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Building damage assessment in natural disasters: A trans- and interdisciplinary approach combining domain knowledge, 3D machine learning, and crowdsourcing☆

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ABSTRACT

Recent natural disasters have claimed many lives. Reliable damage predictions and timely assessments are essential for effective rescue operation planning and efficient allocation of limited resources. Currently, experts in the field perform damage assessment manually, which is resource- and time-intensive. To address this issue, we propose a general trans- and interdisciplinary concept that combines the strengths of domain knowledge, automated computational methods, and crowdsourcing. The objective is to provide relevant and timely damage information after a natural disaster. The specific implementation presented for the earthquake damage use case includes (1) the development of a set of novel, innovative methods, (2) their combination to obtain timely and reliable damage information, (3) fully defined interfaces between all components to ensure an automated data flow, (4) implementation as a fully open-source framework, and (5) the participation of end users in the development of the framework from the beginning, contributing their expertise. Compared to other existing individual solutions, our interdisciplinary implementation has shown to provide fast and accurate information in disaster situations, aiding the management of consequences and saving lives. We consider the implementation transferable to various types of natural hazards due to its open-source realisation and the flexibility of its modules and interfaces.

1. Introduction

Assessing damage caused by natural disasters has traditionally been a manual process, requiring significant time and resources from on-site experts. This can delay rescue and remediation efforts, which are most effective when initiated promptly. In addition, initial information on the extent of damage is often lacking, hindering the efficient allocation of resources [1]. If damage information is available, it is usually not made widely available and shared between rescue teams. Moreover, existing approaches to damage assessment typically focus on the development of individual damage assessment methods, neglecting the synergies of combining multiple methods from different disciplines into a comprehensive concept with defined interfaces [2]. Finally, to ensure the provided information supports local rescue teams in the best possible way, it is necessary to continuously integrate the knowledge of stakeholders and end users in the development of such a concept [3,4]. Successful development and application of useful research approaches can only be achieved by involving end users, strengthening the role of non-academic participants, and bridging the gap between knowledge at different levels and institutions. Such transdisciplinary frameworks [5,6] enable scientists and stakeholders to work together in co-design, with results benefiting both research and practice. As demonstrated for the use case of the viability of public spaces in cities under increasing heat [7] transdisciplinary research designs, which involve end users and

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stakeholders from the beginning can effectively integrate their expertise into the developed framework and increase its acceptance in practical application.

To address this issue, open-source interdisciplinary and transdisciplinary approaches are needed. These approaches should combine available methods from different disciplines to enable rapid and accurate assessment of the damage situation following a natural disaster. This will enable rescue teams to take informed action and manage human and material resources effectively. In this contribution, we therefore present our developed inter- and transdisciplinary concept for damage assessment after a natural disaster. We then demonstrate its implementation for the earthquake use case.

We present a new trans- and interdisciplinary concept (Fig. 1), which is designed to combine the strengths of domain knowledge, automated computational methods, and crowdsourcing for timely and reliable damage assessment. Stakeholders and end users are involved in the development of the framework from the outset, contributing their knowledge and expertise. The concept is designed to be iteratively modified to meet their needs and facilitate easy usage in emergencies. Current approaches to damage assessment often concentrate on developing individual methods for single steps of a workflow. However, we propose combining multiple methods from different disciplines into a new comprehensive concept with defined interfaces to improve the accuracy of damage assessment.

The trans- and interdisciplinary concept (Fig. 1), applicable to different types of natural disasters, comprises two main steps for the assessment of damage: In the first hours after the event, an initial and timely overall assessment of the damage is required. Therefore, as a first step, numerical approaches calculate damage estimates based on natural disaster parameters as well as building characteristics and vulnerability. This damage calculation is followed by a classification of damage after the event once newly acquired damage data is available. This is realised through an integrated interdisciplinary set of approaches: Automatic approaches for 3D/4D point cloud analysis are combined with crowdsourcing approaches for visual image interpretation to retrieve an improved assessment of damage. Both approaches integrate engineering domain knowledge as decision basis for the classification of the target damage grades. This general concept is designed to integrate a multitude of complementary methods for damage assessment and can be applied to different types of natural disasters.

In the following, we present the implementation of the earthquake damage assessment concept. In the recent past, earthquakes such as those in L'Aquila (Italy, 2009), Nurdagi (Turkey, 2023), and Al Haouz (Morocco, 2023) [8] have caused numerous fatalities and severe damage to infrastructure. Predicting, preventing, and managing earthquake damage remains a challenge for the future. Reliable predictions and estimates of earthquake damage and the seismic behaviour of buildings play a critical role in seismic risk analysis. In the aftermath of an earthquake, a timely and reliable damage assessment is essential for the effective planning of rescue and evacuation operations and the efficient allocation of limited human and material resources. In addition, accurate damage classification is important for assessing stability and identifying deficiencies that play an important role in aftershocks and subsequent earthquakes [9,10]. Furthermore, the classified damage can be used to investigate the relationship between the damage, the infrastructure behaviour and seismic design parameters to improve seismic codes [11,12].

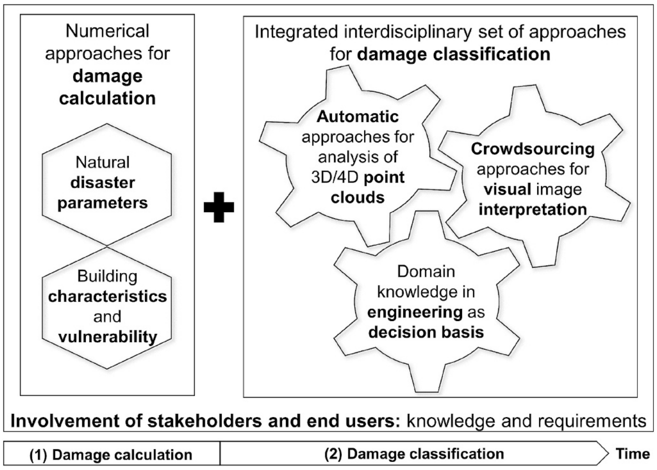

Fig. 1. General trans- and interdisciplinary concept for damage calculation and classification after a natural disaster to provide timely, reliable, and detailed information on building damage and to allow targeted use of limited human and material resources.

The use of fragility curves [13–17] is a common method for estimating building damage. Fragility functions describe the probability of exceeding a damage state level for a given structure and an earthquake intensity measure. By utilizing fragility functions for generalised building classes [18,19] and the experienced earthquake ground motions, it is possible to rapidly calculate an initial estimate of the expected building damage shortly after the event. The next step is the damage classification based on the newly collected building damage data. A fast way to provide information about severe damage is the analysis of 3D point clouds such as those obtained from photogrammetry or LiDAR (Light Detection and Ranging) using automated approaches [20]. Assessing different damage grades beyond binary damage detection (damage versus no damage) is challenging due to the wide variety of possible damage characteristics and the need for clear differentiation between damage grades [2]. In addition, crowdsourcing can be used by involving volunteers to interpret the damage using remote sensing data. The human ability to scan large areas as well as to detect and evaluate details can aid the classification of damage for all damage grades [21]. The decision basis and logic for damage classification are provided by engineering domain knowledge. The decision rule base must provide detailed and differentiated information about the damage grades to be applied to both automated and crowdsourced approaches [22,23].

The application of the general concept to the case of earthquake damage was developed in the research project "LOKI – Luftgestützte Observation Kritischer Infrastrukturen" (Airborne Assessment of Critical Infrastructures) [3,24]. The resulting open-source software of our LOKI framework is openly available [25,26]. The unique LOKI framework aims to provide an efficient and timely assessment of damage, improve the reliability of the damage information, target existing resources and emergency forces, enable timely remediation actions, and reduce longer-term damage after an earthquake. Our trans- and interdisciplinary approach includes (1) the development of a set of novel approaches and methods as components that make a significant contribution to research within and across disciplines, (2) the use of the combination of methods to achieve the relevant results, (3) fully defined interfaces between all components for data flow from acquisition to analysis, (4) implementation as a fully open and accessible framework, and (5) the participation of stakeholders and end users in the development of the framework. The individual methods were tested using earthquake damage data in the form of images and point clouds from several former European earthquakes. To assess the data flow from acquisition to analysis, the entire implementation with defined interfaces between all components was tested with data from a German test site for rescue and relief training. The results of our inter- and transdisciplinary implementation have demonstrated the ability to provide rapid and accurate information in disaster situations, thereby helping to manage the consequences and saving lives. The following section explains the details of our trans- and interdisciplinary approach.

2. Concept of an integrated interdisciplinary earthquake damage assessment

We have translated the general concept (Fig. 1) for the earthquake use case into a specific implementation (Fig. 2).

In the first step (1), an expected damage distribution in the affected area based on fragility functions and earthquake parameters is calculated (Fig. 2). This provides timely information in the first hours after the earthquake, which is crucial for supporting immediate rescue operations. Fragility functions for different building classes can be developed in advance. Once the specific seismic parameters of the current event are known, the estimation of damage can be achieved through the use of available building information. This damage calculation provides an initial estimate of the damage distribution. It helps to identify areas that may have severe damage before more precise information becomes available. The calculation can also serve as the starting point for the first UAV flights, for example, to survey areas with high damage. To enhance damage assessment, uncrewed aerial vehicles (UAVs) are deployed to capture images of both the entire area and specific buildings during both overview and detailed flights. The data collected by these UAVs, in the form of imagery and 3D point clouds, in conjunction with damage catalogues as a decision basis, constitute the input for the second step (2). Damage catalogues support the damage classification into various damage grades considering different building materials. These catalogues encompass both material-specific and global characteristics, comprising detailed descriptions, specific threshold values, and illustrative images. They serve as decision basis and integrate domain knowledge in the process of damage classification. This subsequent step entails damage classification to support long-term rescue measures such as emergency shelters and assessment of stability and repair or demolition measures. The data analysis consists of two stages: binary damage detection, which distinguishes damage and no damage, and damage classification, which categorises buildings into five damage grades. To achieve this, our approach combines the strength of fast and objective automatic machine learning-based approaches with crowdsourcing approaches using the power of human interpretation in micro-mapping tasks.

The following sequence of events is both temporally and conceptually feasible: Based on areas identified as having potentially high damage, as determined by the initial damage calculation with fragility functions, UAV overview flights are initiated. The data collected in these missions is used in automatic machine learning approaches for damage detection, providing a binary distinction between the presence or absence of damage. Pre-defined or user-defined buildings with damage and/or significance are captured during detailed UAV flights. This is the basis for the subsequent damage classification into five damage grades using automated approaches. Instances, where images or buildings are classified with low accuracy, are subject to further evaluation through a crowdsourcing approach. Volunteers classify the damage in a series of simple micro-mapping tasks for both binary damage detection and damage analysis into five damage grades. This information can be used as further training data to enhance the efficacy of automated machine learning models. Images posing challenges to the classification by volunteers are forwarded to experts for further evaluation. With the help of volunteers, the work of the experts is significantly reduced to difficult and special cases only. Both classification methods require the integration of earthquake engineering knowledge of damage grades into the innovative methods of automated 3D point cloud analysis and crowdsourcing. This is realised through the strong coupling of these methods with damage catalogues as decision basis for the classification tasks.

In our conceptual framework, both the quantity and quality of damage-related information increases over time. New information derived from the analysed UAV data and the outcomes of damage classification iteratively enhance the ability to support local rescue teams with damage information. All information on the damage situation, such as damage calculations, UAV data, and classification results, is made available to the operational management and rescue forces throughout the whole process. This enables them to strategically and effectively plan their missions based on up-to-date information. It also facilitates the prioritisation of specific areas and buildings for UAV flights and damage classification. The engagement of stakeholders and end users has been crucial in the development of the framework, with their knowledge and requirements ensuring that the developed methodologies are suitable for integration into operational use. Stakeholders and end users were involved in the development right from the beginning through meetings, surveys, and interviews. Follow-up meetings served as a platform to present and discuss the framework and components adjusted in response to their input. Moreover, they actively participated in pilot studies involving various components, such as the web-based micro-mapping. In a final workshop, the development status of the prototype within the LOKI framework was discussed and both short and long-term perspectives for the future development of the framework and the integration of modules into end user systems were identified.

The integration and combination of complementary methods and knowledge from different disciplines mitigates limitations inherent to

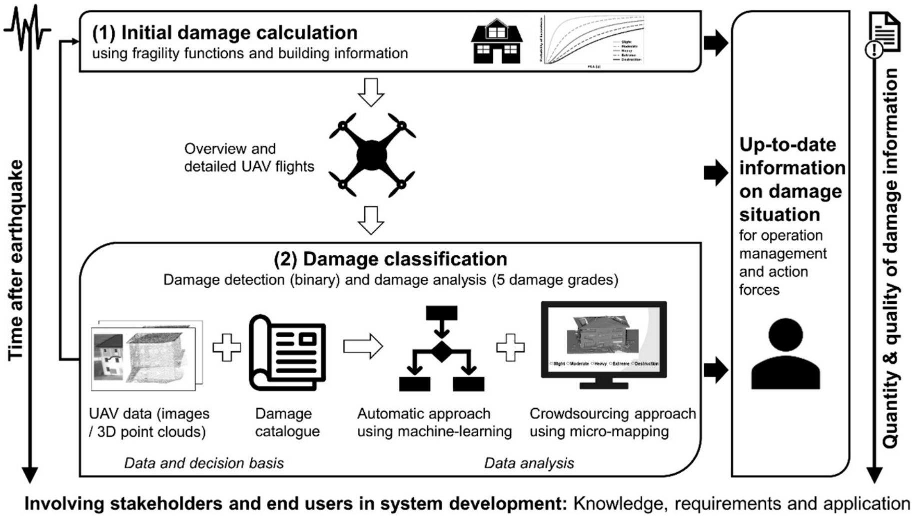

Fig. 2. Specific implementation of the trans- and interdisciplinary approach for the earthquake damage use case, providing building damage information based on computation and classification by combining different methods.

individual methods and improves the reliability of provided up-to-date damage information. The damage distribution calculation is fast and the fragility functions can be established before the earthquake event. The results are based on certain assumptions, however, and are generalised to building classes rather than specific buildings. Increased accuracy in damage classification can be attained through the analysis of real damage data. For this task, UAVs provide fast, objective, and detailed data from multiple perspectives. Analysing these data, automated damage assessment using machine learning can provide rapid damage information. While small damages such as cracks are not resolved in UAV point clouds, the human eye is able to interpret details and small damage albeit with more time needed for the classification. The involvement of a large group of volunteers significantly reduces the time required and relieves experts at the same time. The combination of both automatic and crowdsourcing approaches therefore enables the classification of both minor and major damage. Nonetheless, it remains indispensable to couple these classification approaches with a formalized decision basis for damage classification provided by earthquake engineering. Only by including a well-defined engineering framework based on a good understanding of damage along with its associated patterns and distinctive characteristics, the framework can provide adequate support for rescue operations and structural integrity assessment of buildings.

Finally, the implementation as a fully open-source framework offers many advantages, such as (1) interoperability through open standards and interfaces, (2) greater openness for innovation and extension through new modules and methods, (3) open to community involvement and contributions from users, which allows user feedback and better and faster identification of problems, (4) transparency of functionality, which increases acceptance in end user communities, (5) no licence fees and thus wider applicability in end user communities, (6) no dependencies on proprietary software and manufacturers, and (7) the inclusion of authorities in vulnerable regions with few resources.

3. Proof-of-concept implementation: Methods, interfaces and outcomes

Trans- and interdisciplinary projects typically involve several research groups from different disciplines and incorporate input from end users. Our approach combines interdisciplinarity scientific expertise in geographic information systems, 3D/4D point cloud analysis, crowdsourcing, and earthquake engineering and their respective methods, complemented by practical experience in dealing with natural disasters. This interdisciplinary synergy allows for the development of applications for innovative theoretical methods, as well as for the possibility of bringing expert knowledge into the application by means of innovative methods. A comprehensive description of our research approach is outlined below, focusing on the interaction of the individual methods and the resulting outcomes. The corresponding cited papers provide the in-depth methodology for the approaches. The interfaces connecting the components are fully defined ensuring the exchange of collected data and extracted damage information. The whole framework with all components is open-source [25]. Furthermore, an extensive wiki resource provides both a general project overview and detailed information on the developed components, interfaces, and results of the project, including publications, source code, and data [26].

3.1. *Initial damage calculation using fragility functions*

In the first step, the initial damage calculation rapidly provides area-wide information on the expected building damage as a starting point for UAV flights and subsequent damage classification. This damage distribution is calculated based on the earthquake parameters and the vulnerability of the buildings contained in fragility functions. Fragility functions are a commonly used tool for modelling seismic risk and loss by describing the probability that a damage grade will be exceeded for a given structure and intensity measure [13–17].

Kohns et al. [27] propose a multiscale approach to derive fragility functions for reinforced concrete (RC) structures based on different numerical damage criteria for five damage grades ranging from slight to destruction. The general concept of our approach is material independent. It can be applied or extended, for example, to masonry and reinforced concrete frames with masonry infills, and it can consider the appropriate material-specific and global criteria. In addition, the approach can be adapted to different building classes, as well as to regionally specific characteristics of material properties, construction types and systems. The universality of the approach offers a wide range of possible applications.

This multiscale approach correlates observed damage patterns due to foreign earthquakes, included in the damage catalogues (Section 3.2.1), with the seismic response of the building through thresholds for material-specific and global characteristics at the material, section, and building scales. The five damage grades are associated with several damage criteria, such as strains, strengths, and deformations with their defined limits (Table 1). The number of elements with criteria exceeded and the distribution within the structural elements are relevant, as the first occurrence does not always lead to the damage grade. With the new approach, damage that does not show up as strength degradation on the pushover curve (representing the global seismic behaviour through a relationship between the total force and the displacement of the building) can be detected by material-specific criteria and can be taken into account in the setting of damage thresholds. This approach attempts to consider different possible damage patterns at different scales more comprehensively than the well-known displacement criteria approach [13,16]. The derived displacement values that are associated with the damage grades form the basis for the development of the fragility functions as cumulative lognormal distributions.

In [27], the determination of the pushover curves, the definition of the displacement limits for the damage grades, and the derivation of the fragility functions are shown for a reinforced concrete frame structure as an example. Fig. 3 shows the fragility functions for the five damage grades for the example RC frame building.

Comparisons with other studies show that the damage thresholds and spectral displacements are similar to those found in the literature [27]. Comparisons with existing fragility functions demonstrate that the developed fragility functions are mostly in the middle range, both graphically and for the curve parameters [27]. It should be noted that for general building classes, numerous simulations are required for different material properties, reinforcement ratios and arrangements, section dimensions, and different directions, resulting in higher standard deviations. It is shown that the developed approach achieves fitting and useful results despite differences due to different modelling and analysis approaches, different damage thresholds, influencing parameters, and assumptions.

Table 1
Example of material-specific damage criteria and limits for a reinforced concrete building [27].

Damage Criterion	Threshold
(a) Concrete tensile strength	$\varepsilon_{ct} = f_{ctm}/E_c$
(b) Spalling concrete cover (unconfined concrete)	$\varepsilon_{csp} = -0.0025$
(c) Cracks concrete core (confined concrete)	$\varepsilon_c = -0.01$
(d) Yielding reinforcing steel	$\varepsilon_{sy} = +0.002$
(e) Failure reinforcing steel	$\varepsilon_u = 3/8 * \varepsilon_{uk}$
(f) Cracking curvature	$\varphi_c = \varepsilon_c/x$
(g) Yield curvature	$\varphi_y = (1.75 * f_{yk})/(E_s * h)$
(h) Chord rotation at yielding	EN 1998–3 (A.10a)/(A.11a)
(i) Chord rotation capacity	EN 1998–3 (A.1)
(j) Shear strength	EN 1998–3 (A.12)

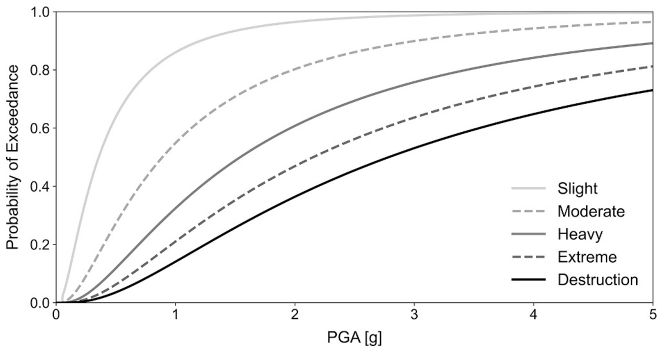

Fig. 3. Fragility functions for five damage grades for a reinforced concrete frame building [27].

3.2. Damage classification

Damage classification constitutes the second step within our integrated interdisciplinary earthquake damage assessment (Fig. 2). Damage classification requires UAV data, such as RGB images and 3D point clouds, and the damage catalogue as decision base as input. Based on these, building damage is assessed through a combination of automated and crowdsourcing approaches in terms of binary damage detection and multi-target classification into five damage grades.

3.2.1. Damage catalogues as decision basis and logic

A systematic assessment and accurate classification of damage is essential to save lives and to support long-term rescue operations such as emergency sheltering, stability assessment, and repair or demolition of buildings. The damage catalogues have been developed as decision basis and logic for damage classification based on UAV data from outside the building. The damage catalogues provide information on the damage grades, indicating which types of damage correspond to each grade. The classification model and volunteers require knowledge of damage characteristics associated with each damage grade. Damage catalogues can also be used for systematic damage classification by experts in the field. These catalogues include a formalized description of generic damage patterns and unique damage features to be extracted in the automatic damage classification (Section 3.2.2). Moreover, they are utilized in the design of instructive tutorials and classification tasks for volunteers in crowdsourcing approaches (Section 3.2.3).

Kohns et al. [22,23] developed damage catalogues for five damage grades for different materials, based on various information to assess earthquake damage characteristics. This information includes damage scales [28–34], damage inspection forms [28,29,31,32], damage documentations [8,35], standards, codes, and guidelines [34,36–39] as well as experimental investigations [40–42]. This component aims to provide clear and generally applicable, comprehensive, and unambiguous damage catalogues for buildings. To achieve a differentiated and as precise as possible classification, five specific damage grades have been chosen. The higher the number of damage grades, the more differentiated the classification can be. However, the differentiation between the grades is more complex as the damage grade characteristics must be unique for each damage grade. As visible damage is assessed, the damage patterns are generalised and independent of the structural system. The damage catalogues are transferable to other geographical regions if the building materials are similar. Furthermore, the damage catalogue concept is transferable to other building types, e.g. special wood-clay buildings.

The developed damage catalogues [22,23] distinguish five damage grades for a detailed classification: (1) Slight damage, (2) Moderate damage, (3) Heavy damage (4) Extreme damage, and (5) Destruction. Both global and material-specific damage patterns and characteristics are described for these damage grades. The structure of the damage catalogues for the low damage grades (1)–(3) is largely determined by material-specific damage characteristics, whereas for the high damage grades (4)–(5) the global behaviour of the whole building is decisive (Fig. 4). A distinction is made between structural and non-structural elements, and possible damage mechanisms are specified for each element. Features and characteristics in terms of size, distribution, and extent characterise the damage according to the damage grade, with crack width thresholds playing a critical role in clearly delineating the low damage grades.

With the subsequent methods for damage classification, but also in the case of visual observation on-site, there are special challenges [22]. The building material and the load-bearing structure are often not directly visible from the outside. Therefore, especially in the case of low damage grades, the cracks and spalling visible on the surface are used as an indication of the damage, whereby the assessment is chosen to match the actual deterioration of the load-bearing structure. Moreover, the differentiation between structural and non-structural elements and thus the correct classification of the associated damage is a challenge. Furthermore, cracks and damage that already existed before the earthquake must be taken into account. After the earthquake, these damages are classified, regardless of whether they occurred during this event or another event since the actual condition after this earthquake is assessed for rescue measures and stability. In the case of uncertain classification, the more conservative damage grade should be chosen. However, solutions should first be sought to achieve a classification that is as realistic as possible, especially to prevent a conservative assessment of the building in the long term. It is also important what data and methods are used to assess the damage. For damage classification based solely on UAV imagery, the damage patterns described in the damage catalogues must be visually or geometrically derivable from the data and visible from the outside. There needs to be a unique set of damage characteristics to differentiate between the five damage grades.

3.2.2. Automatic approach for 3D data analysis using machine learning

Automatic building damage assessment using machine learning serves the purpose of detecting and analysing building damage in the damage classification step. It makes use of typical damage characteristics defined in the damage catalogues (Section 3.2.1) to determine the target damage grades from UAV point clouds. Moreover, the automatic approach is closely linked to the crowdsourcing component (Section 3.2.3), as both components complement each other in the fast and accurate assessment of multiple damage grades at different spatial scales.

Automatic building damage assessment based on the analysis of 3D point clouds is capable of delivering fast and objective information on the damage situation within a matter of hours [20]. UAV-borne acquisition strategies thereby can provide dense 3D representations of the scene with point spacings down to a few centimetres [43,44]. Moreover, they can facilitate the capture of urban quarters and entire cities in high detail within reasonable time frames (a few hours). This enables damage classification at the scale of individual building components, a crucial aspect for identifying damage patterns indicative of higher damage grades. A comprehensive assessment of multiple damage grades improves the allocation of resources and assists in evaluating the structural stability of buildings and repair measures, as building damage can be of various types and severity.

The assessment of different damage grades, beyond binary damage detection, presents a huge challenge due to the considerable diversity of possible damage characteristics [44]. Moreover, the transferability of methods developed for a specific study site to other geographic regions is often limited, particularly for state-of-the-art machine learning classifiers [2].

Zahs et al. [43] therefore present a method for classifying damage grades with supervised machine learning employing a random forest (RF) classifier, which is trained on simulated point clouds from virtual laser scanning (VLS) (Fig. 5). Damages are assessed per building based on geometric change between pre-event and post-event point clouds.

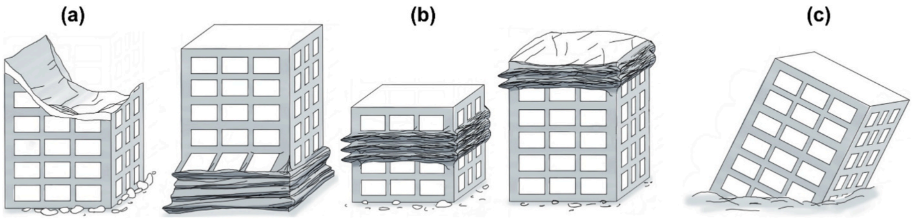

Fig. 4. Examples of global damage patterns for extreme damage: (a) inclined plane due to collapse of structural elements on one side, (b) pancake collapse of one or more floors (bottom/middle/top), and (c) inclination of the whole building.

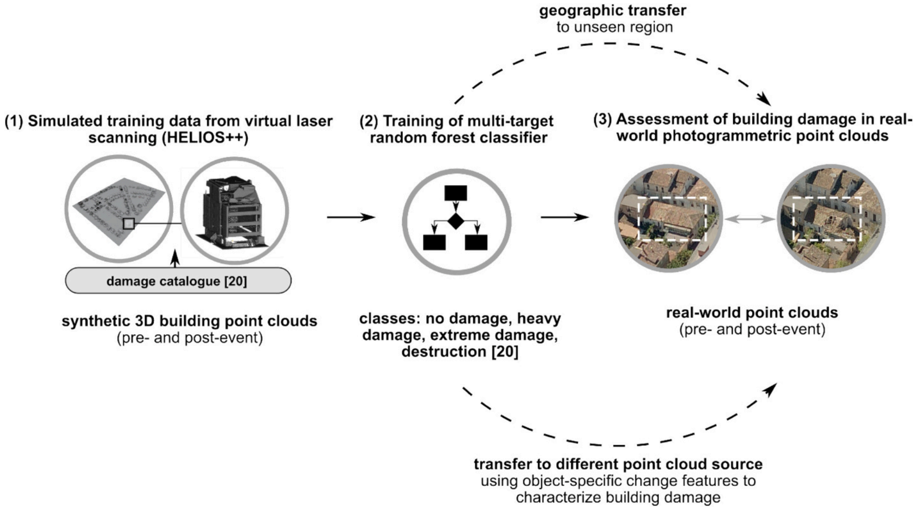

Fig. 5. Overview of the approach to classify building damage using a machine learning model trained on simulated laser scanning point clouds.

The RF model is trained using simulated point clouds from VLS [45], which incorporate known properties from labelled 3D input scenes. In the event of an earthquake, training on simulated data can save valuable time as pre-trained classifiers can directly be applied to assess damage in event-specific real-world datasets without time-consuming labelling and training with event-specific data [43]. Well-informed modelling of damage patterns in the artificial 3D input scenes is thereby essential for the accurate representation of damage in the simulated point clouds. Therefore, domain knowledge in earthquake engineering is integrated into the modelling process to ensure that our training data covers the full spectrum of damage patterns expected in the real-world dataset. More specifically, for each target damage grade (heavy damage, extreme damage, destruction), the damage catalogues presented in [22] (Section 3.2.1) are used to introduce typical damage patterns into 3D building models of the virtual scenes in the generation of simulated point clouds. In this context, the damage catalogues serve as an interface bridging engineering expertise and automatic algorithms for 3D data analysis.

Our interdisciplinary approach shows that the classification of multiple damage grades in the real-world dataset yields high levels of damage classification accuracies, with overall accuracies ranging from 92 % to 95 %. The introduction of real-world region-specific training data improves only slightly the accuracy by approximately 2 % when compared to using VLS data instead. Comparable outcomes are achieved for the binary case of detecting damaged buildings: The classifier trained on generic simulated training data detects 85 % of damaged buildings with the use of real-world region-specific data resulting only in a minor improvement of the detection rate by 3.1 %. [43].

3.2.3. *Crowdsourcing approach for data analysis using micro-mapping*

While automatic damage classification (Section 3.2.2) approaches enable an objective and fast analysis of large UAV data, the ability of humans to visually interpret details in the data can be used as (1) validation of the automatic classification and (2) alternative method where the automatic approach shows high levels of uncertainty. Therefore, we propose web-based crowdsourcing as a complementary method for the assessment of structural building damage after an earthquake event. The damage catalogues (Section 3.2.1) describing the characteristics of the target damage grades are the basis for an instructive tutorial and the design of classification tasks. Our web-based approach applies to different types of tasks and damages.

Data on damaged and destroyed buildings has been collected by thousands of volunteers and used for disaster management several times after natural disasters [46–48]. However, crowdsourcing approaches for remote mapping face the following major challenges [49]: (1) Breaking the overall task down into individual components (micro-tasks) which are easy to solve by volunteers within seconds [50], (2) organizing a large group of people to contribute, (3) combining and aggregating the individual contributions into a coherent overall result, and (4) dealing with the heterogeneity of user-generated geodata in terms of quality and level of detail. Moreover, adequate training material needs to be developed to assist volunteers in solving more complex tasks.

In the LOKI research project [3,24], we investigated these challenges and developed a web-based crowdsourcing approach [51] for the image-based detection and classification of structural building damage after an earthquake. Damage analysis is based on (1) overview and detailed UAV images of the affected area and (2) the criteria for the assessment of multiple damage grades developed in the damage catalogues by Kohns et al. [22] (Section 3.2.1).

According to the multi-level data acquisition and damage assessment process, the classification of damage in the developed web-based approach comprises two task types: (1) damage detection (damage versus no damage) using overview UAV images and (2) detailed damage identification into five damage grades (slight, moderate, heavy, extreme, destruction) using detailed UAV images (Fig. 6). Thereby, one

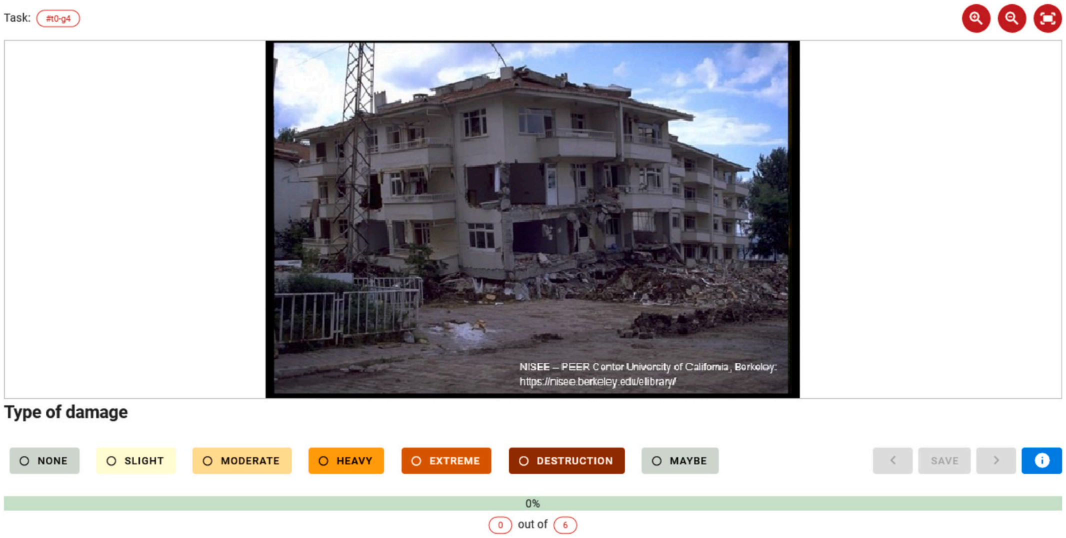

Fig. 6. Example of multi-class damage classification using the web-based crowdsourcing approach [51].

building might be represented by multiple images that are assessed separately, i.e. in separate micro-mapping tasks. The developed web-based crowdsourcing approach [51] enables the collection, organization and post-processing of a large quantity of UAV images in its database, even by non-expert users. To help distinguish between the different damage grades, a comprehensive tutorial (in two languages) has been developed to support volunteers in solving the micro-mapping tasks. The tutorial starts with an overview of the five damage grades to integrate all previous levels of knowledge. This is followed by a specific section for each damage grade showing the different damage patterns and characteristics depending on the building material. In addition, images of different crack widths are presented for the lower damage grades. The structure of the tutorial addresses the challenge of creating small and easy tasks for all participants while ensuring an accurate damage assessment from an earthquake engineering perspective.

Building-specific damage grades from the per-image damage assessment in micro-mapping tasks are derived through the aggregation of damage grades of all images representing the same building.

The tool was tested with diverse user groups of varied backgrounds and expertise levels in the field of earthquake response such as the German Red Cross, Federal Agency for Technical Relief, and local authorities. We evaluated the classification accuracy for each target damage grade using expert-based reference data. Our results indicate that low damage grades (slight damage) and high damage grades (extreme damage and destruction) are classified with high accuracy by all user groups. Difficulties in the correct classification occurred for moderate and heavy damage due to ambiguities in the recognition and interpretation of damage patterns in the shown images. For these damage grades, however, it is still possible to derive a damage range, which has been found to be useful information for rescue teams. Hence, the crowdsourcing approach provides a valuable tool for the assessment of structural building damage especially for buildings with slight or moderate damage, which are difficult to classify in the automatic approach (Section 3.2.2). In addition, the tool and the tutorial were evaluated using a questionnaire-based method for evaluating participatory methods according to Ballatore et al. [52]. Through regular feedback, the web-based approach could be iteratively optimised and adapted to the needs of the end users. An important point is the creation of simple micro-tasks [50]. The web-based crowdsourcing approach developed is considered to be a simple and accessible tool. Users only need a notebook or smartphone and register once. They can then solve tasks independently of time and place.

4. Discussion

With the proposed framework for damage assessment, we have demonstrated the substantial benefits of integrating complementary methods and expertise from different scientific disciplines. This collaborative approach considerably improves the timeliness and reliability of damage information, thereby providing support to rescue teams during natural disasters. The results achieved by the newly developed components make significant scientific contributions to their fields, while at the same time enhancing damage assessment strategies through their combination with each other within the comprehensive framework using fully defined interfaces.

In an early phase, our framework integrates the developed fragility functions [27] to rapidly determine the probable distribution of damage. Related vulnerability functions can provide information on economic and human losses [13,16,53]. Our multiscale approach, which uses damage criteria at different scales to relate all observed damage patterns to the seismic response of the building, considers different possible damage patterns at different scales more comprehensively than the well-known displacement criteria approach [13,16]. Comparisons with existing fragility functions show that the developed fragility functions are mostly in the middle range, both graphically and for the curve parameters [27]. Fragility functions can also be validated by other approaches expressing seismic performance, such as experimental studies and seismic indices [54]. The approach is universally applicable to regionally specific characteristics of material properties, construction types and systems, and general building classes. When developing fragility curves for the target site, it is crucial to consider the existing building typologies and structures by varying the materials and construction techniques according to the year of construction and the seismic code. The fragility curves should account for the specific properties of the building classes to ensure a reliable damage assessment. Moreover, to apply the fragility curves on a large scale, it is necessary to have information about the geographical distribution of building classes. Considering the existing building classes, fragility functions can be derived in advance to prepare for an earthquake event and used immediately after the earthquake, even before data is available for the classification methods. Additionally, UAV overview flights are initiated based on the probable damage distribution. Mission planning software can identify the most damaged areas using building-level damage estimation or aggregated damage distribution. The derived UAV images are input for damage classification.

To improve the quality of the up-to-date information, the building damage is detected and classified based on the UAV data. Using UAVs to survey building damage offers a practical means to get rapid information immediately after the earthquake. The timing and extent of UAV flights and post-processing strategies for generating point clouds should be aligned with the available resources and the geographic scope of the earthquake-affected area. Although large-scale nadiral flights provide a comprehensive overview, detailed flights targeting specific buildings require closer distances and varied perspectives to capture all aspects adequately. Close-range flights for detailed acquisitions, especially in urban settings, pose challenges. However, in such cases, similar buildings can serve as examples. In situations where resources are scarce, our approach introduces a hierarchical strategy for efficient prioritisation. This ensures that critical data is collected and analysed effectively, maximising insights even in resource-constrained scenarios. This facilitates comprehension of the situation and enhances decision-making effectiveness. Moreover, UAV data increases the safety of emergency responders by identifying heavily damaged areas and buildings, allowing them to respond to the effects of aftershocks. However, there are buildings where damage is only visible from the inside. In these cases, having knowledge from UAV images that the damage is unlikely to be severe enough to manifest externally reduces the risk for emergency services.

The developed damage catalogues [22,23] are the decision basis and were developed specifically for the assessment of externally visible damage. In comparison to existing damage scales [28–34], five specific damage grades are differentiated and unambiguous damage characteristics are defined. For the low damage grades, crack widths are defined to separate the different damage grades. Moreover, damage patterns are generalised and independent of the structural system, as visible damage is assessed. For example, a reinforced concrete frame structure and a reinforced concrete wall structure have different load-bearing structures, but the damage patterns that occur in either the columns or the walls are similar and are included in the damage catalogues. If the building material is similar, these damage catalogues are transferable to other geographic regions. In addition, the concept of the damage catalogue can be extended to other types of buildings, e.g. special wood-clay buildings, to apply to all existing building types including country-specific buildings. These catalogues provide a formalized description of damage patterns and features to serve as a decision basis for an objective and reliable classification of the damage.

A major strength of our approach is the combination of automatic damage classification and domain knowledge in earthquake engineering [43],. The inclusion of knowledge of typical damage patterns in the generation of realistic simulated training data allows model training on geometric change, which characterises the target damage grades across diverse geographic regions. A strong transferability of the trained machine learning model across region-specific site characteristics is achieved, in contrast to other studies [2]. In case of an earthquake event, training on simulated data can save valuable time as pre-trained classifiers can be readily applied. Virtual laser scanning thereby provides the possibility to generate tailored training data for the machine learning model and respective use case, including the full range of expected damage patterns for the target damage grades. This overcomes the challenge of assessing different levels of damage. Furthermore, our approach is transferable to multi-source input point clouds used for model training (VLS) and application (real-world photogrammetry). This interdisciplinary approach contributes to multi-class structural building damage assessment, particularly for applications where timely damage information is required, and sufficient pre- and post-event real-world training data is not available.

Moreover, our approach benefits from the integration of web-based crowdsourcing for remote mapping of damages [51] which has shown to be a valuable complement to automatic approaches, especially for the assessment of low damage grades. While the spatial resolution of UAV-derived point clouds constrains the automatic assessment of damage to higher damage grades, UAV images can serve as input for the visual classification of low damage grades by volunteers in web-based crowdsourcing. Damaged and destroyed buildings have been assessed by volunteers in previous studies [46–48]. In our web-based approach, more complex tasks are presented and can be solved through the provided guidance and the tutorial. Results of our micro-mapping studies demonstrate that volunteers assign these damage grades with high accuracies, supported by the developed tutorial based on the damage catalogues [22]. Of course, it is advantageous if the tutorial is already related to the site of interest. However, the volunteer training process can also be performed in advance with non-site-specific damage. In contrast to individual methods, the novel combination of automated and crowdsourced approaches can save time and resources and improve the quality of damage classification. Buildings that cannot automatically or visually be classified with sufficient certainty can be forwarded to experts for manual evaluation, thereby greatly reducing the number of buildings that need to be manually inspected by experts, saving resources and time. This multi-level evaluation process ultimately improves both the quantity and quality of damage information. In addition, the micro-mapping results can be used as training data for the automatic approaches, and volunteers gain knowledge of damage classification that they can use in other contexts.

Throughout the development process the entire framework for damage estimation, detection, and classification and the different methods have evolved through continuous exchange and feedback from stakeholders and end users working in the field of disaster management, including Federal Agency for Technical Relief, German Red Cross, fire department, and Integrated Control Center [3,26]. Their requirements and ideas for our concept were collected in the first step. During the conceptualization and implementation process, we held follow-up meetings to discuss the concept continuously and update it iteratively. For instance, end users actively participated in the development and evaluation of the web-based crowdsourcing tool and related tutorials via pilot studies, questionnaires and interviews, ensuring alignment with their requirements and providing the best possible support. Together we identified short- and long-term perspectives for future developments and integration of modules into end users' systems. This transdisciplinary approach is important to develop systems that can be of real benefit to those who employ them in real-life scenarios and to society. Additionally, the close collaboration with end users and stakeholders in the disaster response domain thereby has helped to raise awareness about the existence of such tools and their advantages for assisting rescue teams in the timely and reliable assessment of structural building damage.

The limitations of the present implementation are particularly apparent when the material of the building structure is not visible from the outside and when the damage is not detectable due to the resolution of the images or the facade cladding of the building. In addition, the distinction between structural and non-structural parts is a challenge for automated approaches and volunteers. Furthermore, the structure to be assessed should be viewed from different perspectives, both from the building's outside and the inside, as minor damage in particular is not always obvious. If the building is only photographed from the outside during UAV flights, slight damage cannot be excluded. The automatic approach is particularly suitable for larger, geometrically clearly visible damage. For smaller damage, such as cracks, a high geometric resolution of the point clouds is required to detect changes. The application of the web-based crowdsourcing approach shows that, even with training materials and pre-training, not all cases can be solved by volunteers without a background in structural engineering. A further challenge is posed by subsequent catastrophes after an earthquake, such as liquefaction [55], fires or tsunamis. These may result in different damage patterns that need to be considered in the developed methods.

It has been proven in theory and practice that the transdisciplinary and interdisciplinary combination of methods coupled with domain knowledge can provide fast and accurate damage information during disaster situations, helping to manage the consequences and save human lives. While the framework has been implemented for the use case of earthquakes, the generic workflow and defined interfaces of each component facilitate the combination of different methods also in other disaster contexts. In the case of natural disasters such as floods or tsunamis, for example, damage patterns and related classification methods have to be adapted, but the general concept remains applicable. This will require the development of new fragility functions and damage catalogues, the training of new classifiers, and the design of new crowdsourcing tasks and tutorials. For example, damage catalogues can also be developed for flood damage. Flood level and flood extent are important points in this respect. The idea of Griesbaum et al. [56] could be taken a step further within our inter- and transdisciplinary approach and instead of earthquake damages, flood levels could be extracted. Thus, different drone flights would lead to images for the micro-mapping of flood levels, while the acquired point clouds could be automatically analysed to define the flood levels. The same applies to the spatial flood extent. Of course, the damage classification would have to be adapted and the classifiers would require new training data. This approach then could be combined with participatory mapping of flood extent and level with local citizens and stakeholders [57,58]. The potential for broad practical and research applications is underscored by the transferability of our trans- and interdisciplinary approach.

5. Conclusion

We propose a trans- and interdisciplinary concept that provides relevant and timely damage information after a natural disaster through the combination of strengths of domain knowledge, automated computational methods, and crowdsourcing. We also provide a specific implementation of this approach for the use case of earthquake damage [3,24–26]. Our framework comprises a combination of innovative approaches and methodologies, fully defined interfaces, and is entirely open-source.

The application of this approach for assessing earthquake damage demonstrates its ability to provide timely, accurate, and objective information about the damage situation. This is achieved by integrating a well-defined engineering framework, which is based on a good understanding of damage and its associated patterns and distinctive characteristics, within innovative classification methods. The approach supports rescue operations and structural integrity assessment of buildings. Combining the benefits of automated and crowdsourcing approaches allows for resource- and time-efficient results and transferability to other regions and data. In resource-limited situations, our approach introduces a hierarchical strategy for efficient prioritisation that maximises insights and improves the effectiveness of decision-making.

Moreover, the collaborative involvement of stakeholders and end users from the beginning is crucial to our methodology. This ensures practical utility and continuous refinement. End user engagement has played a key role in shaping the iterative development process, resulting in a framework that is applicable in disaster management scenarios.

Future research should focus on fully automating our implementation, which will require transferring modules and interfaces into software. Furthermore, research efforts should be extended to cover a wider range of infrastructures and materials in order to enhance classification accuracy.

Finally, our concept is a highly adaptable and generic framework that can be applied across various natural hazard scenarios. The potential for broad practical and research applications ultimately contributes to enhanced disaster response and preservation of human life.

CRediT authorship contribution statement

Julia Kohns: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Conceptualization. **Vivien Zahs:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Conceptualization. **Carolin Klonner:** Writing – review & editing, Methodology, Investigation. **Bernhard Höfle:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Lothar Stempniewski:** Writing – review & editing, Supervision, Funding acquisition. **Alexander Stark:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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