GIS and Image Understanding for Near-Real-Time Earthquake Damage Assessment

Paolo Gamba and Fabio Casciati

Abstract

This paper evolved from the results of RADATT (RApid Damage Assessment Telematic Tool), a project funded by the European Commission, whose goal was to sensibly reduce the effects of a devastating seismic event by providing the responsible agencies a rapid and reliable damage detection and estimation of the extent and location of the suffered area.

This result was accomplished by the integration, within a single user interface environment, of data access and standardization techniques, image processing tools, and GIS technology. A two-phase operating model has been conceived. In the pre-event era, images and data about buildings and infrastructures are collected and analyzed exploiting GIS capabilities. Immediately after the occurrence of the earthquake, the system must be ready to receive near-real-time imagery of the affected area to be compared with the pre-event data set.

In this paper the capability of this quick change-detection analysis, given the availability of the pre-event information in the GIS environment, is discussed.

Introduction

Recent natural disasters have stressed the importance of a rapid and reliable damage assessment and loss estimate in order to face both short- and long-term emergency response. It has been demonstrated that the entity of earthquake damage is only partly due to the strength of the natural event; it also depends on the delay and inadequacy of the rescue and reconstruction intervention.

A reliable post-disaster damage assessment would allow the guarantee of rapid emergency response, and sensibly reduce the effects by providing an immediate estimate of the extent and location of the damaged area and making this knowledge available to the responsible agencies. Moreover, it should be pointed out that, in case of suddenly occurring natural disasters, the identification of damage by means of analytical models alone is often unreliable because soil conditions, geological complexities, and different environmental aspects may result in difficult to predict damage patterns.

On the other hand, recent developments in image analysis techniques allow their integration with loss estimation and vulnerability models and make possible the investigation of more complex and effective approaches to the task of developing a reliable system for damage assessment.

This paper outlines the principal issues for the development of a software system for damage and loss estimation in an emergency due to earthquake disasters. This goal is achieved by integrating, within a single user interface environment, existing database information, GIS (geographic information system) technology, and image processing techniques. First, a brief overview of the original RADATT project is offered, with particular stress on the image processing tools. A detailed damage assessment chain is then presented, followed by documentation of the experimental results obtained by applying the proposed approach to many case studies. Finally, conclusions are presented.

The RADATT Project

The RADATT (RApid Damage Assessment Telematic Tool) project (Casciati *et al.*, 1996; Casciati and Giorgi, 1996a) discussed the feasibility for a system architecture satisfying the following requirements:

- Given that a seismic event occurred, can comparison of pre- and post-event imagery be used to detect the damage extent within a few hours from the shake?
- Can this comparison be conveniently supported by the appropriate interaction with an available building inventory?
- How is it more convenient to link, within a GIS environment, such a database with the spatial geo-referenced information of interest?

The project conceived a system architecture (Figure 1) and implemented modules to form a first prototype for seismic damage assessment and loss estimation from comparison of pre- and post-event images. The comparison is further
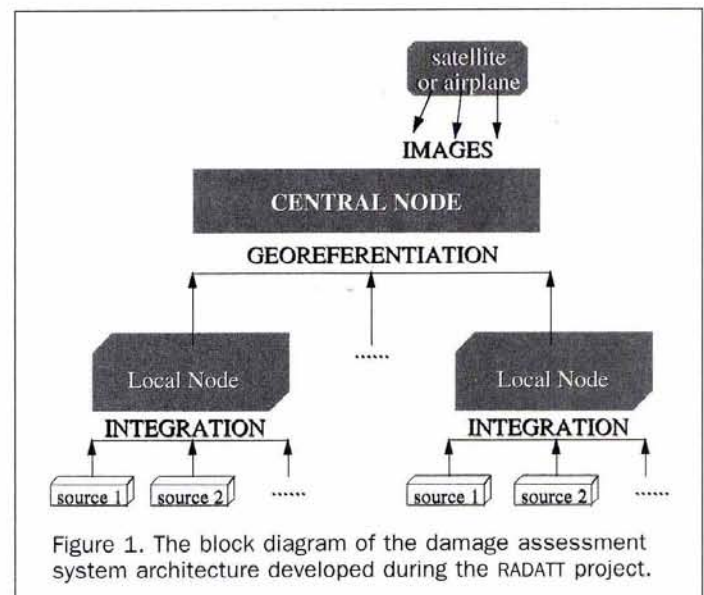

Figure 1. The block diagram of the damage assessment system architecture developed during the RADATT project.

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supported by on-line consultation of the existing available building inventory (Casciati and Giorgi, 1996b).

The system architecture was conceived with reference to the following aspects: database management, geographical information system, airborne and satellite imagery acquisition and processing, and final image comparison. Some other aspects showed their importance despite their marginal role with respect to the project: communication tools, image digitization, and geo-referencing are just some examples (Casciati and Giorgi, 1996c). Note that the goal is the detection, from the comparison of images taken before and after a seismic event, of any change corresponding to tangible and intangible losses. These changes can affect buildings, infrastructures, and the territory in their extension.

RADATT and Remote Sensing Image Processing
The conceptual system architecture of Figure 1 was built having in mind the use of pre- and post-event aerial and/or satellite images of the same scene. Some general remarks are given below:

- immediately after a catastrophic event occurred, the system must be able to receive near-real-time imagery of the damaged area. The work was carried out on the hypothesis of a fast delivery service linking satellite or airborne image providers with the operative civil protection units; and
- to detect minor changes in structures, 2-meter ground resolution images are necessary. This high resolution is presently obtained only by a limited number of sensors.

The conceived procedure for damage detection by image comparison had already been tested in a case study on the Greek town of Egion (Acaia region), which suffered a devastating earthquake on 15 June 1996 (Casciati et al., 1997). A parallel study on the Azores Islands (PT), struck by a seismic shake on 01 January 1980, was similarly performed (Gamba et al., 1997).

These preliminary works revealed some problems, and suggested further improvements that are the topics of the present paper. In particular, it was found that simple approaches to image comparison are generally not sufficiently robust to cope with data corrupted by noise, registered with different light and day conditions, and having different view angles or positions of the sensor; in a single word, with the imprecisions that affect, more or less, each pair of images to be simultaneously analyzed. Even if the same approaches could be changed in order to be more robust with respect to these problems, the feeling was that it was necessary to explore new and more suitable image processing methodologies, aimed at overcoming the noise and, possibly, exploiting all the characteristics of the images (Carlotto, 1997; Peli, 1990; Kawamura, 1971; Therrien et al., 1986; Carlotto et al., 1992). Among these approaches, the artificial intelligence approaches (Hadipriono et al., 1991; Pellegretti et al., 1994) seem particularly interesting.

Moreover, the difficulties that were faced during the extraction of the differences and while adapting the images to be analyzed and used for comparison brought to the consideration that, for a rapid damage assessment, one needs a tool capable of performing change detection in a reduced time interval, optimizing the trade off between accuracy of analysis and the need to provide a prompt loss estimation. So, no complex and CPU time-consuming algorithm, extremely sophisticated approaches, or machine-dedicated programs could be allowed.

On behalf of the preceding analysis, the solution was to implement image processing methodologies robust with respect to the noise, simple to be implemented, and in a user-friendly environment. This can be accomplished by modifying the basic environment of commercially available image processing software that can be customized by the user, adding a number of *ad hoc* algorithms.

As for the methodologies, two algorithms were identified, on the basis of the experience gained:

- pre- and post-event image analysis by means of edge and contour detection, and
- change detection through shape analysis and perceptual grouping.

The Integrated GIS and Image Analysis Procedure
The two algorithms were integrated in a GIS environment (the ArcInfo commercial product), where also the building inventory and corresponding risk level were stored. The implementation was accomplished, whenever possible, by means of generally available software, such as the Khoros image processing tools, programmable by the visual interface Cantata.

However, we must note that these procedures simply use the GIS role to connect in a simple way (by geo-referencing them) the different images referring to a given place, and in this sense it can be considered as a *passive* aid to image analysis. However, the RADATT experience showed the fundamental role to be played by the geographic information systems in all steps of the damage detection process, including as a powerful aid to image comparison algorithms. In future developments, it will also be possible to implement an *active* role of the same GIS by considering that it can be used to give hints as to which parts of a given image should be analyzed first (for the post-event *situation*) on the basis of the information introduced with the pre-event classification. In other words, the *knowledge* introduced in the system should be exploited not only in a strictly geographic sense (to give information about *where* an object is) but also as a link, for instance, to the database of the buildings of a given town, and so give information about *what* an object is.

Image Processing by Means of Gradient Techniques
The usual analysis of complex scenes starts from the spectral (grey-level) and spatial analysis of the original image, to extract higher level information.

In an aerial photo of an urban environment, one can use the *a priori* knowledge about the structure of the objects that are probably present in the scene to focus one's research and develop simple but efficient algorithms. In our case, a first means to obtain information about a building is to search for closed contours. This can be done in a variety of ways, and with standard techniques. For instance, in Figure 2 a procedure is shown implemented in Cantata towards this goal. It consists of an edge extracting routine, based on a linear filter and a multi-edge model (Shen and Castan, 1986; Shen and Castan, 1987), implementing a band-limited Laplacian operator. The filter is computed by assuming a simple model of the image as a signal plus white noise, and is an *optimal* one in the sense that it is optimized to discriminate step or multi-step functions embedded in this kind of noise.

Moreover, a gradient analysis of the image is provided to an edge closing routine, which exploits both sets of information to detect where the edges must be connected. The last procedure is iterated to refine the result, giving for instance the output of Figure 3. In this figure the aerial photograph of the town of Santomenna (central Italy) after the 1980 earthquake is depicted: it is clear that the closed contours no longer correspond to undamaged buildings, except for the small square house at bottom right.

The Pre- and Post-Event Analyses Comparison
The quickly analyzed post-event images can by themselves give useful hints to the human operators; however, better
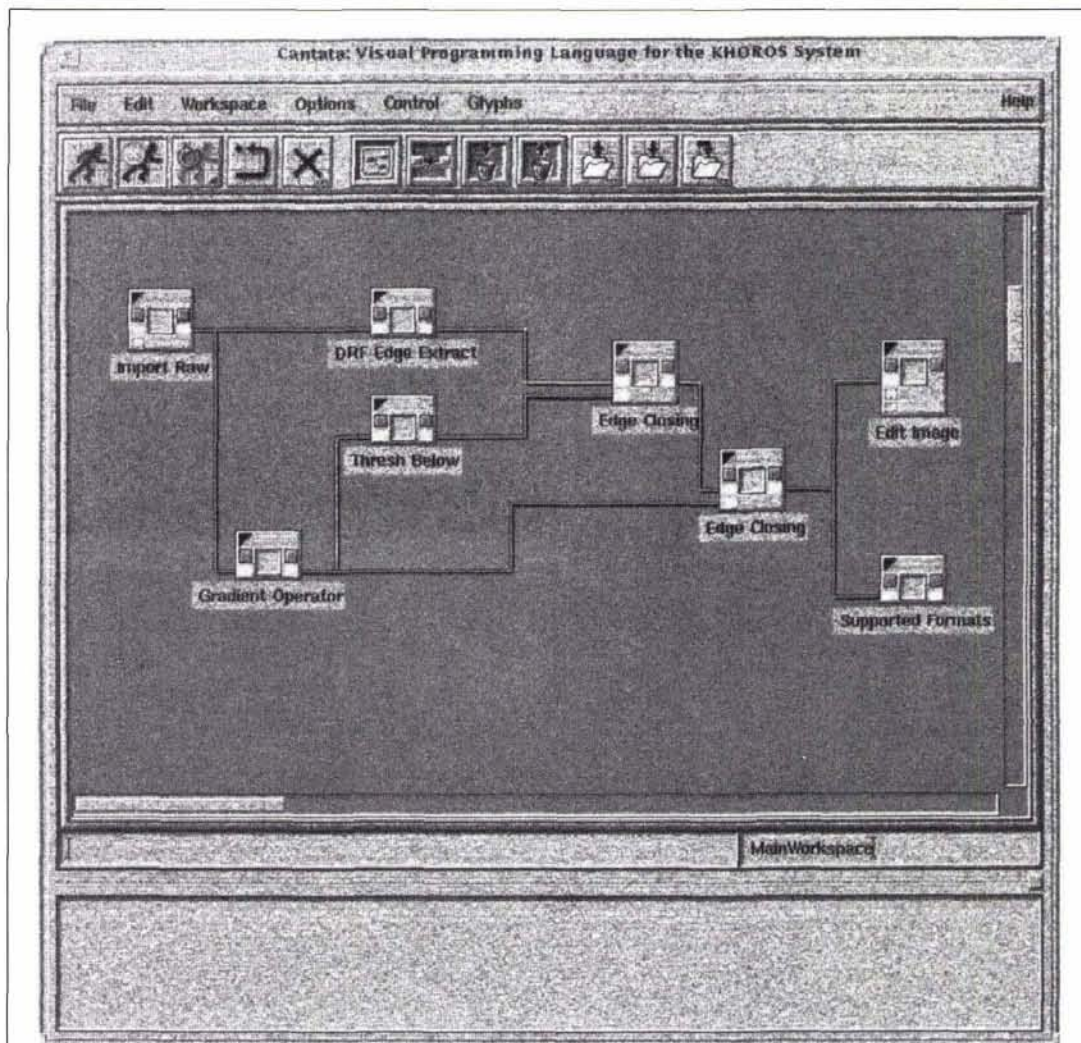
Figure 2. The Khoros implementation (using its visual interface Cantata) of the image analysis procedure based on edge detection and contour closing.

analyses are obtained by comparison with the pre-event imagery. This step can be efficiently achieved by means of the GIS software. Indeed, ArcInfo allows one to directly interact with the image processing software to exchange data: in particular, the results of the above delineated processes are translated into grids (vector formatted images) and easily composed with the corresponding *coverages* (the pre-entered layers of the GIS, in this case the buildings, or the streets and roads). To this aim, the most important step is the georeferencing of the pre- and post-event images: unfortunately, this is the only step of all this procedure that must be performed manually, because it requires that corresponding control points are indicated in both images. Even if it is possible to implement this step in an automatic way, the differences between the pre- and post-event images may be so large that it is safer to rely on a human operator.

Change Detection by Means of Perceptual Grouping
A different approach to the same problem can rely on the use of perceptual grouping concepts (Lowe, 1985). The idea is to identify interesting urban structures and infrastructures by extracting simple "building blocks" from the images by means of easy and inexpensive procedures and group them

exploiting the laws of human perception. This method can be applied not only to find closed contours, as in the previous procedure, but also to detect, for instance, small and large roads (parallel lines), blocks (textured parts), etc.

From a practical point of view, we follow the procedure to extract edges from the images, store them into a list, and progressively build other lists of more and more complex structures by verifying more and more conditions expressible in terms of continuity, proximity, collinearity, parallelism, and so on. The edge detection here is obtained by a simpler algorithm than before, by convolving the isotropic gradient operator (Philips, 1994) represented by the standard mask

$$\mathbf{M} = \begin{bmatrix} -1 & 0 & -1 \\ 0 & 4 & 0 \\ -1 & 0 & -1 \end{bmatrix}. \quad (1)$$

with the original image.

The following perceptual grouping procedures are structured by looking first at straight edges and then connecting near edges with similar orientation. Three parameters must be chosen: the minimum edge length, the allowed error in orientation, and the maximum distance between two near segments. All of them are chosen by looking at the statistics
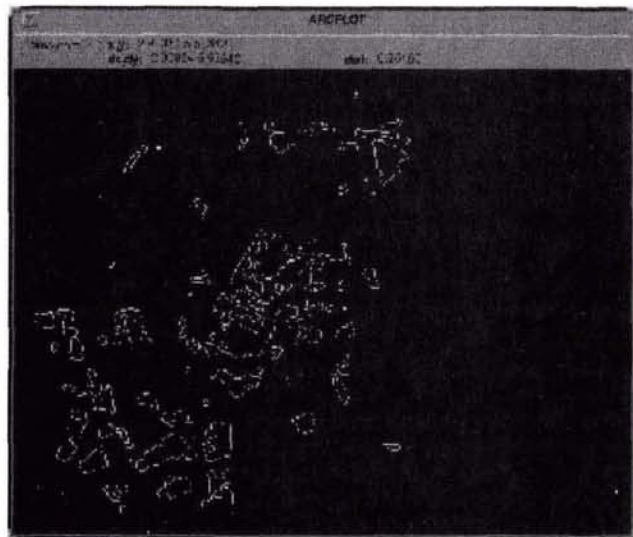
Figure 3. The post-earthquake image of the small town of Santomenna (central Italy): only the small square house at bottom right was not destroyed. The closed contours extracted (at right) make explicit this observation.

of the extracted edges to adapt the algorithm to the different images (for instance, the first parameter is determined by the mean edge length added to its standard deviation). The second step aims to find corners by grouping straight edges nearly perpendicular to each other (again, maximum distance and angle error are required). Finally, couples of corners constitute quadrangular objects by looking at the direction

and closeness of the chords closing their two sides into a triangle.

Therefore, as in the example shown in Figure 4, we start from the original image, and then we can collect collinear edges (Figure 4b), couples of edges grouped in nearly 90° corners (Figure 4c), and the four segments' sets representing hypotheses on quadrangular buildings (Figure 4d). By a com-
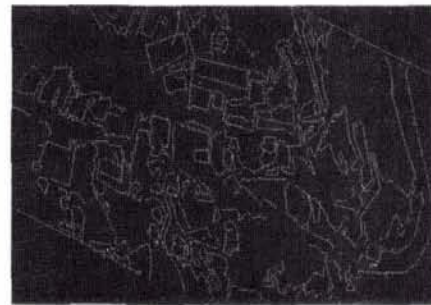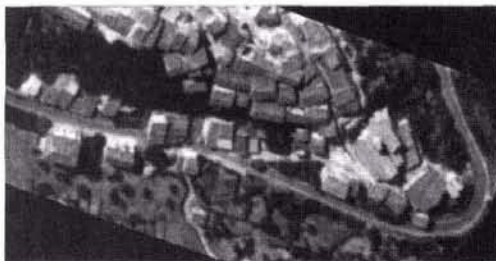
(b)
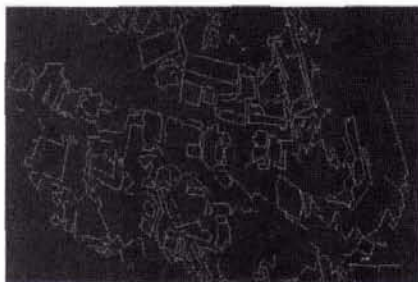
(c)
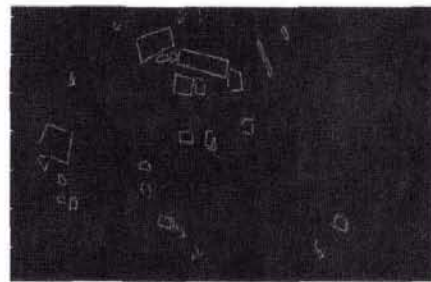
(d)

Figure 4. The perceptual grouping concepts applied to a part of the image depicting the town of Castelnuovo (southern Italy): first the edges (b), then the corners (c), and the quadrangles (d) were extracted by means of collinearity, proximity, and continuity Gestalt rules.

Figure 5. Pre- and post-event images of Conza (Irpinia, southern Italy), struck by a tremendous earthquake in 1980.

parison of these structures before and after the earthquake, we have the joint hypotheses on the damage suffered by the urban agglomerate we are working on. Moreover, because the damage assessment is made by comparing structures instead of images (as in the previous approach), the georeferencing step is not as important as before: here it is necessary only that corresponding objects be located close together, so that they can be recognized, but that no correction for optical distortion is needed.

Experimental Results

The procedures outlined in the preceding paragraphs have been applied first to aerial and satellite photos taken before and after different hazards that struck Italy in the recent past. The results presented in this section are the first ones referring to the complete digital image processing chain, and therefore can be considered as partially ameliorable; in any case, the overall performance of the system is extremely satisfying with respect to the first-aid purposes we outlined in the introduction.

The Irpinia Earthquake (1980)

In this paragraph, we refer to the tremendous earthquake which occurred in Irpinia (southern Italy) on 23 November 1980. In particular, we present here the results of the analysis of the data regarding a small town, Conza. The images were taken by a camera mounted on an airplane flying at different altitudes (around 1100 and 1700 m); therefore, it was necessary first to rescale the images to the same detail level.

The effects of the earthquake are clearly visible in Figure 5 where the rescaled images before and after the event for the center of Conza are presented. We can observe that only a few buildings have survived; in particular, three houses at the bottom of the photos, as well as three others to the right together with two smaller buildings at bottom-left and one isolated house at top-right.

The low contrast of the post-event image, due to the high-level scattering by the ruins of the buildings, prevents the use of a simple threshold analysis on the image. More refined methods, such as the one presented in the previous section, work very well, and highlight with high precision the interesting objects still visible in the aerial photo. In Figure 6 the results of this processing procedure are shown, and in Figure 7 the result of the complete comparison between the two images of the same town can be observed. The automatic procedure in its present form involves, as explained

above, the assistance of the operator only in detecting corresponding points in the two images, in order to rectify and refer them to the same reference system; the complete procedure takes only a few seconds on a standard PC working under the Linux operating system.

The Umbria Earthquake (1997–1998)

A different, but equally destructive, earthquake was sensed in the Umbria region (central Italy) starting with a big quake in October 1997, and lasting until the present (May 1998) with a series of small (and sometimes bigger) quakes. The images used in this work were taken from a satellite (the Russian KVR-1000, with a resolution of 2 m.) and by a photocamera operated from a helicopter. The data were recorded on August 1994 and November 1997, respectively, and are shown in Figure 8. The effects of the earthquake are here
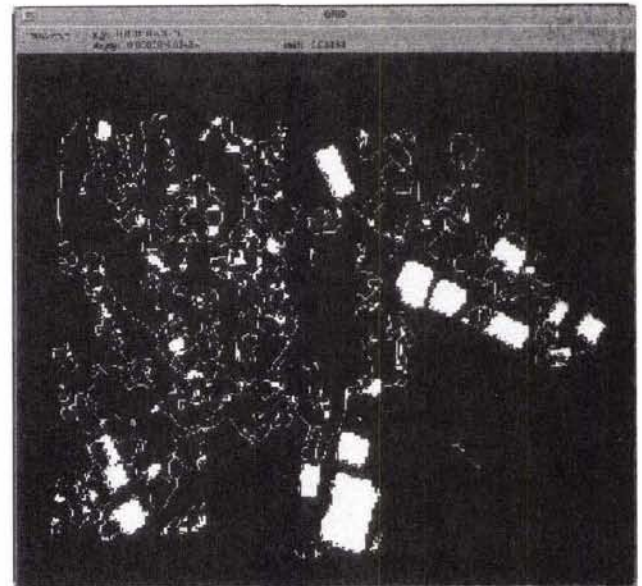

Figure 6. The closed contours extracted from the post-event image of Conza, showing the few buildings that survived.
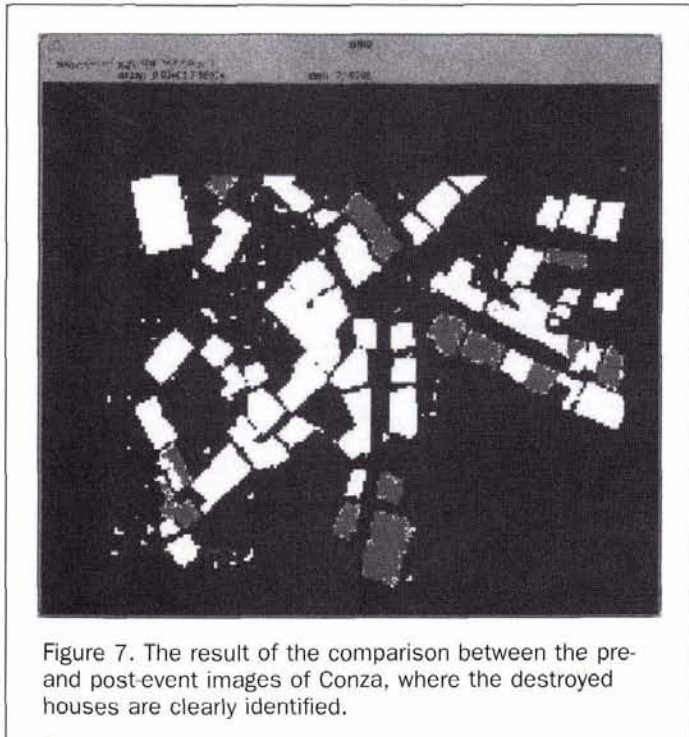
	Detected Buildings	Missed Buildings	Misclassified Buildings
Figure 6	12/15	3/15	2
Figure 9	10/10	—	3

Figure 7. The result of the comparison between the pre- and post-event images of Conza, where the destroyed houses are clearly identified.

closed contours elaborated with Cantata are shown, while in Figure 9b the pre-event building layer in ArcInfo (manually extracted) is depicted. Both sets of data, in grid format, are presented in Figure 9c for a visual analysis, while the final comparison can be seen in Figure 9d. As expected, the collapsed house has been identified, while the less damaged houses were not considered. As a first step towards damage assessment, this can be considered a satisfying result, but for better, more refined analyses, more precise image processing tools are still necessary.

Finally, the statistics regarding the two examples in Figure 6 and Figure 9 are shown in Table 1. It is clear that the gradient algorithm succeeds in determining almost all the buildings that were not destroyed, even if a few errors are present. In particular, the three misclassified buildings in Figure 9 are very small objects that a further control about their area would discard.

Conclusions

In this paper we have proposed a complete procedure for earthquake damage assessment by image processing tools and GIS integration, paying particular attention to the image analysis approaches more suitable to the task of near-real-time earthquake damage assessment.

The results of this first study were satisfying, even if more refined analysis can be offered with more complex processing methods. In any case, the feasibility of the entire system studied during the RADATT project has been clearly

less visible than in the previous example: only the house at the top has collapsed, while less damage to the roofs of other buildings is present.

After the necessary rescale operation, the same procedure defined for the previous analysis was applied to this new situation. The results are indeed quite satisfying, and are presented in Figure 9. In particular, in Figure 9a the

Figure 8. Pre- and post-event images of the town of Arvello (Umbria, central Italy), struck by the earthquake of 1997-1998.
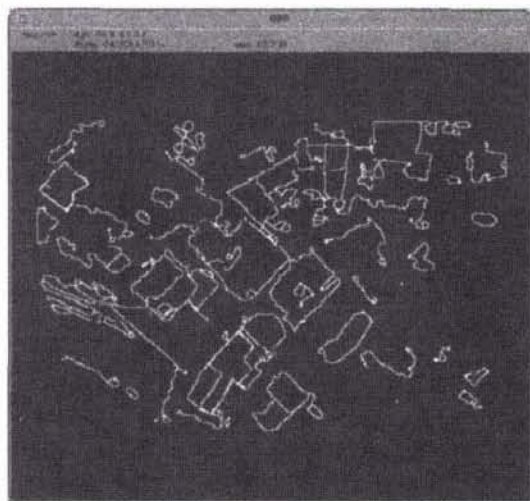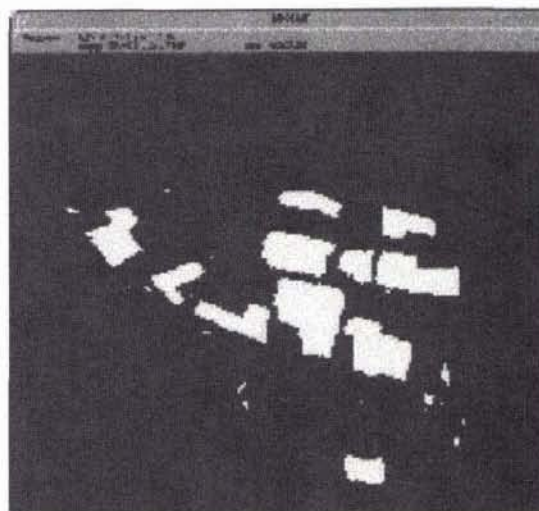
(a)　　　　　　　　　　　　(b)
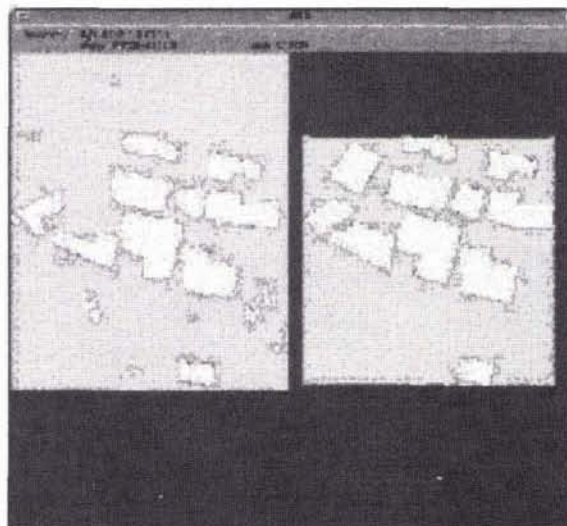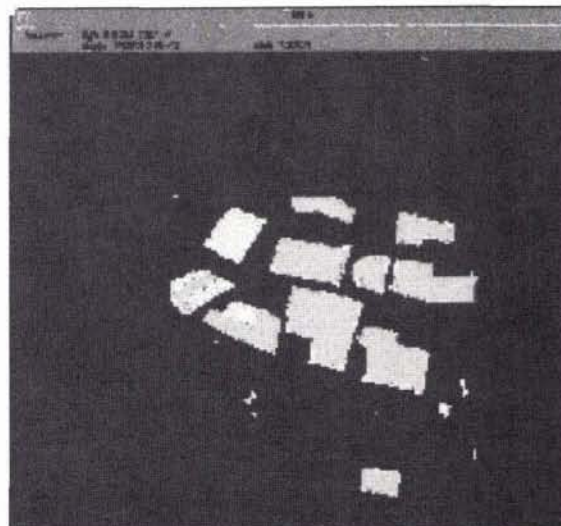
(c)　　　　　　　　　　　　(d)

Figure 9. The contours (a) of the survived buildings extracted from the image of Figure 8, (b) the pre-event building layer in ArcInfo, (c) both images in grid format, and (d) the final comparison.

demonstrated by means of freeware image processing tools (Khoros) and standard GIS (ArcInfo), so that the system can be easily accepted by Public Administrations.

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