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Classification of Collapsed Buildings for Fast Damage and Loss Assessment

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Abstract. Fast and reliable identification of collapsed buildings is essential in case of earthquake disasters in urban areas. Airborne laserscanning offers the possibility to fulfil this task. Based on height measurements, geometrical surface models of buildings can be generated with this technology. Comparing the undamaged pre-event models with those recorded after an earthquake, the location of collapsed buildings and the dimension and characteristic of their damage can be obtained. The knowledge about typical damage types of collapsed buildings is necessary to interpret the changes found between the pre- and post-event building models. As existing building damage classifications don't meet the requirements of this novel technique, observations and reports of building collapses were analysed. This leads to a new classification system of collapsed buildings and the definition of the so-called "damage catalogue".

The *damage catalogue* is a composition of different damage types of entire buildings typically occurring after earthquakes and it contains the observed dimensions of the geometrical features such as volume reduction or inclination change for each damage type. Besides the detectability of these geometrical features in airborne laserscanning data, the differentiation of the damage types takes effects on casualty numbers and on different search and rescue needs into account. The damage catalogue was developed by evaluating the associated database, which contains the characterisation of real damaged buildings by the defined geometrical features.

The paper includes the conception of the damage catalogue and of the associated database, their use for the described reconnaissance technique and their further application possibilities.

Key words: airborne laserscanning, building collapse, casualty estimation, damage pattern, damage type, geometrical features, search and rescue demand, trapped victims

Abbreviations

SAR – search and rescue
CRC – collaborative research centre
DSM – digital surface model
DMT – disaster management tool

1. Introduction

Destructive earthquakes in urban areas cause thousands of casualties every year. For the large majority of earthquakes, deaths and injury are primarily caused by building collapse (compare Coburn and Spence, 2002). The trapped survivors in collapsed buildings could often be rescued by fast and efficient measures. But in the aftermath of earthquakes, especially in urban areas, the number and location of collapsed buildings are unknown and it is not clear how many people are affected. As a result it is difficult to coordinate the operations and to allocate the limited search and rescue (SAR) resources of the disaster area in an optimal way. It must also be considered that the survival probabilities of the trapped persons and the rescue possibilities highly depend on the structure of the destroyed building. Airborne laserscanning offers the possibility of an early and reliable determination of collapsed buildings and their damage type as basis for the estimation of trapped victims and for an optimal distribution of rescue resources.

The realisation of this technology is one of the objectives of the Collaborative Research Centre 461 (CRC 461) "Strong Earthquakes: A Challenge for Geosciences and Civil Engineering" at the University of Karlsruhe. This long term research project, founded in 1996, is a multidisciplinary attempt at earthquake damage mitigation, with regional focus on the Vrancea events in Romania. This paper presents work done within the subproject C7 "Novel Rescue and Restoration Technologies" in collaboration with other subprojects of this CRC.

Knowledge about the structure of collapsed buildings is necessary for the interpretation of the data collected by airborne laserscanning. Since existing classifications don't meet the requirements of this new technique, a so-called "damage catalogue" was developed. The damage catalogue is a composition of different damage types of entire buildings and contains typical geometrical features of each damage type.

In this paper first the concept to rapidly determine the collapse types of affected buildings in case of an earthquake disaster will be briefly described. This is followed by a detailed presentation of the damage catalogue which is used to classify the detected damage. The included damage types and the geometrical features used to describe them are introduced and the associated damage catalogue database is presented. Subsequently the utilisation of the damage catalogue for the mentioned reconnaissance technique is discussed. In the last part, the application possibilities for casualty estimation and for the ascertainment of the required search and rescue resources are presented.

2. Concept of Rapid Damage Detection

One of the important requirements for successful disaster management in urban areas after strong earthquakes is the fast retrieval of reliable information about the location, the extent and the characteristics of totally or partially collapsed buildings. To rapidly obtain information about the damage situation of buildings in affected areas, a method based on airborne laserscanning is being researched within the CRC by our colleagues from subproject C5. In the following the concept of this reconnaissance technique is outlined briefly as it is fundamental for the understanding of the newly developed classification system of collapsed buildings. For a detailed description of their research compare e.g. Steinle and Vögtle (2001) and Vögtle and Steinle (2004).

Airborne laserscanning (see Figure 1) was chosen for acquiring the basic data because of advantages such as fast data collection in large areas and independency of weather and light conditions. The laserscanning technology is an active airborne scanning technique that is operational and has successfully been used for dense three-dimensional point measurements since the early nineties (see e.g. Ackermann, 1999). The results are height data sets, in this approach digital surface models (DSM). Based on these digital surface models an automatic method was developed to produce three-dimensional vector models of the buildings.

The geometries of the buildings are stored as vector models because they are more advantageous for the analysis of the structures regarding their damage than the originally derived raster data. To be able to detect earthquake caused building damage, the buildings' geometry must be known in their initial state. This means that a database of building models should be set up in regions where the detection of changes is intended. After an earthquake the pre- and post-earthquake building models are superposed to detect the changes between the two states and to quantify them by using change measures like volume differences, plane orientation change, height change or size alteration. As changes in urban areas are not necessarily caused by damage, they must be analysed further to differentiate the normal modifications e.g. by construction activities from earthquake caused modifications (see Steinle and Bähr, 2002 for details). Buildings that are identified as damaged during the change detection undergo further analysis to interpret the changes found.

A basic prerequisite for the interpretation was the development of the damage catalogue, which contains possible damage types of entire buildings and their geometrical and therefore detectable features. The interpretation is done by the classification of the identified changes based on the damage catalogue, but it suffers from the fuzzy nature of damage. Therefore,

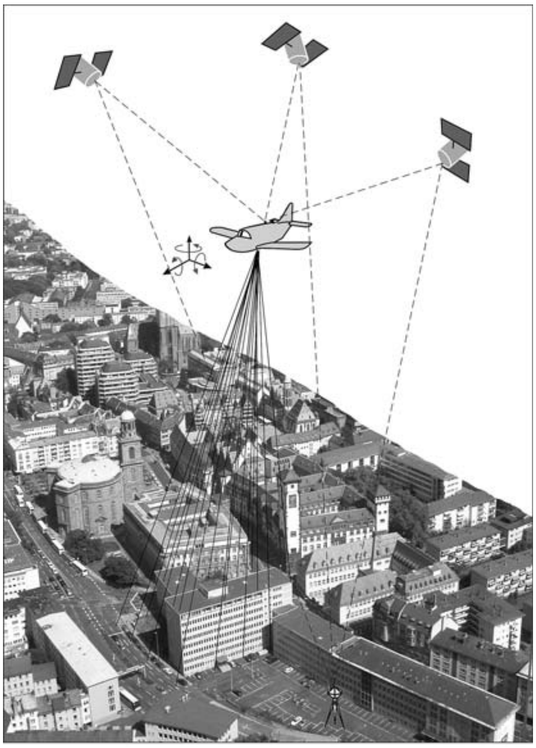

Figure 1. Principle of laserscanning.

methods based on fuzzy logic are used and the results are given in combination with a decision uncertainty indicator.

3. Damage Catalogue

For the reconnaissance technique described above a novel classification system of collapsed buildings was necessary that on the one hand meets the requirements of this technique and on the other hand can be used for further applications that are important in disaster cases, e.g. like the estimation of casualties. For this reason a so-called *damage catalogue* was developed. The damage catalogue is a compilation of different damage types of entire buildings typically occurring after earthquakes and contains the observed dimensions of the geometrical features like volume reduction or the inclination change for each damage type.

The damage catalogue was set up using various after-action and damage reports as well as photographs of damaged buildings, which were collected and analysed for this purpose. The result is a catalogue with 10 different damage types and the geometrical features that characterise them.

3.1. Damage types

In this approach damage types describe the damage situation of entire buildings. The definition of the damage types is based on the classes suggested by Okada and Takai (2000). Their classification system was developed for a fast survey of damage by observers walking within the affected areas and it only covers a small number of damage structures. Therefore, their damage type list was adapted and enhanced. The compilation of possible collapse forms was made according to the following criteria:

- coverage of all typically occurring damage types at earthquakes
- detectability of the peculiarities of the damage types in airborne laser-scanning data
- differentiation of damage types that cause different casualty numbers or have different SAR rescue requirements

In the following the five groups of damage types are presented and described:

3.1.1. *Damage types – Inclined layers*

The group of the "inclined layers" consists of the three damage types "inclined plane", "multi layer collapse" and "outspread multi layer collapse" (compare Figure 2). The damage type "inclined plane" describes the inclination of the highest level of the building. The general cause for this type of damage is that the support of a floor slab or a flat roof collapses on one side and withstands on the opposite site. The difference in height can be several meters, but maximum the height of one storey. The size of the inclined plane can correspond to the size of the footprint but also only to a part of this.

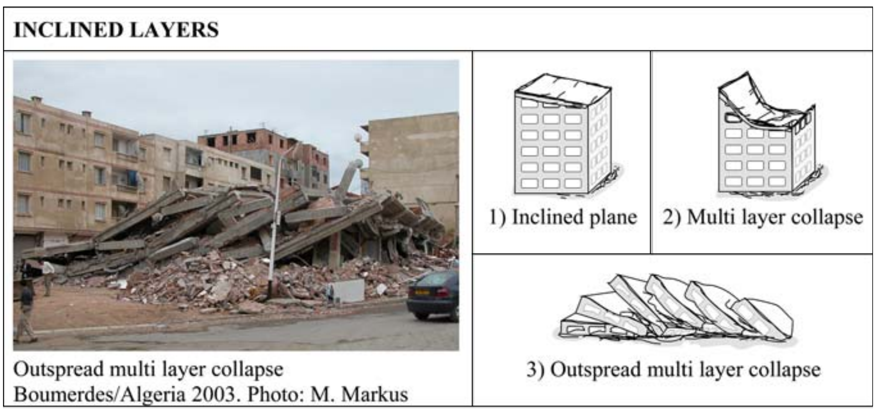

Figure 2. Damage type group – Inclined layers.

More frequently than the damage type "inclined plane" the damage type "multi layer collapse" occurs. In this case several floors are affected where floor slabs form stacked layers after one side of the supporting structure has collapsed. The difference in height is several floors and here again the extent of the damage can concern the whole footprint or just a part of it.

When a whole building collapses, an outspread multi layer collapse can occur. Due to a non-uniform failure of the structural components the building falls to one side or a corner, so that the expansion of the damaged structure goes beyond the borders of the footprint area. The floor slabs are mostly well preserved whereas the supporting structure of the involved floors is destroyed. From the air, only parts of the particular slabs are recognisable, since they are covered by the slabs above.

3.1.2. *Damage types – Pancake collapses*

Pancake collapses are characterised by the failure of particular floors, which collapse almost uniformly. To a large extent the building is preserved in its form and structure but has been reduced in height. Seven types of pancake collapses are distinguished, depending on the part of the building that is damaged and if one or more storeys are affected (see Figure 3).

The cause for the failure of the ground floor is often that these floors are so-called soft storeys i.e. the stiffness of the ground floor is lower than of the rest of the building. The collapse of one or several middle floors during an earthquake can be triggered by insufficient bracing or too high moving loads by machines and material storage. A frequent cause is also the mutual pounding effect. Buildings with different natural frequencies and insufficient

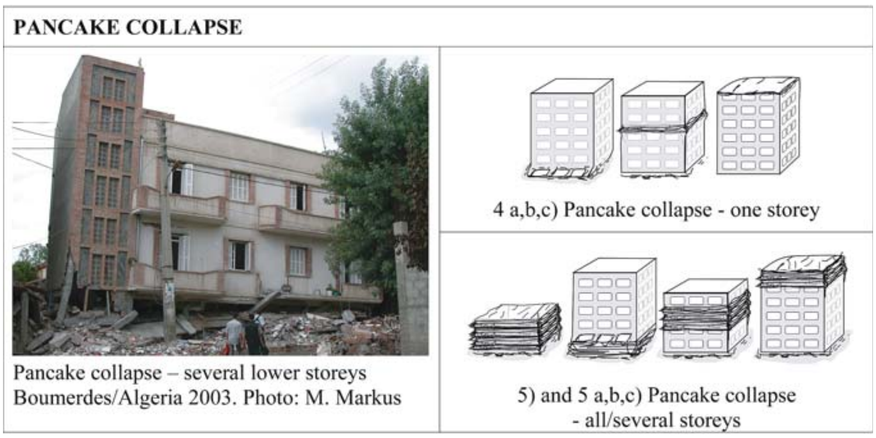

Figure 3. Damage type group – Pancake collapse.

gaps between them pound against each other during earthquakes and the higher building breaks at the edge to the lower neighbouring building (compare Coburn and Spence 2002 and Münchener Rück, 1986).

Seen from above the most characteristic attribute is the nearly uniform height lowering over the entire footprint area, the size of the height difference comparing with the original building permits the differentiation between the damage types 4 and 5.

3.1.3. *Damage types – Debris heaps*

Debris heaps result from the failure of all structural elements. The cause can be the event itself but also the failure of several structural elements can trigger the collapse of the whole structure (compare Gehbauer *et al.*, 2002). Four forms of debris heaps are differentiated (see Figure 4).

Damage type 6 describes the case of the upper floors collapsing and the top surface of the building is formed by a completely non-uniform structure from small debris parts. The lower floors of the building are not destroyed, but they are loaded statically in a different way than in the original state due to the accumulation of debris in the upper part. For the damage type "heap of debris" many or all floors are collapsed in a disordered way. No larger parts of the building are preserved. The surface is irregular and consists of small debris.

For the damage type "heap of debris with plates" all or almost all floors are concerned, too. Within the heap of debris larger plates can be identified, which withstood the collapse in one piece. The damage type "heap of debris with vertical elements" usually only occurs at unreinforced masonry buildings. The difference to damage type 7a is that some of the vertical

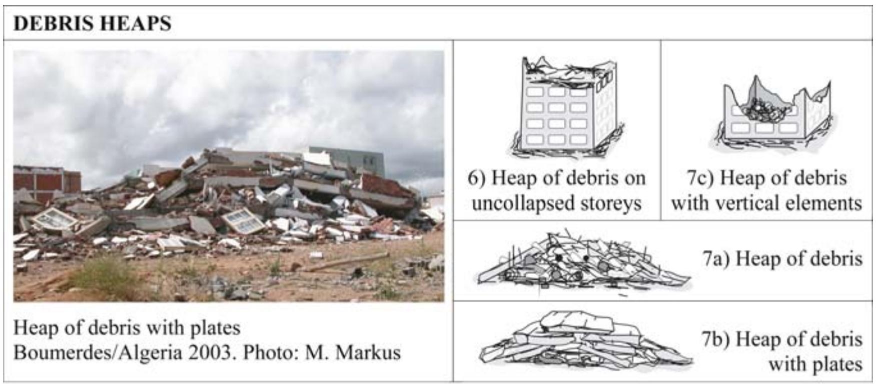

Figure 4. Damage type group – Debris heaps.

elements are not destroyed. For this reason height differences are recognisable within the debris structure, that are not found at the other two types of debris heaps.

3.1.4. *Damage types – Overturn collapses*

This group consists of the damage types "separated overturn collapse", "inclination" and "overturn collapse" (see Figure 5). For a separated overturn collapse the lower part of the building is still at its original position, whereas the upper part lies separately next to it due to substantial forces. This damage type can be well differentiated from other damage forms, because the initial footprint is still recognisable but a new structure can be found next to it.

The change of the inclination of the building axis for damage type 9a can have different causes. On the one hand the soil conditions play an important role, on the other hand different failure of the supporting construction in the lower floors can lead to the inclination of the building.

For a complete overturn collapse the building still only forms one corpus but this lies outside of the footprint area on one of the sides or corners. This damage type is rare, due to the fact that in urban areas the complete overturn of the building is often prevented by neighbouring buildings or debris.

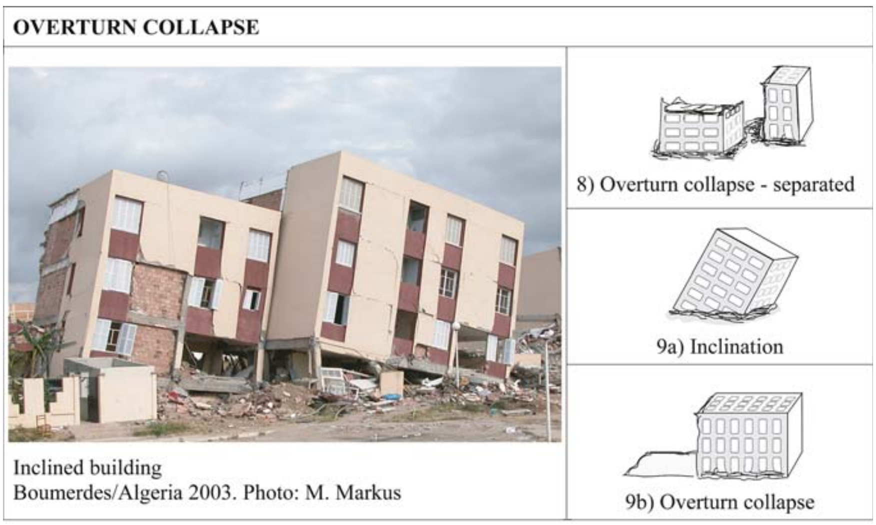

Figure 5. Damage type group – Overturn collapse.

Figure 6. Damage type – Overhanging elements.

3.1.5. *Damage type – Overhanging elements*

This damage type describes the case that supporting external walls are destroyed, but the slab or the roof above remains at its initial position (see Figure 6). Through the missing support a cantilevering slab is formed. Although this damage type is rarely observed after earthquakes and can not be easily detected by the described airborne laserscanning technology it is included in the damage catalogue for the sake of completeness.

3.2. Geometrical features

To determine the damage types in the course of the damage interpretation from airborne height measurements, geometrical features must be defined which are detectable when comparing the pre- and post-event data. For this reason, geometrical features were determined by means of photographs from collapsed buildings and their development for the different damage types were analysed. The selection of the geometrical features that were to be examined was made on the condition that the features are recognisable from the air, can be recorded with the used technology and show different characteristics for each damage type. The following geometrical features were determined:

- Total height difference to initial height
- Volume reduction
- Recognisability of the footprint borders
- Surface structure (unchanged, erratic, with large planes)
- Inclination change with reference to the initial situation within the footprint
- Size of the recognisable upper planes
- Debris structure outside the footprint

- Size of the debris outside the footprint
- Additionally covered area outside the footprint
- Height difference at the footprint border
- Number of visible walls
- Roof structure

Each damage type is characterised by the combination of different geometrical features and by the development of the different features. To find the typical development of the geometrical features for each damage type, 1576 pictures of 143 different damaged buildings were analysed and stored in a database.

3.3. Damage catalogue database

The *damage catalogue database* contains the indication of the damage type and specifications to the geometrical features for each of the 143 damaged buildings. It specifies whether the respective feature could be found at the regarded building and if so in which development. Furthermore the found damage patterns are given for each building.

Damage patterns are used by German rescue teams; they serve as a systematic description of damage to buildings or building elements. They refer mainly to the destruction forms of certain rooms and locally limited rubble structures. Therefore a completely destroyed building will normally have many different damage patterns. Due to many years of experience with these damage patterns, the position of trapped victims, their survival chances and the related rescue works can be inferred. With the knowledge of the typical occurring damage patterns for each damage type, the search and rescue needs can be deduced. Thus the damage patterns are of particular importance for the ascertainment of the search and rescue needs (compare also Section 4.2). Further details can be found in Gehbauer *et al.* (2002) and Schweier and Markus (2004).

In addition, the damage catalogue database contains the construction type of the buildings, their social function and the initial number of floors. The data records are complemented with place and time of the damaging event that led to the collapse and with the photographs, which were used for the investigation of the building.

The most buildings archived in the database collapsed during earthquakes but also building collapses due to other events such as gas explosions or floods were added if the collapse forms were similar to those of earthquake events. Nevertheless about 90% of the analysed building collapses are due to earthquake events that occurred between 1988 and 2003 in Algeria, Armenia, India, Japan, Mexico, Romania, Taiwan and Turkey. The following Figure 7 shows the user interface of the database:

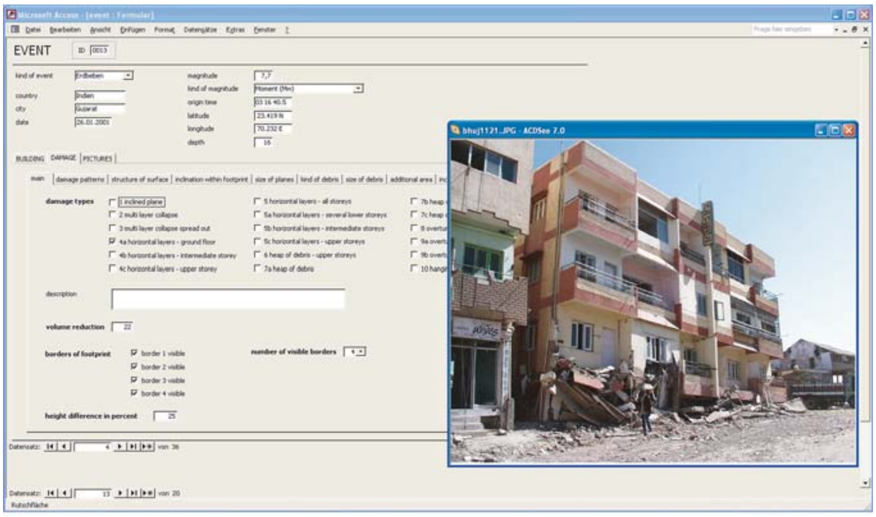

Figure 7. Damage catalogue database.

3.4. Utilisation for the reconnaissance technique

The collected data was evaluated with the help of the database. For each damage type a compilation of typical geometrical details was provided and if possible the typical development of the features was also quantitatively indicated. This makes it possible to infer from the found geometrical features to the existing damage type by comparing the laserscanning derived pre and post event data. Separate compilations were provided for the frequently occurring combinations of damage types since many collapsed structures can't be characterised by just one damage type and this circumstance has relevant effects on the geometrical details that can be observed. As an example, some of the features of the damage type "multi layer collapse" (compare Figure 8) are summarised.

During the evaluation of the collected data it became apparent that with a large probability all borders of the footprint area are recognisable from the air for multi layer collapses. The reason is that for this damage type mainly the upper parts of a building or only parts of the footprint area of a building are affected. Especially in the last case the course of the footprint borders is recognisable because of the undamaged building parts. The volume reduction is small and the height difference at the highest point of the damaged structure is zero percent. In principle the highest layer within the damaged area is formed by large plates and the inclination of the layering is usually between 45° and 55°.

In exceptional cases the layers can be more inclined which results in the destruction of the slab structure in most cases. Even in these cases, two

Figure 8. Damage type "Multi layer collapse"; India, 2001. Photo: M. Markus.

large slab parts are normally recognisable from above. The debris parts outside the footprint are normally not bigger than $9\,m^2$ and the additional area outside the footprint covered by debris is at most a fifth of the initial footprint. The roof structure is mostly obliquely positioned, but most parts are still connected.

Comparable but more detailed compilations were provided for each damage type. As apparent, not only quantifiable but also soft features were regarded, since they also contribute to the determination of the damage type. Great importance was given to finding those geometrical features which distinguish one damage type from the other. In the further process these compilations of typical geometrical features for the different damage types are to be implemented in a software in order to automatically interpret the damage.

4. Application Possibilities

One of the functions of the damage catalogue has already been introduced. It enables the automated damage interpretation of the data gathered by airborne laserscanning. Although the fast determination of the collapsed buildings and the determination of their damage degrees and damage types are already a great help in earthquake cases, it is sensible to use this information as input for further important tasks in disaster cases such as the estimation of the casualties or the determination of rescue demand.

4.1. Human casualty estimation

Starting from damage types as input information a novel method to estimate the human casualties was developed. This model allows the estimation of the casualties, especially the number of the trapped victims for each collapsed building after an earthquake. The differences to existing estimation models like for example the HAZUS method (National Institute of Building Sciences, 1999) are that:

- the casualties are estimated at the level of single buildings and not for an entire zone or region
- the model mainly focuses on the estimation of trapped victims. In addition the number of injured and killed persons is also given and divided in four injury classes, e.g. as used in the HAZUS method.
- the estimation is carried out after the event using the real damage situation of the buildings as input. Other models estimate the casualties based on the damage degrees of the buildings calculated before the event.
- only the casualties for collapsed buildings are estimated and not for all damaged buildings.

Consequently the objective is to use the results to support those responsible during the disaster response to organise the rescue work and to allocate rescue resources. As input the developed model uses the evaluated information from the laserscanning overflights. These are the determination of the collapsed buildings, the damage type of the collapsed structures, the detected geometrical features as well as the computed changes in the geometry caused by the impact, e.g. height and volume reductions. The second input information is the number of the people present in the buildings at the time of the earthquake (occupancy). This information is calculated based on data collected for each building before the event. The estimation model for the trapped victims is based on the assumption that there is a strong correlation between the volume reduction of a building and the number of the persons trapped in it. Subsequently the damage type and the volume reduction of the collapsed structures are the most influencing factors. A more detailed description of the human casualty estimation concept can be found in Schweier and Markus, 2005. A detailed explanation of the methodology will be published soon.

4.2. Assessment of search and rescue requirements

Based on the damage types and the estimated number of trapped victims per collapsed building, methods were developed to ascertain the demand for search and rescue (SAR) resources for the concerned buildings. The ascertainment of the required SAR personnel and equipment for each individual collapsed building is helpful for the disaster management in order to allocate the limited SAR resources of the disaster area in an optimal way.

The SAR demand for each collapsed building depends mainly on the construction and the damage type of the building, the building size, the degree of the collapse and the number of casualties. To detect the qualitative and quantitative influence of these parameters on the SAR demand, after-action reports related to SAR activities in collapsed buildings and questionnaires from a conducted international expert survey were analysed. Furthermore the experience of rescue organisations was taken into consideration. Two different approaches to assess the needed search and rescue personnel and equipment were developed. The first is a compilation of a primary demand for SAR resources for each damage type. The second approach is a method to assess the needed SAR personnel depending on the damage type and the estimated number of trapped victims. For further details compare Schweier and Markus (2004).

4.3. Disaster management tool

The presented methods (a) to rapidly gather information about collapsed buildings in urban areas by the evaluation of laserscanning derived data, (b) the geometry-based casualty estimation model and (c) the two methods to assess the SAR demand for individual buildings are to be integrated in the so-called "Disaster Management Tool" (DMT) to make them applicable. The DMT is a software system supporting decision makers, surveillance and intervention teams during a disaster response. It is developed within the Collaborative Research Center (CRC) 461 "Strong Earthquakes" based on the results of its engineering research projects. The DMT is designed for earthquake disasters in Bucharest as a test case, but planned to be adaptable to urban areas in industrialising countries with various disaster types. For more details compare Markus *et al.* (2004).

5. Conclusions and future work

This paper has presented the concept of the damage catalogue, its purpose and its application possibilities. The damage catalogue is a novel classification system of collapsed buildings using damage types and their detailed description by their geometrical features. The associated database contains the characterisation of real damaged buildings by the defined geometrical features. This was carried out on the basis of photographs of the collapsed structures, which are also included in the database. The typical development of the geometrical features for each damage type was determined by evaluation of this database. The different damage types and geometrical features were introduced in detail and the conception and purpose of the damage catalogue database was described.

The damage catalogue is used to enable the damage interpretation of collapsed buildings detected by comparing pre and post disaster data that was gathered by airborne laserscanning. This reconnaissance technique was presented briefly as well as its application possibilities for casualty estimation and for the ascertainment of the required SAR resources.

The damage catalogue database will be enlarged with a focus on including buildings and damage types that are under-represented in the current database. By enlarging it the description of the damage types by their typical geometrical features will be more precise and reliable and will therefore support the development of the damage interpretation process.

The presented reconnaissance technique as well as the estimation tools for human casualties and SAR resources demand will be included in an integrated Disaster Management Tool to make them applicable for pre and post event management tasks.

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