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A comprehensive workflow for digitizing and determining condition indicators for bridge and building construction

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ABSTRACT: This article describes a comprehensive workflow in several phases that integrates the latest information and communication technologies and enables significant improvements in the assessment of both our infrastructure structures, especially our bridge structures, and our building structures. For building construction, the workflow includes not only the PERIOD mode (= PM) for the normal situation, but also a so-called RESCUE mode (= RM), which provides significant support for emergency services in the event of natural disasters such as earthquakes. In all applications in infrastructure and building construction, a digital twin is created along the structural axis in Phase I and automatically converted into a BIM model (= BIM_{UAV}). The resulting BIM_{UAV} model forms the basis for documenting the general condition of the construction in Phase II, which is referred to as the level of maintenance (= LOM) and documented using component-specific damage catalogs. In both Phases I and II, autonomous multi-agent condition estimation for UAVs and innovative sensor technology (Lidar, GPS, UWB etc.) will be used, the application of which will be demonstrated on a specific bridge project. The anomalies represent performance indicators of the components or structure and are categorized according to component-specific damage catalogs, which also determine the respective degree of damage. The classification of anomalies into damage classes is automated using neural networks or AI. In the infrastructure sector, the algorithm in Phase III enables the asset management of bridge maintainers to conduct real-time condition analyses, service life predictions and estimates of the scope of upcoming refurbishment work using real monitoring data. In building construction, the archiving the LOM in the BIM model carried out in the PM in Phase II represents immense added value for the real estate. The rescue mode (RM) is specifically designed for emergency services and, based on simplified dynamic models in Phase III, enables rapid decision-making support for emergency services on site.

KEY WORDS: Monitoring for bridges and buildings, digital twins, BIM, drones, drone-sensor, condition assessment, level of maintenance, condition analysis, service life prediction and refurbishment.

1 GENERAL GUIDELINES

Improvements in information and communication technology like digitizing and the commitment to climate compatibility are leading to disruptive changes to our existing strategies in planning, construction and maintenance concepts as well. [1]
Building Information Modeling (BIM) and condition assessment using innovative sensors combined with innovative drone technology (UAV) have led to the disruptive improvements in structural inspection and thus the maintenance of our building constructions, both in the planning and construction process. The workflow described here for largely automated structural inspections in the future integrates the above-mentioned technological improvements for a comprehensive assessment of our existing buildings, both for bridge construction and building construction. This technology transfer in structural inspection helps us, above all, to utilize our existing resources more effectively and, above all, for longer, and in this kind is a significant contribution to climate compatibility in our construction world. The asset management of the bridge maintenance company, which focuses on the implementation and evaluation of structural inspections, is therefore the coordinated activity for the maintenance and therefore important for the national economic of every state.

Structural inspections for our existing buildings must be done regularly and are regulated by regulations, e.g., for buildings, by the ON-B1300 in [2] or by the state-specific building regulations in [3]. For our infrastructure structures, the type and scope of bridge inspections are regulated by the RVS guideline in [4]. The purpose of structural inspections of buildings and infrastructure is to document the level of maintenance (= LOM) of a structure throughout the service life and represents this data an important information with enormous national accounting. If natural disasters, such as earthquakes and explosions disaster as well, occur during a service life, the structural inspection is carried out in the so-called RESCUE mode (= RM). This allows on-site emergency services to receive a rapid, high-quality assessment of the stability of the supporting structure or parts of it. In the research project according to [5], the workflow 3D BUDI for the designated rescue mode was expanded and tested. The described workflow includes a continuous, digitally based structural inspection and, in Phase I, also enables the digitization of the existing building in the form of a BIM_{UAV} model. Digitization is also an essential prerequisite for sustainable construction, as the acquired dataset enables targeted improvements for the refurbish concept.
BIM (**B**uilding **I**nformation **M**odeling) has already established itself as a planning tool for new buildings, enabling a

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supporting, so-called "digital twin" to map all information about a building, from planning through construction to operation. What is new, however, is that the temporal degradation processes of the performance indicators that occur during a building's very long service life can be archived in the digital twin, thus ensuring that the building's condition is always available in real time and enabling meaningful condition analyses to be carried out at any time. The digital twin, in combination with the informations of the level of maintenance (LOM), therefore offers the possibility of efficiently performing service and load-bearing conditions in condition analyses using recalculations. If unexpected natural events occur during a building's service life, a digital model becomes even more essential, as the research project in [5] was able to confirm. Digital building models enable rapid and efficient structural assessments based on simplified dynamic models, as can be seen in section 4.1.

Digital models or BIM models, which contain beside geometric and material information all informations about the level of maintenance (LOM) from the structure, have the quality to provide qualified statements about reliability, the probability of failure, and ultimately the service life prediction using probabilistic methods. This makes it possible for the first time in structural inspection to conduct an assessment of structures based exclusively on an objective basis, as opposed to the previously mostly subjective assessment.

The information of level of maintenance (LOM) of our existing buildings comes with the highest design-level for BIM model and leads to enormous resource and CO2 savings. The informations only of geometry and material from digital model is therefore not insignificant for further refurbishment and replanning of the existing building. The BIM-modelling started in the design-phase with informations only of geometry and material (LOI = Level of information, LOG = Level of geometry) through the approval planning (LOC = level of concept) and ends, according to the current state of the art, after the construction of a building (LOD = level of development) in the as-built documentation (see also [6]).

For the BIM model, the documentation of the building's level of maintenance (LOM) thus achieves the highest level of maturity of a BIM model as well. The present workflow now makes it possible to automatically transfer the digital information on the level of maintenance into the digital twin (BIM model).

In bridge construction, the qualified review of a structure over time is carried out by Structural Health Monitoring (SHM) and is usually confronted with enormous amounts of data when evaluating the acquired data sets. Furthermore, the usual point cloud models created using the latest sensor technology do not routinely correspond to the standard of BIM model in all four BIM levels (LOI, LOG, LOC and LOD)

This workflow is implemented using drones are supported, which include autonomous multi-agent condition estimation according to [7] and can be controlled autonomously even in GPS-shielded areas. This drone technology is intended to make a significant contribution to the digitalization of our existing buildings in the future. In a first phase, the existing structures will be converted into a 3D BIM_{UAV} in level LOG as autonomously as possible, and in a second phase, their condition will be documented and archived to scale over time in the highest level of maintenance (LOM). A key component of the patent-pending workflow [8] is automated damage detection using neural networks, as has already been implemented, for example, for solid bridges in [9].

Ultimately, such improved BIM models including LOM, which have such a high maturity level, also enable detailed condition analyses and service life predictions via the structural assessment in the Phase III. Furthermore the intensity of the refurbish-work can be easily and precisely described.

The individual phases and tools of the workflow are briefly described below:

2 PHASE I: 3D BIM_{UAV} MODEL OF THE EXISTING STRUCTURE

A digital twin of the existing building with real geometric and physical properties is created in the form of a BIM model using autonomously controlled UAV equipment (multi-agent condition estimation with UAV) with special sensors. The BIM model created from the real dimensions and properties serves as the basis for real global structural models (global factor method according to [10]) in both modes, the PERIOD mode (PM) and the RESCUE mode (RM).

The feasibility of phase I was demonstrated on a test bridge building during the research project [10]. Seven sensors were used: UWB, Lidar, digital-camera, GPS, barometer, magnetometer and IMU.

The drones were localized using UWB, GPS and IMU sensors. Figure 1 shows the test bridge with the drone swarm (Fig. 1b) and the UAV equipment in the operational area (Fig. 1a).

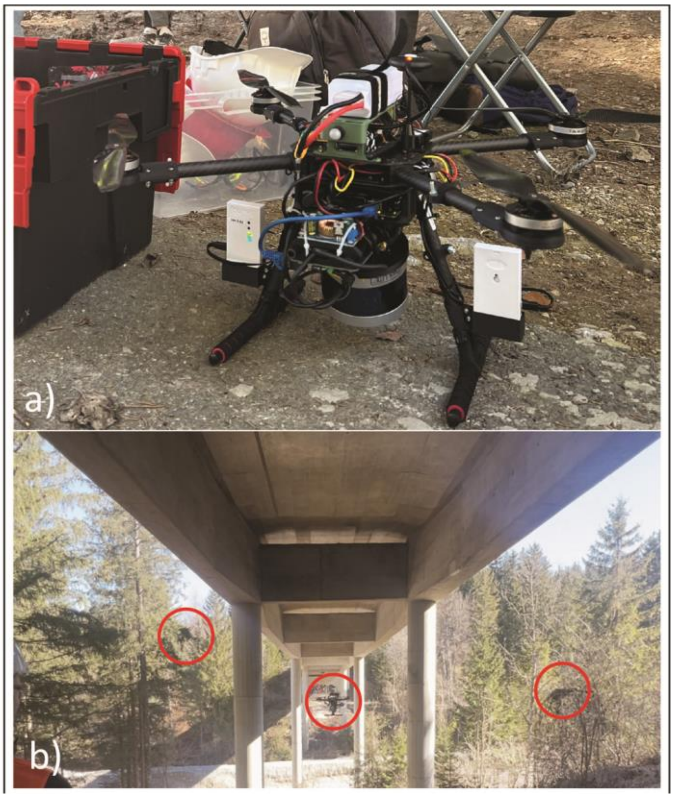

Figure 1. bridge-testing a) UAV with sensors, b) UAV swarm around the bridge in phase I

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2.1 Phase I for bridge constructions

The workflow in [8] envisions the control of autonomous UAV swarms along the bridge axis, which create point cloud ring models using innovative sensors Lidar and cameras. Ring models have the advantage over full point cloud models that they generate significantly smaller amounts of data, which must be generated into a network model in a second step. Cross-sections are generated from the network model, with initial tests (see Figure 1) already showing that very high levels of accuracy in cross-sectional geometry (precision 10^{-3} [m]) can be achieved from the mesh-models. The cross-sections generated in the third step are then transferred to the BIM_{UAV} model using commercial drawing software, e.g., Allplan software for bridge construction, in the fourth step.
Figure 2 illustrates the four work steps.

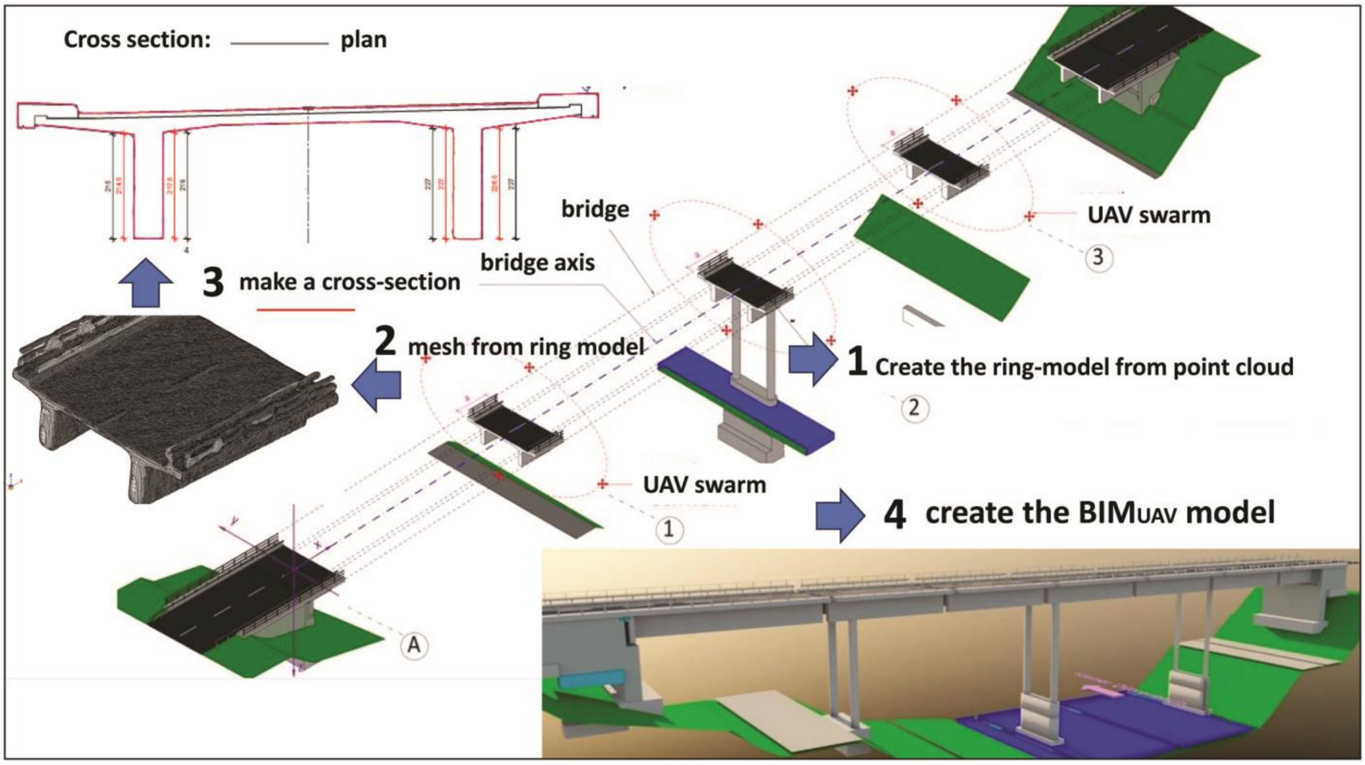

Figure 2. Four steps in phase I to create the BIM_{UAV} model for bridges

2.2 Phase I for building construction

In building construction, the workflow provides for the control of autonomous drone swarms along the vertical building axis, with the UAVs inside the building communicating with the UAVs on the exterior facade. As in bridge construction, point cloud ring models are used to create the BIM_{UAV} model. The level-by-level linearized floor plan cross-sections (precision 10^{-3} [m]) are transferred to the 3D BIM_{UAV} model of a conventional software program such as software from Allplan or Revit using special excel sheet interpreters.

The BIM models created with the algorithm are referred to as 3D BIM_{UAV} models.

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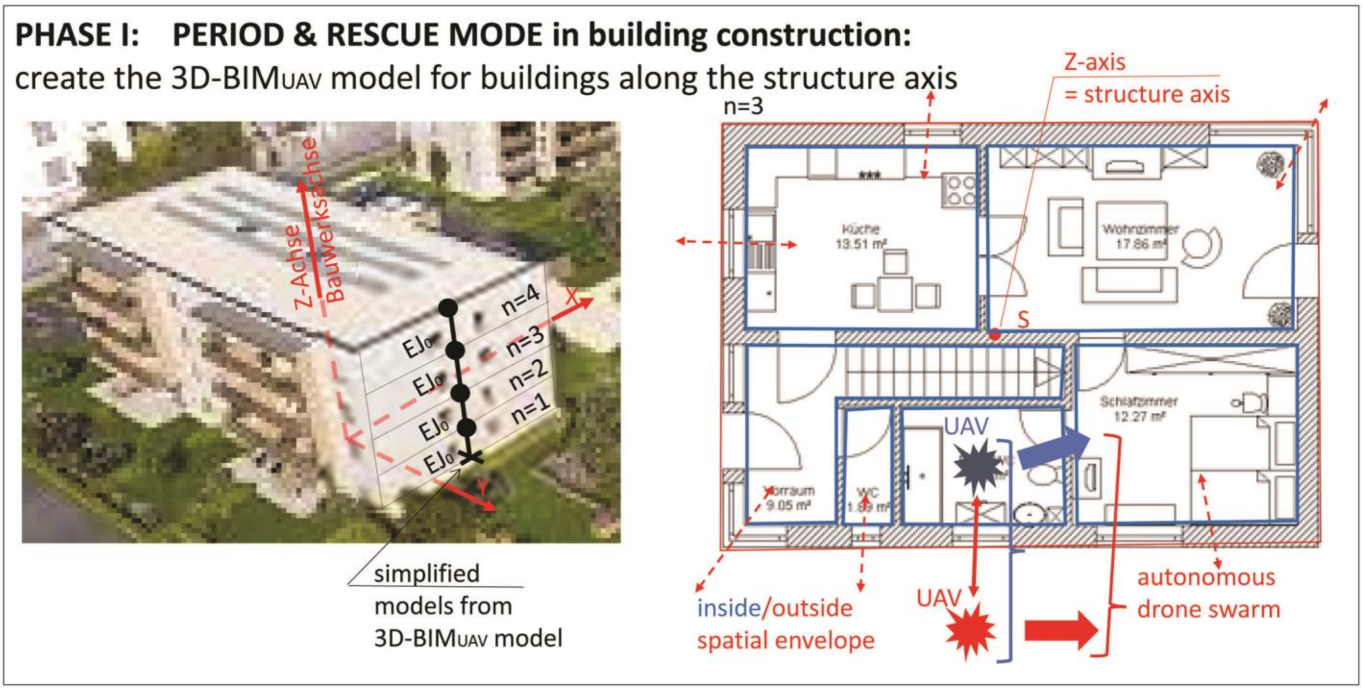

Figure 3. steps in phase I to create the BIMUAV model for building construction

3 DETERMINATION OF THE LEVEL OF MAINTENANCE IN PHASE II

For surveying the level of maintenance LOM the workflow using also autonomously controlled drones along a planned flight path, which can be created by the inspector in the BIM model. Damage classification like crack or spalling results the performance indicators by using AI and are summarized into a damage-catalog which based on special empirical values. The performance indicators classified by a damage-catalog are then graphically documented in the BIM model with simplified pictograms. But note that not every damage is also a performance indicator. This digitally records the level of maintenance of the construction and can be accessed at any time.

3.1 performance indicators of bridge constructions

In bridge construction, the inspector designed in asset management determines the inspection plan, which performance indicators on the individual components are subject to routine monitoring and which kind of damages are to be identified during the inspection, thus process defining the flight path in phase II of the autonomously controlled UAVs.
The point of interest in bridge construction represents the performance indicator (e.g., crack) on the main girder, as shown in Figure 4.

Automated damage detection using neural networks (AI), as in [9], classifies the performance indicator based on standardized damage catalogs separated by every modes – for Period mode (PM) and Rescue mode (RM) - and determines the degree of degradation of the performance indicator at the time of inspection.

Both the history and actual damages represented by performance indicator are recorded to scale on the surface of the BIM model for visual inspection.

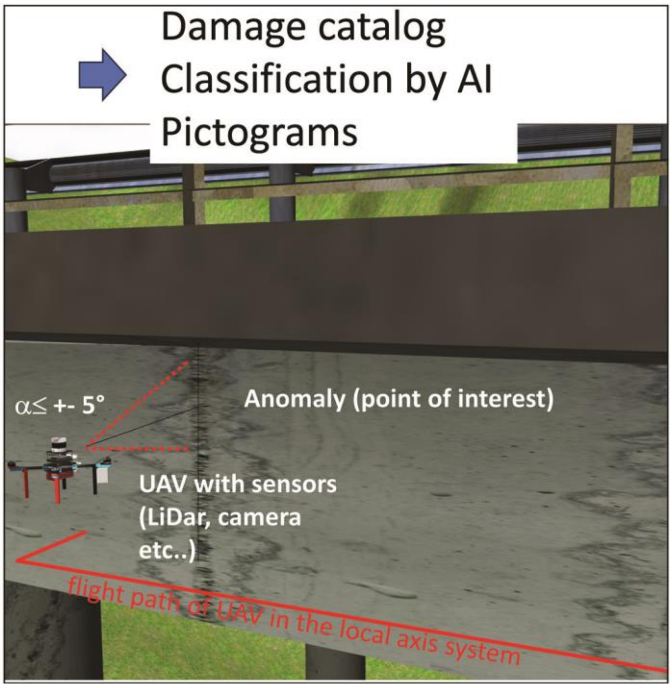

Figure 4. point of interest in phase II

3.2 Classification of damage and damage-catalogs for building constructions

During periodic structural inspections (PERIOD mode) in building construction, the inspection plan is usually implemented using a swarm of drones processed instead of

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individual drones. Individual drones are not sufficient to reach the point of interest inside the building. In building construction, the point of interest represents, for example, a component (e.g., wall panel, column, etc.) on each level.Images of this location are taken using innovative sensors, from which the material of the component can be determined and a damage classification can be carried out. With the help of the data set, automated damage classifications can also be carried out via neural networks and assigned to damage-catalogs. Separately defined damage-catalogs by material and component, such as those presented in [11] for the RESCUE mode (RM), enable an estimation of the stiffness reduction factors (EJ_{RB}) according to the respective type of load (bending)In RESCUE mode, severe damage or destroyed floor sections are often present, requiring not only consideration of stiffness reduction at the component level for each floor, but also global statements at the building level. In RESCUE mode, therefore, statements about the load-bearing capacity of individual components or floor levels, as well as statements about the overall stability of the building, are necessary. A total failure of
individual levels (the so-called soft-floor effect) is therefore also included in the structural assessmentOne added value provided by a complete 3D BIM model is undoubtedly the data archiving of the condition of the components or the entire building, which is done by recording the level of maintenance (LOM), certifies a highest level of maturity of the BIM model. The BIM model in PERIOD mode is enhanced with LOM to provide complete digital information on the condition of the individual components of the load-bearing structure, including their precise location, at the respective time of inspection. As already mentioned at the beginning, this enables a wide range of improvement options for the existing building with regard to renovation or refurbishment.

Figure 5 shows the damage classification sequence when a digital model of the existing structure is available in RESCUE mode.

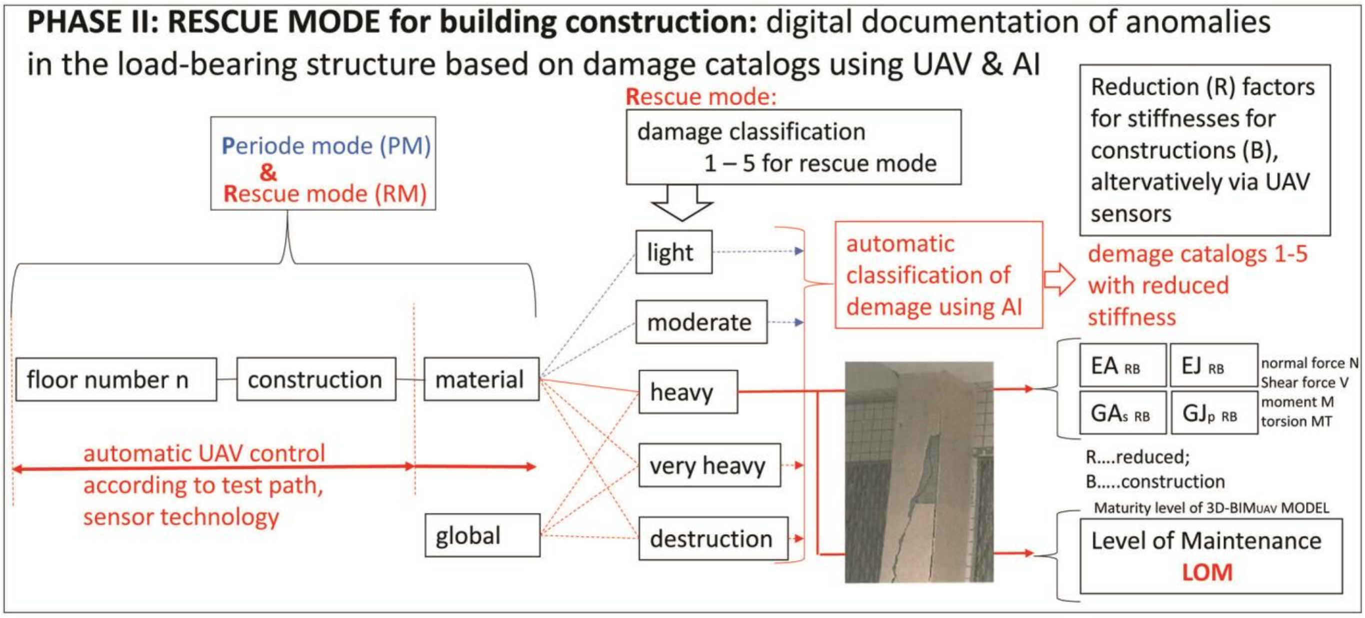

Figure 5. demage classification in phase II for the RESCUE mode (RM)

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4 MODEL-BASED STRUCTURAL ASSESSMENT IN PHASE III

The dataset derived from Phases I and II enables detailed condition analyses, remaining service life prediction and continuous updates of the cost of refurbishment.

Knowledge about the level of maintenance (LOM) of the key components of the existing structure over time and location, as well as their visual inspection in the BIM model, enables precise *condition analyses* regarding the causes of degradation and the future performance of the existing structure. Using the BIM model, different structural models can be generated for both modes, the period mode (PM) and rescue mode (RM), resulting in the following advantages:

Advantages of a perusal condition analysis in PM:

- Early detection of undesirable developments at the system level
- Early initiation of targeted improvements to extend the service life

Advantages of a perusal condition analysis in RM:

- Enable consolidated structural assessment for emergency services using simplified dynamic models

4.1 Condition analysis in phase III

A perusal structural assessment of the effects of local structural damage on the structural condition of the structure under consideration can be performed using traditional static analyses from FE models or using modal parameters according to [12]. Modal parameters, especially in RESCUE mode, has the advantage of providing a high-quality statement about changes to the structure due to damage. Furthermore, model updating can be enhanced with local dynamic test results, leading to highly meaningful results. In the simplified dynamic assessment, a simplified model is created from the 3D-BIM$_{UAV}$ model, in which the total of the story stiffnesses (EJo) is reduced to a single beam. Material, structure, and construction methods are subsumed into a single member stiffness for this beam. The advantage is that, even within the same construction methods of buildings or bridge types, only marginal differences in the responses arise, thus resulting in significant simplifications compared to conventional static analyses, especially for rapid deployment in the event of a disaster in RESCUE mode.

A comparison of the change patterns of the natural frequencies and mode shapes between the reference model and the model update, which leads to reduced component stiffness due to the damage, enables a qualified statement on the failure probability ρ_f of the supporting structure in the event of a disaster A corresponding demonstrator was successfully completed in [12] and is already fully operational

Since complete data sets regarding the level of maintenance (LOM) of our existing buildings and consequently, a structural assessment of our buildings and infrastructure are currently largely lacking, it would be useful to close this knowledge gap in the future through further research on digital structural testing and structural assessment.

Figure 6 shows the process of the simplified story stiffness calculation for dynamic models in RESCUE mode.

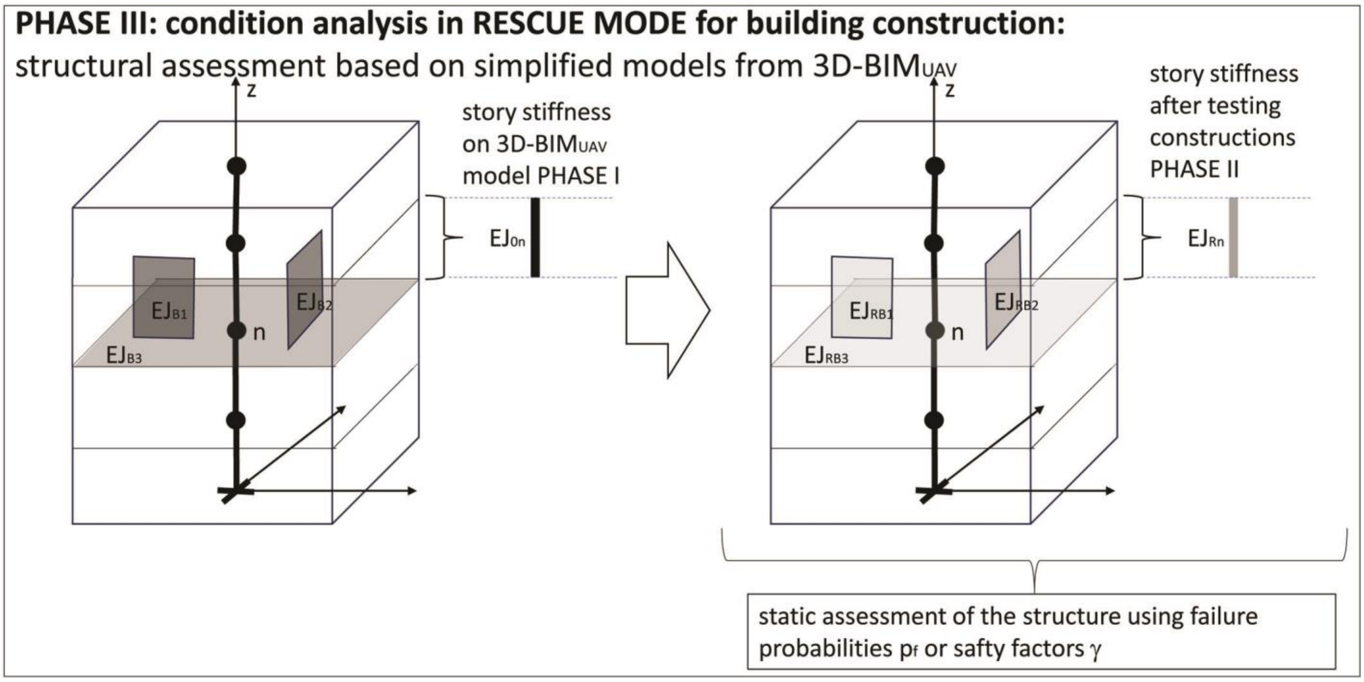

Figure 6. conditions analysis in phase III in RESCUE mode for building construction

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4.2 *Determination of the service life prediction using probabilistic methods*

The tool in 3D BUDI for determining the service life prediction of the structure uses the probabilistic assessment method based on performance indicators according to [10] to determine the reliability level β or the failure probability ρf. Through the time interval of regular monitoring established in the structural inspection, the performance indicators can be continuously updated with regard to the degree of degradation, and the corresponding safety index β value can thus always be determined and compared with the target reliability determined from the design. This results in qualitatively assessable statements about the service life prediction as well as statements about the maintenance and further intervention strategy.

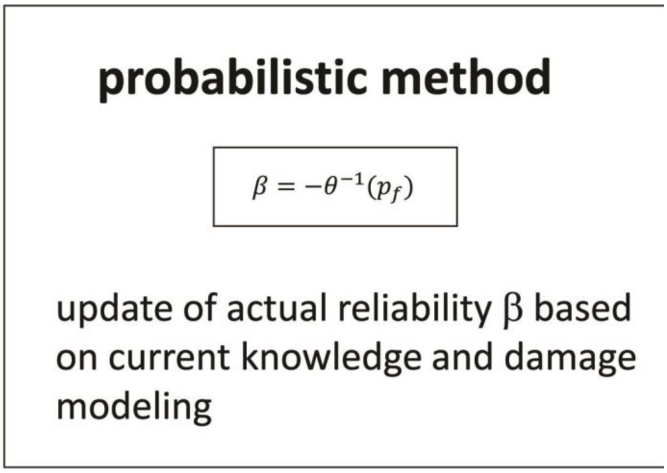

Figure 7. probabilistic method in phase III for service life prediction assessment

4.3 *Knowledge of the extent of rehabilitation in phase III*

The quantitative determination of the level of maintenance from phase II across the entire structure enables the determination of the overall scope of a planned refurbishment at the time of inspection, both in building construction and bridge construction. These data sets enable the building owner to continuously update the costs of refurbishment for the respective structure that may be derived from the state of preservation. This provides the client with a qualitatively assessable basis for decision-making for upcoming initiatives on the building.

Figure 8 schematically illustrates the potential of a bridge with a continuously updated state of preservation in terms of type and extent for future initiatives by the maintainer.

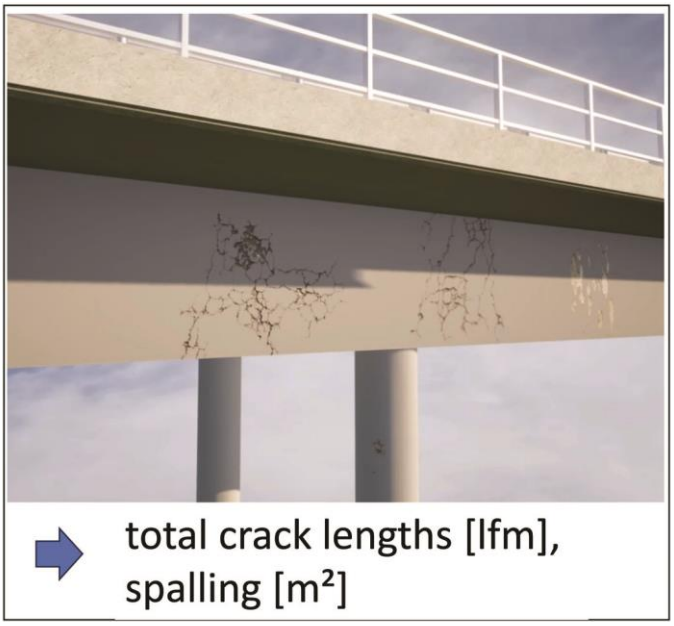

Figure 8. Automated determination of the rehabilitation scope from the LOM in phase III

In summary, it can be said that the present workflow 3D BUDI will enable clients to evaluate their existing buildings according to objective criteria and derive targeted arrangements from this. If we can preserve buildings longer through these measures, this will reduce our CO2 emissions, which arise from the nationally and globally construction industry, and thus make a significant contribution to climate neutrality and thus to our society.

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