to shut down. Modern structural health systems can provide real time damage detection based on changes in dynamic properties of the monitored structures [16]. There is a variety of methods both in time and frequency domain such as autoregressive methods, stochastic subspace identification, frequency domain decomposition method, which can assess the seismic performance and health condition through different indicators [17]. The comparison of measurement data and simulation data allows a more precise prediction of damage stage and distribution within the infrastructures. Moreover, the existence of a geotechnical seismic sensor close to the monitored facilities, allows the application of either output only or input/output methods [18]. For different structural types, different types of damage indicators may be more effective [16]. The functionality of the measurement chain, selected damage indicators and assessment methods will be verified in scaled benchmark structures and substructures in laboratory in advance. In the aftermath of an earthquake, the fundamental information that should be extracted from the monitoring system concern the operational ability of the corresponding infrastructure depending on the distribution of damages. The smart data acquisition devices, which are capable to process data in real time and forward the crucial information to the communication network [19] play an important role in the integration of local monitoring system to the whole early warning and response system.

4.3 Integration health monitoring system in BIM modelling

The integration of the local monitoring systems of critical infrastructures in 3D BIM models is one of the objectives of the research project. BIM is an intelligent 3D model - based process, which promotes the interdisciplinary cooperation of different architects, engineers, constructors and facility operators [20]. The integration of SHM systems in BIM offers geospatial content to the measured and processed data and provides better control and management of the infrastructure [21]. In case of an earthquake with damage potential, the visualization of damages provides a fast and structured overview for operators of critical infrastructure and supports the decision-making processes. Another asset concerns mainly the rescue teams for whom a comprehensive graphic overview of the damages before entering a facility is important. Finally, the knowledge of the updated health status of infrastructures is a useful tool for the effective management and decision making at regional level.

The implementation is divided in two main parts: (i) the generation of a BIM Model including sensors and (ii) the coupling of the graphic objects with sensor data. For the creation of a 3D BIM model, Revit Structure 2020 [31] is selected. The principle is presented using the example of a simple steel frame structure. At first, the steel frame is designed according to the Eurocodes. The next step is the implementation of accelerometers as separate family component by means of an IFC class for the graphical representation of the sensors. The accelerometer created as a family component is imported in the main model. The IFC class names IfcSensor and IfcSensorType in Revit are classified as specialty equipment object [22]. Therefore, a subcategory “accelerometer” is manually defined in the file “exportlayers-ifc-IAI.txt”. Alternatively, it is possible to use an existing object from the Revit library, such as fire alarm. However, this may result in misunderstanding between different users. Revit gives the opportunity to provide static information like position, Id/name, manufacturer, type, cost etc. to each sensor [23].

However, the key challenge is the development of a "dynamic" BIM Model with continuous connection to the actual sensor data. For this purpose, Desite MD (Manage Data) is chosen [24]. Desite MD provides the opportunity to import BIM Models as IFC files and to interact with them through a Javascript API. The interaction is possible via an internal customized web browser, which allows the development of user-oriented applications [25]. Two main tasks have to be implemented: (i) the coupling of the IFC objects representing sensors with the corresponding measurements on the database and (ii) the representation of seismic damages in a 3D model. Concerning the first target, through the API, when a graphic sensor is selected by the user, its ID is identified and can be linked with data available in the database. The data are requested by the API from the corresponding table of the database. In general, it is possible to request either raw data or post-processed data. The sensor values are updated in time intervals appropriate for the specific application. The measurements can either be represented in tabulated views or in diagrams. The color of the sensor objects can be adapted considering the sensors operation status and the corresponding measurements. For example, an accelerometer can be: (i) grey: for sensor out of function, (ii) green: for sensor in function and maximum recorded acceleration during the last 30 sec. lower than m_1, (iii) orange: for sensor in function and maximum measurement during the last 30 sec. between m_1 and m_2 and (iv) red: for sensor in function and maximum measurement during the last 30 sec. higher than m_2. Threshold values (m_1, m_2) depend on the requirements of each structure. Moreover, through the web form module, a graphical interface will be developed, where the user can request various data from sensors – namely from the database (raw or evaluated values, maximum/minimum values within a time period etc.).

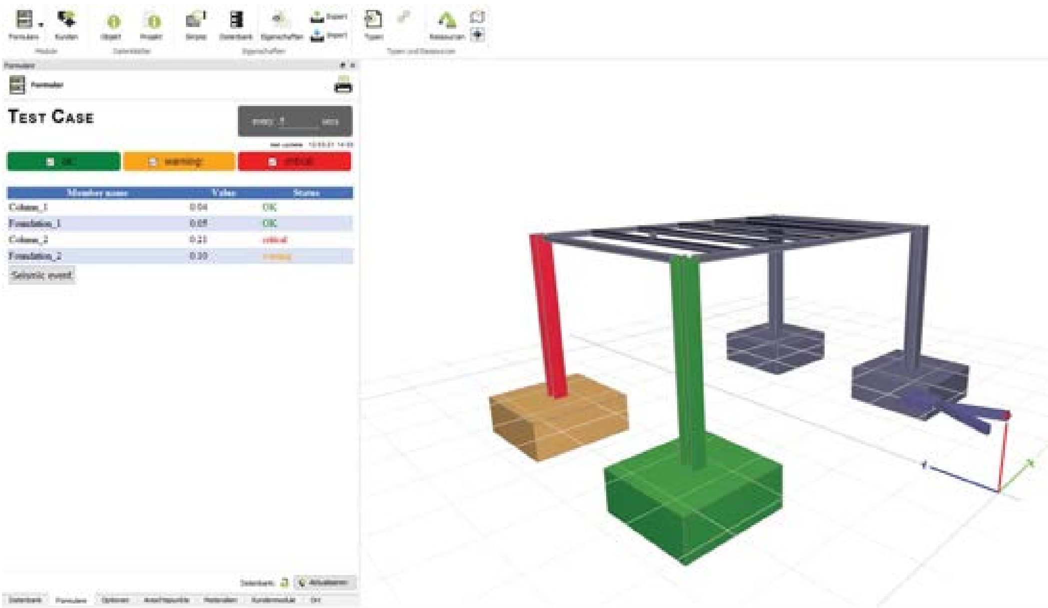

Figure 4: Visualization of damage detection after a seismic event

Regarding the damage detection, the color of monitored members/components is adapted depending on defined damage threshold values (Figure 4). The predefined threshold values (for instance interstorey drift ratio limits) are compared with post-processed sensor data, which result from one or more sensors. The updated model with the adapted colors of critical members/components and sensors is saved and compressed in a packed model after every update. After a seismic event, members and sensors maintain the most unfavorable health status-color, even if measurements return to values below thresholds after the seismic event. The compressed file of the model including the visual distribution of damages is forwarded to the interested subscribers. Civil protection and rescue teams equipped with a BIM-Viewer will be able to open on tablets or smartphones the adapted compressed 3D model, in which the identified damages are indicated e.g., by colors and descriptive labels.

5 CONCLUSION

The presented paper describes the concept of a user-oriented earthquake early warning and rapid response system based on interconnected decentralized smart sensors and sensor systems integrated in BIM models. Aim of the project is to contribute to the mitigation of seismic risk, especially with respect to critical infrastructures. The investigated system is prototypically applied in Lower Rhine Region, which is one of the most important seismic areas north of the Alps. Although its seismicity can be categorized as moderate in European context, the seismic risk due to the population and infrastructure density is high. Exemplarily, a road bridge and a chemical industrial facility will be monitored and investigated in a holistic approach, considering their interactions with other infrastructures and networks. The essential relay between the seismic network (responsible for the early warning), the local monitoring systems (responsible for the evaluation of the seismic performance and detection of damages of critical infrastructure) and the interested parties, namely the facility operators and the local authorities, is the decentralized communication network, which enables the transfer of warning, health status and other critical information. The integration of SHM system in BIM models is a step forward in the management of infrastructures. The opportunity to visualize the detected damages in 3D models will improve the understanding and the decision-making processes for facility managers and will increase the resilience by reducing production interruptions and related economic losses. Furthermore, it is a useful tool to support rescue teams.

6 ACKNOWLEDGEMENTS

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