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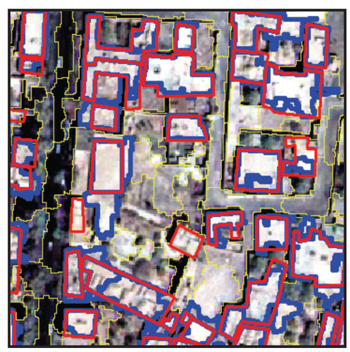
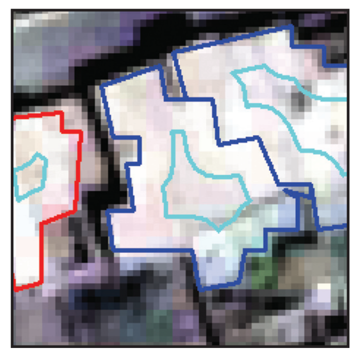
Remote Sensing for Resilient Multi-Hazard Disaster Response

Volume II: Counting the Number of Collapsed Buildings Using an Object-Oriented Analysis: Case Study of the 2003 Bam Earthquake

by
Luca Gusella, Charles K. Huyck and Beverley J. Adams



Technical Report MCEER-08-0021

November 17, 2008

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Luca Gusella,[1] Charles K. Huyck[2] and Beverley J. Adams[3]

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1 Consulting Engineer; Former Research Fellow, Department of Civil and Environmental Engineering, University of Bologna, Italy
2 Executive Vice President, ImageCat, Inc.
3 Managing Director, ImageCat Ltd.

MCEER
University at Buffalo, State University of New York
Red Jacket Quadrangle, Buffalo, NY 14261
Phone: (716) 645-3391; Fax (716) 645-3399
E-mail: *mceer@buffalo.edu*; WWW Site: *http://mceer.buffalo.edu*

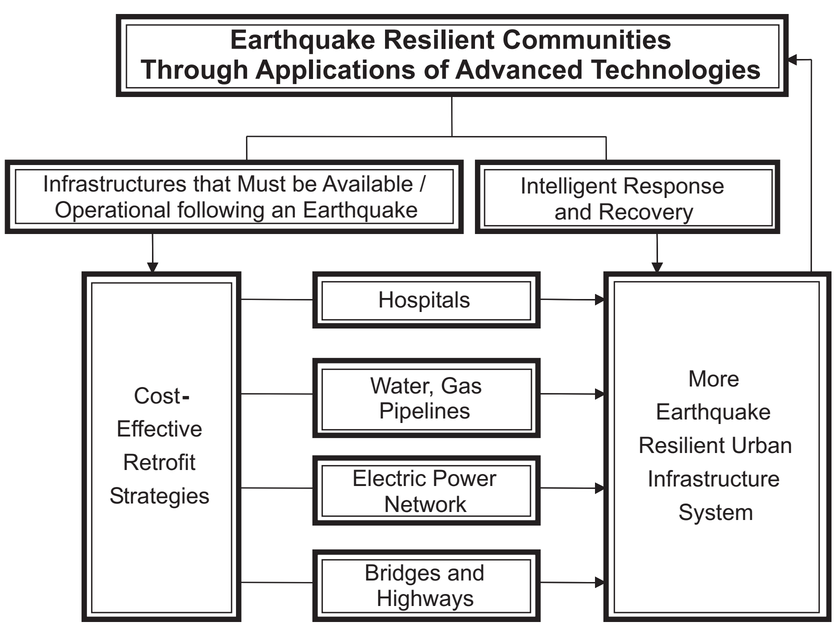
Preface

The Multidisciplinary Center for Earthquake Engineering Research (MCEER) is a national center of excellence in advanced technology applications that is dedicated to the reduction of earthquake losses nationwide. Headquartered at the University at Buffalo, State University of New York, the Center was originally established by the National Science Foundation in 1986, as the National Center for Earthquake Engineering Research (NCEER).

Comprising a consortium of researchers from numerous disciplines and institutions throughout the United States, the Center's mission is to reduce earthquake losses through research and the application of advanced technologies that improve engineering, pre-earthquake planning and post-earthquake recovery strategies. Toward this end, the Center coordinates a nationwide program of multidisciplinary team research, education and outreach activities.

MCEER's research is conducted under the sponsorship of two major federal agencies: the National Science Foundation (NSF) and the Federal Highway Administration (FHWA), and the State of New York. Significant support is derived from the Federal Emergency Management Agency (FEMA), other state governments, academic institutions, foreign governments and private industry.

MCEER's NSF-sponsored research objectives are twofold: to increase resilience by developing seismic evaluation and rehabilitation strategies for the post-disaster facilities and systems (hospitals, electrical and water lifelines, and bridges and highways) that society expects to be operational following an earthquake; and to further enhance resilience by developing improved emergency management capabilities to ensure an effective response and recovery following the earthquake (see the figure below).



A cross-program activity focuses on the establishment of an effective experimental and analytical network to facilitate the exchange of information between researchers located in various institutions across the country. These are complemented by, and integrated with, other MCEER activities in education, outreach, technology transfer, and industry partnerships.

This report presents a new image processing technique based on 'object-oriented' analysis to count the number of buildings that collapsed during the 2003 Bam, Iran earthquake. Two methodologies are presented, both using a two-phase process comprising building inventory development and damage assessment. Building inventory development provides a count of the total number of structures (both damaged and non-damaged) based on analysis of the 'before' building stock. The damage assessment employs reclassification and edge extraction theoretical techniques to identify the presence of collapsed structures. This is Volume II of a five part series of reports that investigate the use of remote sensing techniques for resilient multi-hazard disaster response.

PREFACE

This preface introduces a five volume series, documenting scientific research conducted by MCEER researchers at ImageCat, Inc., investigating remote sensing techniques for resilient disaster response.

Volume I: INTRODUCTION TO DAMAGE ASSESSMENT METHODOLOGIES

Volume II: COUNTING THE NUMBER OF COLLAPSED BUILDINGS USING AN OBJECT-ORIENTED ANALYSIS: CASE STUDY OF THE 2003 BAM EARTHQUAKE

Volume III: MULTI-SENSOR IMAGE FUSION TECHNIQUES FOR ROBUST NEIGHBORHOOD-SCALE URBAN DAMAGE ASSESSMENT

Volume IV: A STUDY OF MULTI-TEMPORAL AND MULTI-RESOLUTION SAR IMAGERY FOR POST-KATRINA FLOOD MONITORING IN NEW ORLEANS

Volume V: INTEGRATION OF REMOTE SENSING IMAGERY AND VIEWS™ FIELD DATA FOR POST-HURRICANE CHARLEY BUILDING DAMAGE ASSESSMENT

The report series embraces MCEER's stated mission of pursuing *the discovery and development of new knowledge, tools and technologies that equip communities to become more disaster resilient in the face of earthquakes and other extreme events*. Accordingly, the research documented here is multi-hazard in nature, spanning international earthquake, flood and hurricane events. In all cases, the research is undertaken with the underlying goal of improving resilience, in particular the *rapidity* and *resourcefulness* of disaster response activities. Further, it is aimed at meeting stated user needs in the immediate aftermath of disasters, such as a rapid estimate of the number of collapsed/damaged structures, and the delineation of flood inundation zones.

These volumes represent a significant milestone in post-disaster damage assessment, constituting the culmination of seven years' research activities. During this time, we have witnessed the 'Coming of Age' of remote sensing technologies and analytical techniques within the disaster response arena. *Technology push* in the form of new sources of high-resolution imagery and increasingly advanced and analytical techniques has driven the development of new capabilities attuned to meet the needs of responders. This has been coupled with heightened *User pull* from sectors including the re/insurance industry, and with the onset of recent catastrophes such as hurricane Katrina, opportunities for operational implementation.

Research collaborations established by ImageCat, Inc. with multi-hazard researchers from the US, Italy and UK, underpin this report series. Through sharing and exchanging a wealth of experience and expertise, the teams of scientists and engineers have advanced the knowledge boundaries of remote sensing damage detection. Particular highlights include:

- ✓ The ability to rapidly count the number of collapsed buildings, where a building is treated as an 'object' within the digital image, rather than a group of pixels (Volume II in collaboration with the University of Bologna)
- ✓ The fusion of pre- and post-disaster imagery captured by different high resolution sensors to facilitate flexible damage mapping irrespective of which sensor passes first over the disaster zone (Volume III)
- ✓ The use of cloud-penetrating to assess flooding extent throughout storm-ridden areas (Volume IV in collaboration with University College London)
- ✓ HAZUS-compatible post-hurricane damage assessment based on remote sensing imagery, when access to the disaster zone is precluded (Volume V in collaboration with Texas Tech University).

In June 2006, MCEER launched its Remote Sensing Institute (RSI), which will *serve as a platform for developing and operationally implementing innovative multi-hazard techniques, strategies and products for rapidly assessing post-disaster impacts, modeling and quantifying the built environment, and monitoring recovery*. The RSI will continue to embrace fundamental and applied research activities to develop innovative new approaches to short- and long-term disaster management. Commercial products and services developed by MCEER researchers and available through RSI include: near real-time flood, surge, hurricane, earthquake and tsunami damage assessment through remote sensing-based damage scales and advanced image analysis techniques; and forensic GPS-registered damage assessment using the in-field VIEWS™ data collection and visualization system.

ABSTRACT

Volume II in this five volume report series documents exploratory research conducted by MCEER researchers at ImageCat in collaboration with the University of Bologna, using a new image processing technique based on '*object-oriented*' analysis to *count the number of buildings that collapsed* during the 2003 Bam, Iran earthquake.

From a resilience standpoint, the ability to swiftly count the number of collapsed buildings is valuable, because it can be used to generate *rapid* loss estimates for urban structures, benefiting the re-insurance industry, and also to infer the number of casualties, helping national and international emergency management teams and aid agencies scale search and rescue and response activities.

Two object-oriented methodologies are presented for quantifying the number of collapsed buildings using high-resolution optical satellite imagery captured before and soon after the event. The methodologies employ a two-phase process, comprising: (1) building inventory development; and (2) damage assessment. Building inventory development provides a count of the total number of structures (both damaged and non-damaged) based on analysis of the 'before' building stock. The damage assessment employs reclassification and edge extraction theoretical techniques to identify the presence of collapsed structures.

For the reclassification, it was found that intact adobe buildings are characterized by homogenous and bright/white domed or flat rooftops. In contrast, the collapsed structures appear as chaotic piles of debris, of a subdued color that is similar to the surrounding soils. For the edge-based approach, damaged buildings were identified through differences between the occurrence of edge features within the before and after images. In this instance, intact adobe buildings are delineated around the margin, with limited texture on the domed roof. In contrast, irregular edges occur within collapsed structures, associated with chaotic debris piles.

Accuracy of the initial building inventory extraction proved to be a major determinant of accuracies achieved with the building damage count. The key processing step of segmentation was found to overestimate the frequency of objects, even when 'optimum' parameters were employed on a scene-wide basis. This suggests that future work should focus on the implementation of different intra-scene segmentation factors, attuned to each major class of building stock.

The reclassification methodology performed better than the edge-extraction technique. The final count of collapsed buildings was 17% higher than the validation dataset developed by Yamazaki et al. (2004). This overestimation is largely due to object split at the segmentation phase and reinforces the importance of further research to improve the accuracy of building inventory extraction prior to damage assessment.

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SECTION 1
INTRODUCTION

1.1 Rationale and Literature Review

Volume II of this five volume report series entitled *Remote Sensing for Resilient Multi-Hazard Disaster Response* documents research conducted through collaboration between MCEER researchers at ImageCat and DISTART at the University of Bologna. The aim of this research is to *develop a new object-oriented methodology for rapidly counting the number of collapsed buildings in the immediate aftermath of a major earthquake*. The 2003 Bam (Iran) earthquake is employed as a case study (see Volume I in this report series for details of the event).

In the aftermath of a disaster, a rapidly produced count of the number of collapsed buildings is valuable, because it may be used for a range of applications including:

- Generating rapid and robust loss estimates for urban structures, benefiting the re/insurance industry;
- Inferring the number of casualties, helping national and international emergency management teams and aid agencies scale search and rescue and response activities.

However, this statistic is often unavailable in the days following an event, due to limited access to the affected area, and difficulties rapidly assessing the damage state of a large number of structures, in an efficient and timely way. For example, almost one month had elapsed before an initial statistic for the number of houses destroyed beyond repair in Bam and the surrounding villages was published by the United Nations (United Nations, 2004). The uncertainty regarding damage and casualties that typically exists in the immediate aftermath of such an event, reinforces the need for rapid and objective loss estimates; for example, in the days following the Bam earthquake, the media reported widely fluctuating casualties that ranged between >41,000 and the more recently accepted statistic of ~25,000 (BBC, 2004). In contrast, the remote sensing-based approach described here offers a *resilient* assessment of the post-disaster situation (Bruneau et al., 2003), through the *rapid* and independently-derived assessment of damage, and the implementation of a *resourceful* approach that is not affected by ground-access issues.

This volume of the report series describes a novel 'object-oriented' methodology for counting the number of collapsed buildings, where a cluster of pixels corresponding with a *building* is categorized as an *object*. Analytically, this approach differs from traditional 'pixel-based' optical analyses (see, for example, Volume III of this report series) used to develop damage maps following the 1995 Kobe, Japan (Matsuoka and Yamazaki, 1998), 1999 Marmara, Turkey (Adams and Huyck, 2006; Chiroiu *et al.*, 2006; Eguchi *et al.*, 2002; Huyck *et al.*, 2004), and 2001 Boumerdes, Algeria (Adams *et al.*, 2003) earthquakes. In theoretical terms, an optical pixel-based approach provides information as a function of the reflectance (spectral) and thematic (textural) characteristics of *single* pixels, rather than group of contextually related pixels within the remote sensing scene (Schowengerdt, 1983). Volume I of this report series provides a theoretical review of pixel- versus object-based analytical techniques.

In addition to the reflectance and textural characteristics studied at a per pixel scale (see, for example, Herold *et al.*, 2002; Liu *et al.*, 2005; Walter, 2004), object-oriented analysis also considers shape; for example, whether the object is elongate like a road or compact like a building. Furthermore, object-oriented analysis also yields *contextual* information. According to Benz *et al.* (2004) advantages include the close relation between real-world objects (such as buildings) and image objects, and the availability of new topological information reflecting the relationship between segments. Consequently, object-based image analysis more fully exploits the information derived from remotely sensed images, utilizing as much of the contextual and relational information as possible (Baatz and Schape, 2000).

Object-oriented analysis may employ several different theoretical approaches, including mathematical morphology analysis and multi-resolution segmentation. Mathematical morphology image processing techniques analyze the shape and form of objects, and are based on set theory integral geometry and lattice algebra (Serra, 1982). Stasolla *et al.* (2005) explore the use of morphological operators in tandem with a change detection methodology for post-earthquake damage assessment.

The multi-scale/multi-resolution approach, which constitutes the focus of this study, operates on the premise that objects of different sizes are present within an image. For example, as the segment resolution increases, objects captured may vary from a chimney stack, to a building roof, to a city block, to an entire urban area. This is achieved by a hierarchical network of image objects, the resolution of which is determined by User specifications (see Benz *et al.*, 2004). Hierarchical processing includes the fractal net evolution approach (Baatz and Schäpe 2000), receiver operating characteristic analysis (Hutchinson and Chen, 2005), mathematical morphology (1992), Wavelet decomposition (Sheikholeslami *et al.* 2000), and building a network of linked objects across the scale-space (Vu *et al.* 2005a, 2005b, 2006). Gamba *et al.* (2005) employ a range of geometric and perceptual rules to extract objects of interest.

From an image processing standpoint, a number of different software options exist for conducting object-based analysis (for details, see Baltsavias, 2004; Gusella, 2006). However, in terms of off-the-shelf solutions available to the research community, eCognition is the first commercially-available object-oriented image processing software (Benz *et al.*, 2004). This has become the focus of an ever expanding research field investigating the object as a basic unit for image analysis. Since this research is concerned with developing a practical methodology for damage assessment, the potential of eCognition for fulfilling this requirement is investigated.

In terms of research applications within urban environments, previous studies have investigated its use to identify urban landuse (Kressler *et al.*, 2005a), delineate buildings (Herold *et al.*, 2002; Liu *et al.*, 2005) and refugee tents (Giada *et al.*, 2003), distinguish roof material types (Lemp and Weidner, 2005), and update inventory databases with areas of new construction (Blaschke, 2004; Kressler *et al.*, 2005b) However, while hazard-related uses ranging from flood detection to agricultural crop monitoring are also documented (Definiens, 2006), comparatively few studies have explored its potential for post-disaster urban damage detection.

Using eCognition, Bitelli *et al.* (2004) successfully identify building damage caused by the 2003 Boumerdes, Algeria, Earthquake through examining optimal levels of a hierarchical object-based framework within high-resolution multi-temporal imagery. This work provided a basis for the University of Bologna and MCEER researchers to collaboratively investigate object-oriented techniques for damage assessment following the Bam earthquake (Gusella *et al.*, 2005).

A limited number of other eCognition-based damage detection studies are documented in the literature, since this is a relatively new and emerging research area. Kouchi and Yamazaki (2005) use a single post-event image and Matsumoto *et al.* (2006) pre- and post-disaster coverage to respectively explore damage caused by the 2003 Boumerdes and 2006 Central Java earthquakes. In addition to direct earthquake damage, eCognition has also recently been used to detect secondary tsunami wave effects caused by the 2004 Sumatra-Andaman earthquake, recoded by pre- and post-event radar imagery (Greidanus *et al.* 2005). Outside the eCognition processing environment, Vu *et al.* (2005a, 2005b, 2006) explore a morphological approach for post-earthquake damage detection in Bam, Iran, and damage mapping in tsunami-affected areas.

1.2 Approach

Change detection is an important methodological component of damage detection studies such as these. A range of techniques have been explored for detecting and characterizing urban changes arising from disasters and urban development, some of which are based on pixels, and other objects (for a useful summary see Hall and Hay, 2003). As shown by the methodology flow diagram in figure 1-1, a series of two different image processing and analytical approaches are explored here for counting building collapse:

1. Method 1: Reclassification
2. Method 2: Edge-based damage threshold

Reclassification uses information extracted from a set of sample buildings in the 'after' image to reclassify building footprints extracted from the 'before' scene into classes of collapsed and non-collapsed. This is arguably the simplest and most rapid procedure, since it is conducted within the eCognition image processing software and does not require the extraction of event-specific statistics. However, there are several potential disadvantages: first, the accuracy achieved in reclassification is dependent on the identification of representative examples of damaged buildings as training samples; and second, unless the characteristics of building damage are constant between events, this method does not lend itself to generalization, and thus automation. In contrast, the damage thresholds involve assigning specific textural (in this case edge-based) characteristics to building collapse, which have the potential to be used more generally for automated damage assessment. Further, these damage assessment procedures may be implemented in conjunction with the object-oriented approach described in the following sections, or at other 'pixel-based' levels of the Tiered reconnaissance framework, with for example, generalized thresholds providing a basis for a rapid neighborhood assessment.

Following a summary of the datasets employed and preprocessing procedures (Section 1-3), Section 2 and Section 3 describe the method and results obtained using a reclassification-based object-oriented image processing technique. Sections 4 and 5 present the method and results for an edge-based approach. In both cases, the method employs the same pre-processed images of Bam, and involves two major components: (a) initial processes for building inventory development, to identify the total number of buildings (both damage and non-damaged) within the city; and (b) subsequent damage assessment processes for establishing which of these structures collapsed.

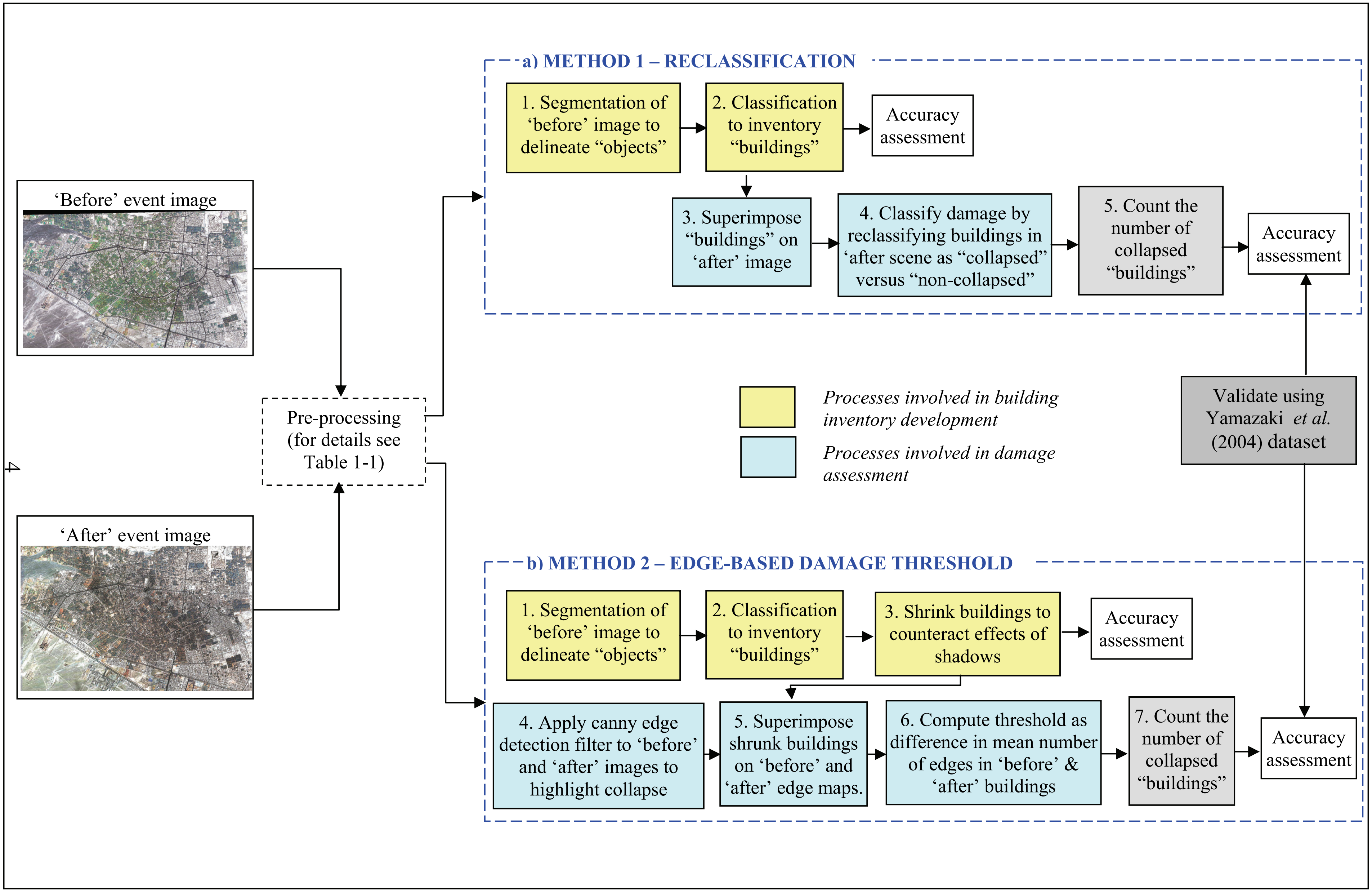


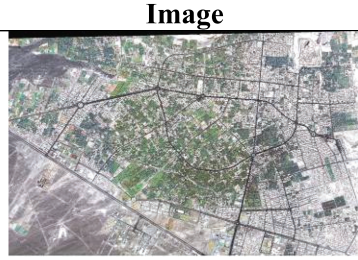
Figure 1-1 Methodology Flow Diagram Illustrating the Two Different Techniques Investigated for Counting Building Collapse in Bam: (a) Reclassification; and (b) Edge-Based Damage Threshold.

The object-oriented image processing techniques employed for Method 1 (reclassification) and Method 2 (edge detection) were conducted using eCognition image processing software. Although alternative segmentation algorithms (see, for example, Meinel and Nubert, 2004; also Gusella, 2006) and feature extraction programs are also available (Feature Analyst, Visual Learning System, Inc.), an evaluation of these software is reserved as a topic for future work. Pre-processing was conducted in ENVI software (RSI, 2002) and pixel-based processes such as the edge enhancement for Method 2 were completed using Matlab. Accuracy assessments were conducted using ArcGIS.

1.3 Datasets and Pre-Processing

From table 1-1, the Method 1 reclassification and Method 2 edge-based object-oriented techniques for assessing building collapse employ high-resolution standard product Quickbird imagery, collected before and in the immediate aftermath of the Bam earthquake. From a theoretical standpoint, building collapse is clearly visible on high-resolution remote sensing imagery of Bam (figure 1-2). Within the before image, the roofs of traditional adobe structures that typify much of the built environment, appear as homogenous bright white objects of regular shape (see figure 1-2e). Contemporary buildings are generally larger than the traditional adobe family dwellings and exhibit various roof colors that include blue (see figure 1-2b). Within the after image (figure 1-2f), for buildings that collapsed, the homogenous roof configuration is replaced by a chaotic pile of debris. There is also a dramatic change in color, with brown/grey colored debris resembling the surrounding non-developed land surface.

Table 1-1 High-Resolution Quickbird Imagery of Bam and Pre-Processing Procedures

<table>
<tr><th>Acquisition Date</th><th>Summary True Color Image</th><th>Spatial Resolution</th><th>Pre-processing steps</th></tr>
<tr><td>“Before”: 09/30/2003</td><td></td><td rowspan="2">0.60 m panchromatic

2.40 m multispectral</td><td>IHS pan sharpening (RGB channels), contrast enhancement (linear with 2% saturation)</td></tr>
<tr><td>“After”: 01/03/2004</td><td></td><td>IHS pan sharpening (RGB channels), contrast enhancement (linear with 2% saturation), registration to “before” using 49 control points (1.8 RMS), first order polynomial mapping function and nearest neighbor re-sampling</td></tr>
</table>

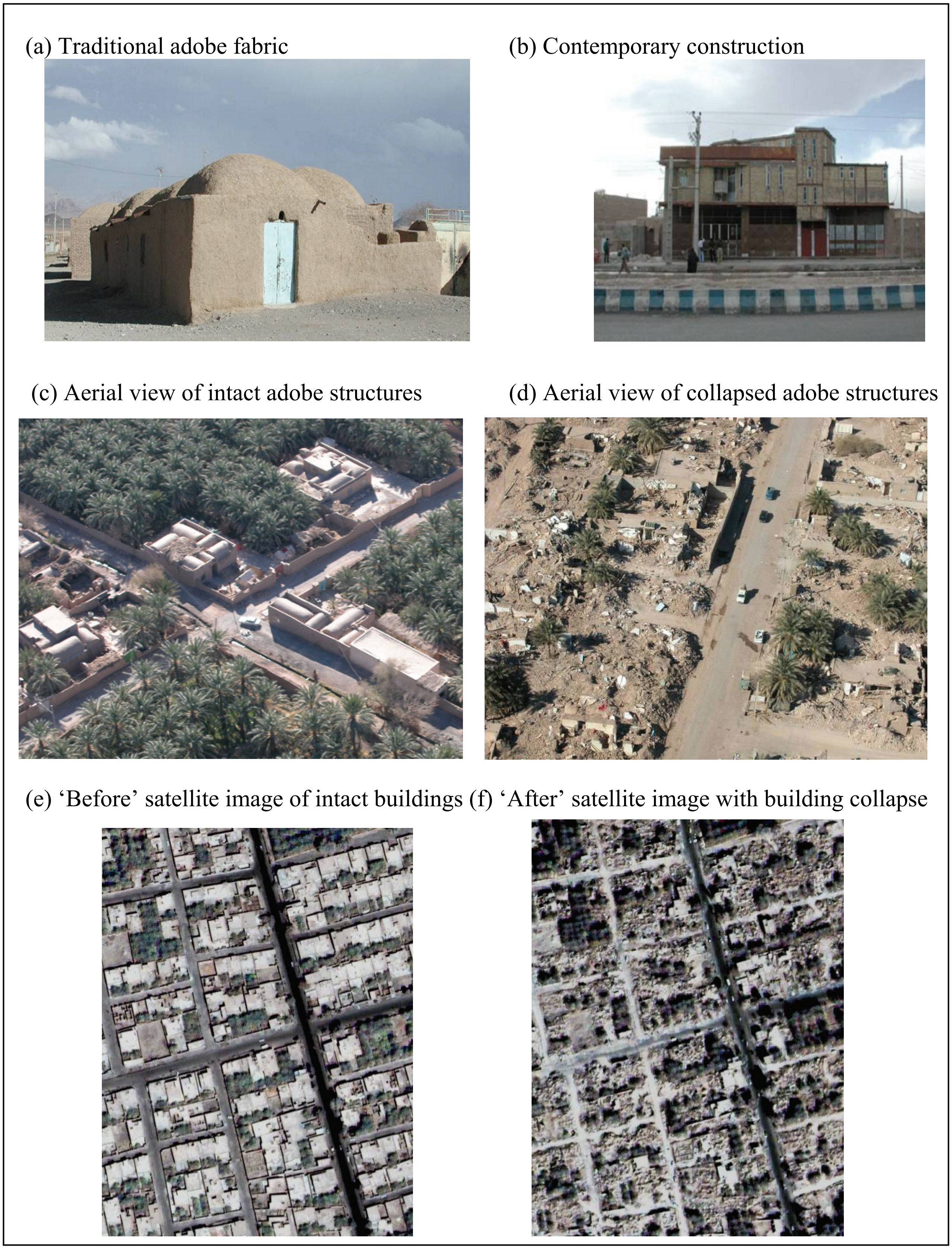


Figure 1-2 Examples of Building Fabrics and Damage in Bam

The city-wide scenes were pre-processed using the image fusion technique of true-color IHS pan-sharpening. This maximized the information content of each scene by combining the spatial detail of the panchromatic band with the spectral signatures captured by the multispectral image bands. A 2% linear stretch contrast enhancement was also employed, to optimize the pre-event appearance of built structures, and the distinction between collapse and non-collapse scenarios in the post-event scene (Liu *et al.*, 2005). To maximize spatial correspondence between the multi-temporal scenes the "after" event image was registered to the "before" image, using a series of 49 spatially distributed ground control points with a first order polynomial transformation.

The validation dataset comprises a visually-based per-building damage assessment of ~10,104 buildings within the remote sensing imagery, conducted by Yamazaki *et al.* (2004) according to the EMS98 scale (see figure 1-3):

- EMS grade 5 and grade 4 (destroyed and partially destroyed buildings); Total number of buildings counted = 5533

- EMS grade 3 and lower (Buildings surrounded by debris or undamaged); Total number of buildings counted = 4571

Figure 1-3 Validation Dataset for Bam, Showing EMS Damage Levels 1, 3, 4 & 5. Courtesy of Yamazaki *et al.* (2004)

SECTION 2
METHOD 1: RECLASSIFICATION

The flow diagram in figure 1-1a outlines Method 1: Reclassification, for counting the number of collapsed buildings in Bam. Together, the building inventory and damage assessment processes include five steps, comprising:

1. Segmentation of the 'before' image to identify objects that could be buildings;
2. Classification of the 'before' image objects to identify those that are buildings;
3. Superimposing these building footprints on the 'after' image to visually distinguish collapsed from non-collapsed structures;
4. Reclassification of the buildings into classes of collapse and non-collapse based on the unique spectral characteristics of these respective damage states within 'after' image;
5. Counting the number of collapsed structures.

The following sections describe each of these processing steps, and include details of the accuracy assessments that were conducted for the image segmentation, building classification and damage count.

Notably, this approach employs both before and after imagery, but the method of damage classification differs from 'change detection' analyses employed in Volume III and by Adams *et al.* (2004) and Huyck *et al.* (2004). It identifies building collapse in terms of the unique statistical characteristics of intact versus damaged structures within the "after" scene, rather than the degree of change between pre- and post-event images.

2.1 Segmentation (Step 1)

For Step 1, the full extent of the Bam pre-processed 'before' image was segmented to group the constituent pixels into "objects". The segmentation is performed using a multi-resolution 'bottom up' region-merging technique. In this context, with a multi-region approach objects of interest typically appear on different scales in an image simultaneously. The extraction of meaningful image objects needs to take into account the scale of the problem to be solved Therefore the scale of resulting image objects should be freely adaptable to fit the scale of the task (Baatz and Schape, 1999). The technique is bottom up (oppose to top down) inasmuch that processing starts with one pixel objects and 'in numerous subsequent steps smaller image objects are merged into bigger ones' (Benz *et al.*, 2004).

Region growing proceeds through an optimization process, which from figure 2-1 involves three concepts: (a) color; (b) shape>smoothness; and (c) shape>compactness. The optimization procedure minimizes the heterogeneity of resulting image objects (i.e. the merge occurs that results in the smallest growth in heterogeneity). The optimization process is stopped by a scale parameter *t*, if the smallest growth results in an average object size that exceeds the threshold defined. The larger the scale parameter, the more objects can be merged and the larger each individual object grows before it reaches the scale threshold (Baatz and Schape, 1999; Benz *et al.*, 2004; Zhong *et al.*, 2005).

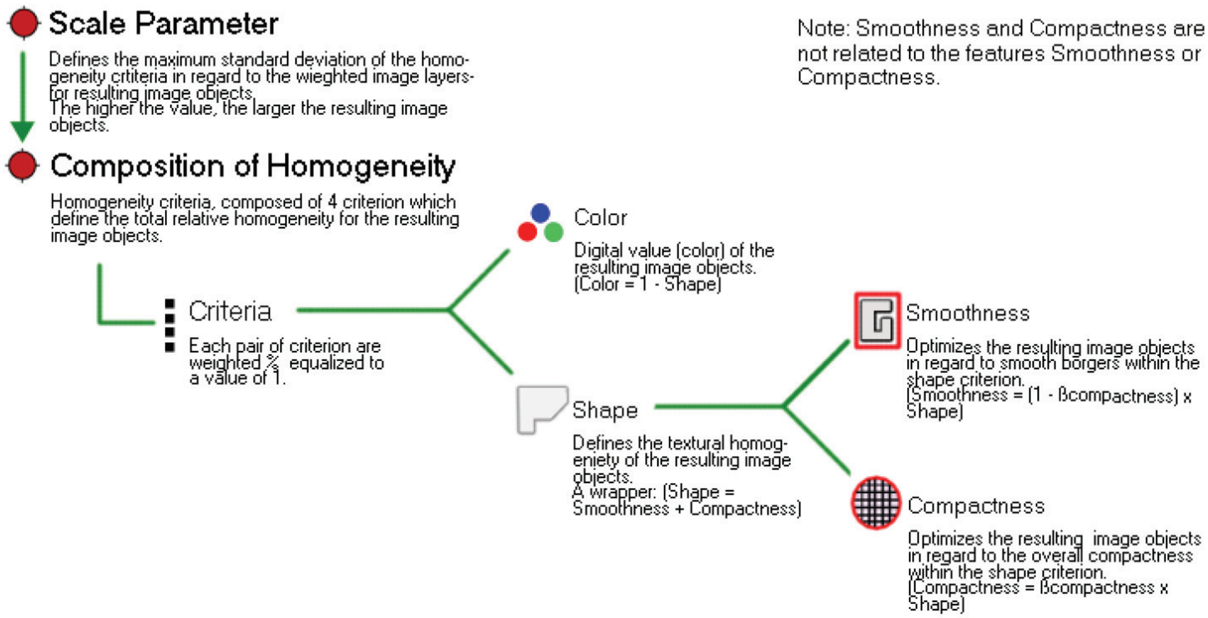


Figure 2-1 Concept Flow Diagram for Multi-Resolution Segmentation (Definiens, 2006)

Based on the flow diagram in figure 2-1, summary definitions and key equations for the segmentation process include (see Definiens, 2006; also Benz *et al.*, 2004; Baatz and Schape, 2000; Frauman and Wolff, 2005; Hoffman, 2001; and Zhong *et al.*, 2005):

Scale parameter (termed Scale):
An important parameter of the multi-resolution segmentation, Scale is used to determine the upper limit for a permitted change of heterogeneity throughout the segmentation process. The scale parameter determines the average image object size; the larger the scale parameter, the larger the objects. For examples of the relationship between scale parameter and object size and frequency, see Frauman and Wolff (2005).

Heterogeneity criterion
The homogeneity criterion is used to determine which heterogeneity attributes of image objects are to be minimized as a result of a segmentation run. Criteria used to describe image object heterogeneities comprise: color criterion (Δh_{color}), and shape criterion (Δh_{shape}). Shape encompasses smoothness and the compactness criteria. The composition of the entire homogeneity criterion is defined by assigning weights (w_{color} and w_{shape}) to each of these criteria. The higher the shape criterion, the less spectral homogeneity influences object composition.

$$f = w_{color} * \Delta h_{color} + w_{shape} * \Delta h_{shape} \tag{2-1}$$

Color criterion
During the merging process, the color criterion represents the degree of change in spectral values within an image object. The color heterogeneity factor is defined by the standard deviation of pixel values within the regions to be merged (σ_{1c} *and* σ_{2c}) and the resulting merged region (σ_{mc}),

for a given spectral band or channel (c), which are weighted by (w_c). The numbers of pixels within each object and the merged object are given by n_{mc}, n_{1c} and n_{2c}.

$$\Delta h_{color} = \sum_{c} w_c(n_{mc}\sigma_{mc}) - (n_{1c}\sigma_{1c} + n_{2c}\sigma_{2c})) \qquad (2\text{-}2)$$

Shape criterion

The shape criterion describes the change in object shape relative to weighted smoothness (w_{smooth}) and compactness ($w_{compact}$) criteria. Where the shape criterion is greater than zero, the degree of smoothness or compactness can be specified.

$$\Delta h_{shape} = w_{compact} * \Delta h_{compact} + w_{smooth} * \Delta h_{smooth} \qquad (2\text{-}3)$$

Smoothness criterion

The smoothness criterion optimizes image objects with regard to the smoothness of borders. The smoothness criterion is useful when working with very heterogeneous data, to inhibit the objects from having frayed borders, while maintaining the ability to produce non-compact objects. The degree of change in smoothness (Δh_{smooth}) is a function of the ratio of the border length (l) and the border length given by a bounding box (b) that contains the object yet follows the line of raster pixels. Again, this measure is computed as the change between these values for the merged versus the discrete objects.

$$\Delta h_{smooth} = n_m \frac{l_m}{b_m} - (n_1 \frac{l_1}{\sqrt{b_1}} + n_2 \frac{l_2}{\sqrt{b_2}}) \qquad (2\text{-}4)$$

Compactness Criterion

In a raster image, the ideal compact form of an object is a square. The compactness criterion minimizes the deviation from the ideal compact form. The degree of change ($\Delta h_{compact}$) is a function of the ratio of the border length (l) and the square root of the number of pixels within the separate and merged objects.

$$\Delta h_{compact} = n_m \frac{l_m}{n_m} - (n_1 \frac{l_1}{\sqrt{n_1}} + n_2 \frac{l_2}{\sqrt{n_2}}) \qquad (2\text{-}5)$$

These parameters co-vary within the eCognition processing environment. In addition to the segmentation-related variables, figure 2-2 shows that the input bands may also be weighted to vary their importance for the result obtained. This flexibility may be significant where different genres of input data are used, such as spectral bands versus a DEM (Hofmann, 2001). Given the exploratory nature of the present study and sole use of spectral information, an equal weighting was applied to all bands.

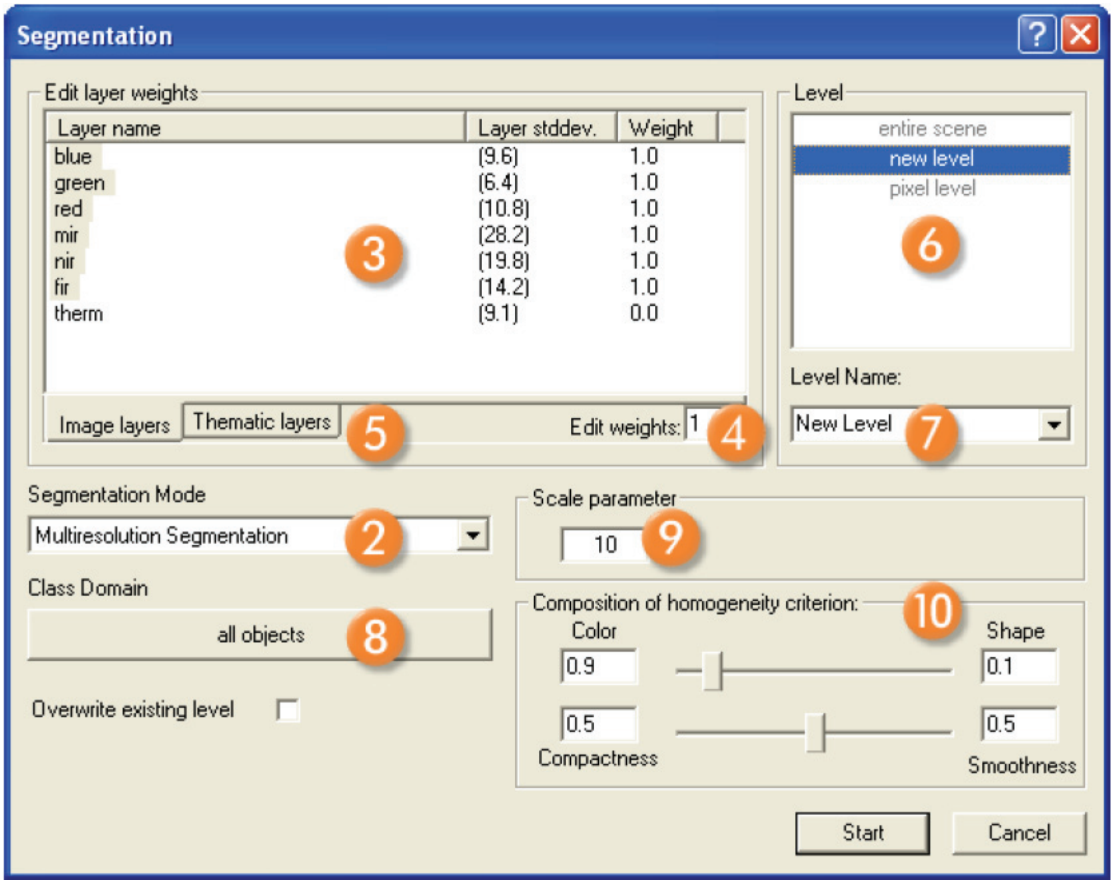


Figure 2-2 ECognition User Interface for Multi-Resolution Segmentation Parameter Specification. Objects of Interest are Identified by Varying Scale, Color and Shape Criteria.

For multi-resolution segmentation, a wide range of different results are possible depending on the input parameters used. For any given application, an important requirement is therefore to define an optimum combination of parameters that extracts objects of interest (in this case, buildings). The objective for this research was to identify a single set of segmentation factors that could extract objects relating to buildings applicable on a *scene-wide basis*. The premise here is that the building stock throughout Bam is relatively homogenous in terms of composition and spatial configuration; the investigation of intra-scene variations in parameter specification for object delineation is a topic for future research.

In defining an optimum set of parameters, as Hofmann (2001) notes, there is an added level of complexity, since the results of image segmentation depend strongly on the inherent characteristics of the image data itself. Thus, it is difficult to develop generalized rules for object-extraction based on previous research that use alternate imagery sources or focus on other geographic locations. Accordingly, the present study employs an iterative testing process to define an optimum set of segmentation parameters. In order to select suitable segmentation parameters, a set of 'ground truth' digitized buildings (see, figure 2-3a) are compared with the segmentation results (figure 2-3b). The ground truth data were obtained by manually digitizing a sample of 108 adobe buildings of varying shape and size, randomly distributed throughout the image.

(a) Digitized buildings (b) Overlapping objects (blue)

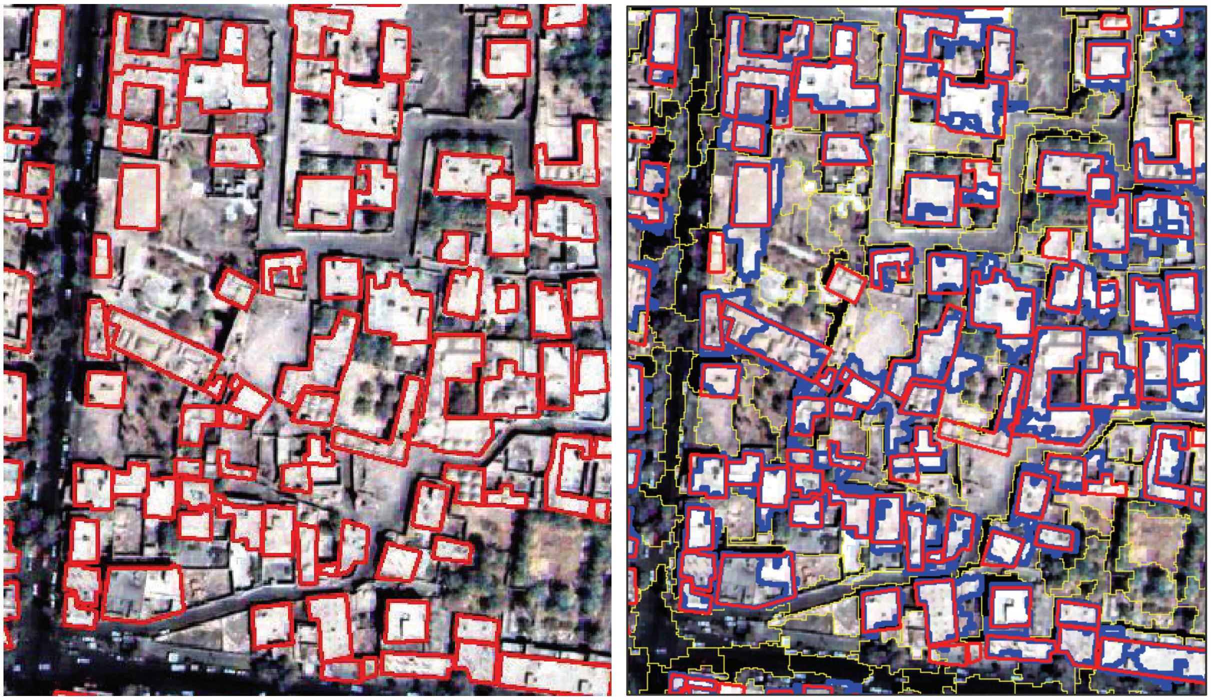


Figure 2-3 Example of Digitized Buildings and Correspondence with Overlapping Objects Evaluated for Segmentation Parameter Optimization in Bam. Segmentation Parameters Used were Scale = 30, Color = 0.1, Shape>Smoothness = 1

A range of different permutations of color, shape and scale segmentation parameters were tested for Bam. Segmentation results for various permutations of these parameters were compared with the digitized "ground truth" footprints (figure 2-4). The segmented objects were overlapped with the digitized set, and the degree of correspondence computed. The ideal case is 1:1 object:building footprint correspondence. If this is achieved, the total number of objects identified within the image matches the true number of ground surface features. A 1:1 correspondence was assumed where there was >50% overlap between the area of the segmented object and the digitized building. Performance was assessed qualitatively for color and shape criterion through visual inspection, and quantitatively for Scale.

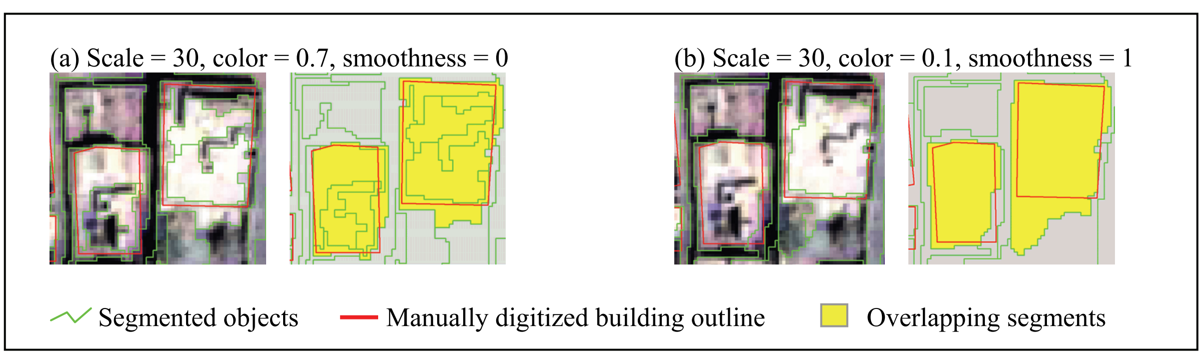


Figure 2-4 Comparison Between Objects Delineated Using Different Spectral and Smoothness Segmentation Parameters

In the case of Scale, figure 2-5 shows how, in theoretical terms, segmentation-based object recognition can affect the count of buildings. With scenario (a) 'perfect fit', for each object there is a 1:1 correspondence; in scenario (b) "object fragmentation", two buildings fall within only one object; in scenario (c) "building fragmentation", two objects are recognized within a single building; and scenario (d) is a combination of (b) and (c). The performance of different scale measures was measured in terms of the occurrences of 1:1 object:building correspondence (Scenario a), and building split (Scenario c).

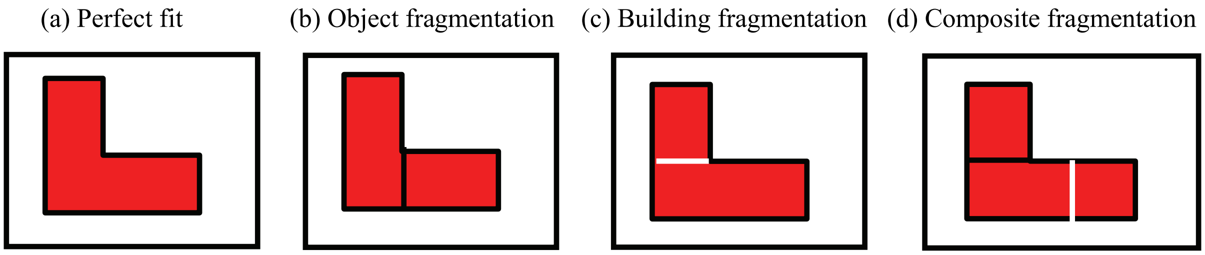


Figure 2-5 Segment (Red Areas Divided by White Line) and Digitized Object (Black Line) Correspondence. Segmentation Scenarios: a) Perfect Fit; b) Object Fragmentation; c) Building Fragmentation; and d) Object & Building Fragmentation.

2.2 Building Classification (Step 2)

The classification process in eCognition may utilize either physical or semantic characteristics of the segmented objects (for details, see Hofmann, 2001). For Step 2 of the methodology (see figure 1-1a), segmented objects spanning the full extent of the 'before' image were divided into physically-based classes of:

1. Building
2. Not building
3. Shadow
4. Vegetation

In order to train the segment-based supervised classification, a sample of training objects for each class was manually selected throughout the image. A single class for 'building' was employed due to the concentration of adobe structures in Bam, exhibiting similar roof characteristics. Studies focusing on more diverse building stock and roof types (see for example, Herold *et al.*, 2002) instead employ a range of classes. A supervised standard nearest neighbor classification was implemented using eCognition software. This is a deterministic approach to classification, which crisply assigns each object to a given class based on a proximity measure to the feature space (see, for example, Wei *et al.*, 2005). It is the most straightforward classification option available, which was deemed appropriate, given the exploratory nature of this research.

Although not employed here, eCognition also offers several more sophisticated classification options. The advanced nearest neighbor option enables a different image feature to be used to define each class, such as spectral versus area-based (see, for example, Herold *et al.*, 2002). The eCognition 'fuzzy' classification methodology enables a broad range of different features including spectral signatures and variables relating to shape, texture, hierarchical and neighborhood properties, to be used for class definition. It returns statistics showing the probability on a scale of 0-1 of each object belonging to a given membership class (Hofmann, 2001; Benz *et al.*, 2004; Chen *et al.*, 2005; Liu *et al.*, 2005). For a theoretical overview of fuzzy classification in urban areas, see Shackelford and Davis (2003). Investigating the performance of these classification algorithms for post-disaster damage classification remains a topic for future research.

The classification was conducted, with image objects assigned to a best-fit class according to an exponential membership function. Within eCognition, the feature vector that underpins the classification comprises spectral and textural (standard deviation of pixel values within the object) characteristics of the training objects (for details, see Definiens, 2004). An accuracy assessment was performed, using a simple random sampling scheme (Congalton, 1982), based on a subset of 327 objects. The classified and actual classes were observed for each object, and a confusion matrix constructed.

2.3 Damage Detection (Step 3 and Step 4)

For methodological Step 3 (figure 1-1a), the objects previously classified as 'buildings' using the 'before' image were superimposed on the 'after' scene. To distinguish between collapsed versus non-collapsed structures (Step 4), the superimposed 'after' image buildings were re-classified with a training set of damaged and non damaged objects from the buildings class, using a standard spectrally-based supervised nearest neighbor approach.

The premise here is that within the 'after' scene, collapsed structures have different statistical characteristics compared with the non-damaged case. This assumption appears to be reasonable, based on the distinctive optical characteristics of these damage states within the satellite imagery, and also field-based photographs; from figure 1-2, intact adobe buildings are characterized by homogenous and bright/white domed or flat rooftops. In contrast, the collapsed structures appear as chaotic piles of debris, of a subdued color that is similar to the surrounding soils.

Alternative damage detection techniques are documented in the literature, which may be explored as part of future research activities. They include a building damage index, which compares the area occupied by a given structure in the before and after scenes (Stasolla *et al.*, 2006), a correlation index, PCA index and boundary compactness index (Hutchinson and Chen, 2005). Blaschke (2004) proposes an area/perimeter based change detection methodology, which although applied to the general concept of landuse change could be applicable to damage detection.

2.4 Counting the Number of Collapsed Buildings (Step 5)

Finally, the occurrence of collapsed buildings was computed based on the total number of structures identified during the building classification in Step 2, the damage detection re-classification result and accuracy level.

SECTION 3
RESULTS 1: RE-CLASSIFICATION

3.1 Segmentation

The Step 1 segmentation results exhibited limited sensitivity to variations in smoothness, since buildings are typically compact compared with roads, for example, which are elongate. However, color proved to be an important factor for extracting roof structures from the 'before' image. When the contribution of spectral information is high, the segmentation results are highly fragmented, because the detail captured within individual roofs by the high-resolution produces an irregular fractal shape with several segments falling within a given roof. Reducing the influence of color improves the result by accommodating slight variations in reflectance and minor areas of shadowing within the roof, producing segments that correspond closely with the building outline.

Figure 3-1 provides a graphical representation of the results for Scale. In figure 3-1a, a Scale of 30 achieves close correspondence between the total building count and the sample of 108 digitized footprints. Although there is a shortfall in 1:1 object:building correspondence, from figure 3-1b, this occurs because of building split. Figure 3-1a shows how, when this split is taken into account, values for the building count (total buildings) and number of digitized footprints converge. Visual inspection of the nature and spatial distribution of building split suggests that these deviations from 1:1 object:building correspondence are attributable to intra-scene variation in building stock composition and configuration. A final segmentation parameter set comprising scale = 30, color = 0.1, shape>smoothness = 1, was employed for the before event image.

3.2 Building Classification (Step 2)

From table 3-1a, the Step 2 classification of objects within the segmented 'before' image identified a total of 22,865 'buildings'. For the accuracy assessment, the accompanying confusion matrix shows the degree of correspondence between classified and digitized buildings for the random test set of 327 objects. The accuracy for the whole classification (diagonal of the confusion matrix divided by the total number of sample objects) is 82.8%. In the case of buildings, a total of 49 test objects were classified as buildings, compared with the 'true' occurrence of 43. From the 'reduced' confusion matrix in table 3-1b, these correspond with a 'User accuracy' of 80% and 'Producer accuracy' of 91%. (Congalton, 1982)

While the object-oriented technique employed here successfully identifies buildings within Bam, as previously observed during the segmentation step, heterogeneity within the building stock causes a number of instances where the 1:1 object:building footprint relation does not apply. The mitigation of this offset through techniques such as intra-scene segmentation optimization will constitute a significant refinement to this methodology, and as such is a major focus for future research. However, for the present study, an adjustment factor is employed to finalize the count of structures in Bam.

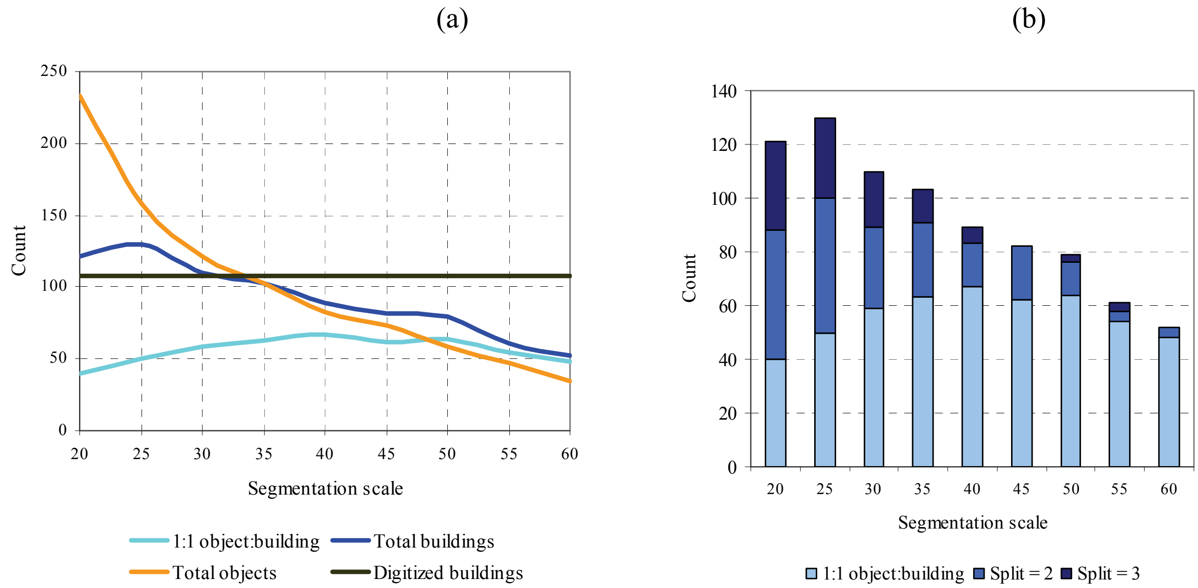


Figure 3-1 Evaluation of Segmentation Scale Factor for a Sample of 108 Digitized Buildings. (a) Correspondence Between Digitized Building Footprints, Segmented Buildings and Objects Using Scale Factors Spanning 20-60. 1:1 Object Building Indicates the Number of Buildings Uniquely Selected for a Given Object. Total Buildings Indicates the Number of Buildings Matched. However, a Given Building May Contain Multiple Objects. Total Objects Indicates the Number of Objects Corresponding with a Building. However a Given Object May Contain Multiple Buildings. (b) Occurrence of Building Fragmentation Scenarios.

Table 3-1a Confusion Matrix for Building Classification Using the 'Before' Imagery. The Total Number of Objects within each Class is also Shown, Together with the Number of Training Samples Used.

Reference/ Classification	Number of training samples	Number of objects	Building	Not Building	Shadow	Vegetation	Total	User Accuracy
Building	157	22,865	39	10	0	0	49	0.80%
Not Building	274	54,875	4	154	0	6	164	0.94%
Shadow	15	7,118	0	1	7	2	10	0.70%
Vegetation	72	36,732	0	15	6	71	92	0.77%
unclassified	-	4,272	0	10	0	2	12	
Total	518	125,862	43	190	13	81	327	
		Producer Accuracy	0.91%	0.81%	0.54%	0.88%		

Table 3-1b 'Reduced' Confusion Matrix (Czaplewski, 1992), Showing "User" and "Producer" Classification Accuracies (Congalton, 1982) for Classes of 'Building' and 'Other' (Not Building, Shadow and Vegetation).

Building Inventory				Accuracy assessment			
	Number of objects & proportion (%)	Interim count (equation [1])	Inventory count (89% reduction)	Building	'Other'	Total	User accuracy
Building	22,865 (18.1%)	21,144 (16.8%)	18,872	39	10	49	80% (39/49)
'Other'	102,997 (81.9%)	104,718 (83.2%)	-	4	274	278	98% (274/278)
Total	125,862	125,862	-	43	284	327	
			Producer accuracy	0.91% (39/43)	0.96% (274/284)		

First, the marginal probability approach employed by Czaplewski (1992) was used to adjust the number of objects classified as building. In Equation 1, x is the true proportion of classified buildings (the unknown), y is the estimated proportion of the building class (from classification), Ha is the Producer building classification accuracy and Hb is the Producer classification accuracy for 'other' classes (see table 3-1b).

$$y = x\,Ha + (1-x)\,(1-Hb) \qquad (3\text{-}6)$$

From table 3-1b, y = 0.18 (the ratio of classified buildings to total objects). Ha = 0.91 and Hb = 0.96. The actual proportion of classified buildings is computed as x = 0.17, producing an interim inventory count of 21,144. Secondly, the object count was adjusted by the object fragmentation factor for Scale = 30 (figure 3-1a). The interim count was reduced by 89% (121 total objects corresponding with 108 buildings digitized). Accordingly, the total building inventory in Bam is calculated as 18,872. This is an overestimate compared with the number of observations contained within the Yamazaki *et al.* (2004) database of 10,104. Reasons for the overestimation require further investigation, but are likely to be in part due to inaccuracies introduced at the segmentation stage when a given building may contain multiple objects. They also point to limitations of using a single set of segmentation parameters for extracting all buildings within a given city. Methodological challenges associated with using a spatially varied set of parameters attuned to the building size and shape requires further investigation.

3.3 Damage Detection (Step 3 and Step 4)

When superimposing the 'before' image building outlines with the 'after' image (figure 3-2), visual inspection of buildings that remained standing suggests that the registration process generally achieved a close correspondence between their footprints on the pre- and post-event coverage. A small margin of offset (on the order of 2-3 pixels) was evident between the location of some outer walls, apparently due to multi-temporal variability in shadowing and sensor look angle.

(a) Before (a) After

Figure 3-2 Minor Offset in Image Registration, Illustrated by Overlaying 'Before' Image Building Outlines with the 'After' Image

Figure 3-3 shows results for the city-wide re-classification, where a nominal 40% of objects were classified as collapsed. To assess the accuracy of the building damage classification, a sample comprising 136 buildings (see Congalton, 1982) was selected and their respective classified and observed damage states recorded. The confusion matrix in table 3-2 shows results for the accuracy assessment, which was conducted using 136 samples from the Step 2 building class. A total of 24 objects were rejected from the confusion matrix, because they were misclassified from building to 'other'. For the remaining samples, the re-classification achieved an accuracy of 70.5%.

Table 3-2 Results for the Damage Re-Classification and Count of Collapsed Buildings. The Confusion Matrix for the Accompanying Accuracy Assessment Shows the "Producer" Classification Accuracy (Congalton, 1982) Used to Compute the Final Count.

Damage Detection						Accuracy assessment			
	Training Sample	Objects classified	%	Buildings classified	Final count (eq [3-6])	Collapsed	Not damaged	Total	User Accuracy
Collapsed	174	8,458	40	7,549	6,473 (34.3%)	44	12	56	78.5%
Not damaged	206	12,686	60	11,323	12,399 (65.7%)	21	35	56	62.5%
Total		21,144	100	18,872	18,872	65	47	112	
					Producer accuracy	67.4%	74.4%		

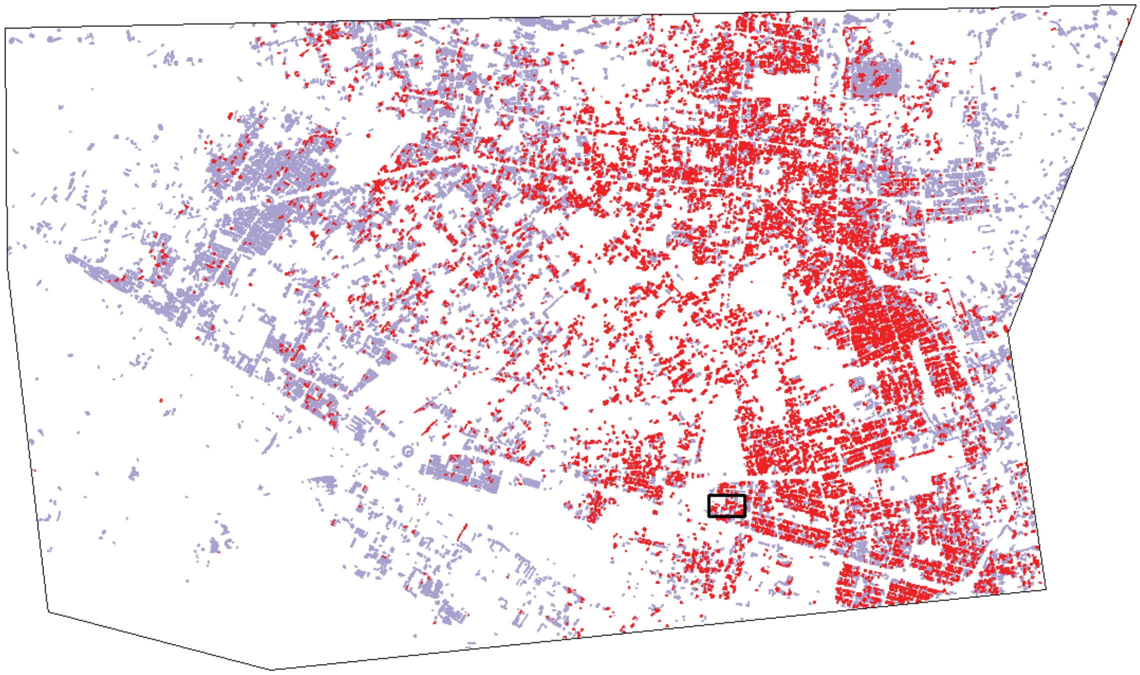


Figure 3-3 Building Damage Map for the City of Bam, Based on Object-Oriented Analysis of Quickbird Imagery Captured Before and After the Event. Collapsed Structures are Shown in Red and Non-Collapsed in Blue.

3.4 Counting the Number of Collapsed Buildings (Step 5)

The proportion of objects classified as collapsed buildings (table 3-2) was adjusted to 34.3% according to the marginal probability approach employed by Czaplewski (1992). Accordingly, the final count of collapsed buildings was calculated as 6,473. Compared with the validation dataset developed by Yamazaki *et al.* (2004), this technique overestimates the number of visually collapsed or partially collapsed structures by 17%.

SECTION 4
METHOD 2: EDGE-BASED DAMAGE THRESHOLD

The methodology flow diagram in figure 1-1 outlines Method 2: Edge-based damage threshold, for counting the number of collapsed buildings in Bam. Together, the building inventory and damage assessment processes include seven steps, comprising:

1. Segmentation of the 'before' image to identify objects that could be buildings
2. Classification of the 'before' image objects to identify those that are buildings
3. Shrinking the building footprints to avoid issues of shadow and look angle variation around the edges
4. Filtering the 'before' and 'after' images using an edge detection operator to highlight building collapse
5. Superimposing the shrunk building footprints on the before and after edge-enhanced images
6. Computing a threshold difference in the number of edges within the before and after shrunk footprints.
7. Counting the number of collapsed structures.

Step 1 and Step 2 of this methodology employs the same datasets and procedures as the Method 1: Re-classification approach (see Section 2.1 and Section 2.2). As such, details of these processes are not repeated here. Step 3 through Step 7 are described in the following sections, together with details of the accuracy assessments that were conducted for the damage count.

Compared with Method 1, this approach employs a more traditional 'change detection' technique (see Volume III), assessing the number of collapsed buildings in terms of characteristic differences between collapsed and intact buildings within the before and after images. However, it is novel inasmuch that damage is assessed in terms of the change in occurrence of edge pixels, oppose to other measures such as dissimilarity/texture that have previously been employed (see Huyck *et al.*, 2004; and Gusella, 2006).

4.1 Shrinking the Building Outlines (Step 3)

Visual inspection of the 'before' and 'after' images indicate that non-disaster related differences are present, which may be a source of inaccuracy in the identification of building collapse when using a change detection methodology. From figure 4-1, the spectral characteristics of non-damaged buildings vary around the margins of the roof. This fundamental difference is due to minor registration errors, and changes in acquisition angle and illumination conditions and direction at the time of image acquisition (table 4-1). Other sources of change may include variations in the spectral characteristics of the roof where the building was imaged by two discrete sensors such Quickbird and IKONOS operating at slightly different wavelengths, or where different processing techniques have been applied prior to data delivery (for example, the pansharpening algorithms in Section 1.3).

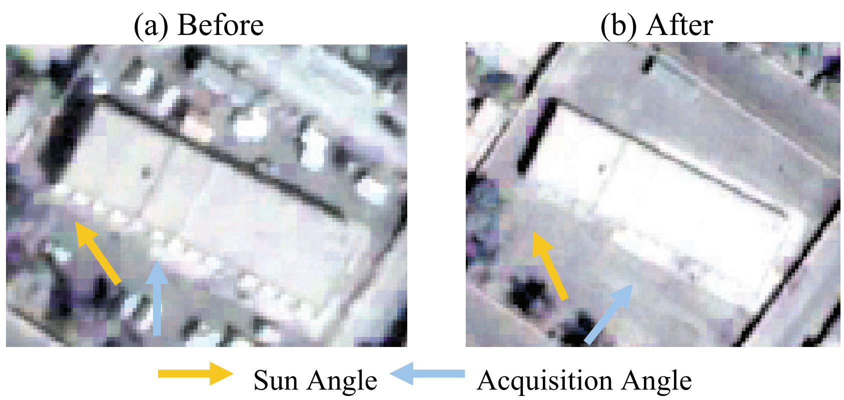


Figure 4-1 Changes Between the Spectral Characteristics Around the Margins of a Non-Damage Roof for (a) Before and (b) After Quickbird Images of Bam. Differences are Due to Variations in Acquisition Angle and Illumination Conditions.

Table 4-1 Acquisition and Illumination Characteristics of Bam Quickbird Images

Date	Sun Azimuth	Sun Elevation	Satellite Azimuth	Satellite Elevation
09/30/2003	145.3	53.0	188.0	79.6
01/06/2004	155.5	34.1	234.1	64.3

To minimize the effect of these anomalous differences in spectral characteristics around the roof margin, and reduce their impact as a source of error in the change detection process, a shrinking algorithm was applied to the building outlines. Shrinking involved globally reducing the size of each building footprint, so that it no longer overlaps with the roof margin. Figure 4-2 illustrates the impact of shrinking for a group of three structures affected by different levels of shadowing around the roof margin. In figure 4-2a, the outline encompasses the roof extent. After overlaying the same outline with the co-registered 'after' scene (figure 4-2b), shadowing to the north of the structure is now included. In contrast, the shrunk footprint only considers the inner portion of the roof, which if collapsed, should provide a representative spectral signature of damage that is non-biased by shadow. Several different levels of shrinking were explored, ranging from 0.6m< shrinkage<1.8m.

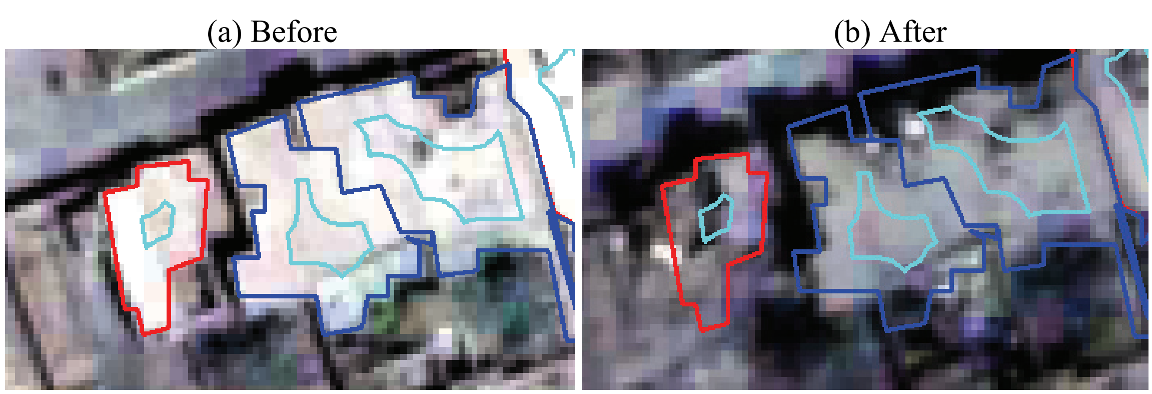


Figure 4-2 Use of Building Shrinkage to Mitigate the Effects of Shadow Differences Between Before and After Images, which Affect the Accuracy of Damage Detection

4.2 Edge Detection Filtering (Step 4)

In an image processing context, edges occur where there is an abrupt "jump" in intensity from one pixel to the next. Algorithms such as Laplacian and Sobel have been developed for edge detection, based on convolution filters. The Canny edge detection algorithm (Canny, 1986) is known as the optimal edge detector. First, it smoothes the image to eliminate noise. It then computes the image gradient to highlight regions with high spatial derivatives. The algorithm then tracks along these regions and suppresses any pixel that is not a maximum. The gradient array is now further reduced by a process of hysteresis, to track non-suppressed pixels. Hysteresis uses two decision rules to create a binary output of edge versus non-edge: (1) if the magnitude is below the threshold, it is set to zero (a non-edge); and (2) if the magnitude is above the threshold, it is set to one (an edge).

In the case of Bam, the Canny edge detection filter (Canny, 1986) is explored as a tool for identifying unique characteristics of collapsed versus non-collapsed buildings. A 17x17 filter was applied to the pre-processed input images.

4.3 Superimpose Shrunk Buildings and Compute Damage Threshold (Step 5 and Step 6)

The shrunk building outlines were superimposed with the 'before' and 'after' Canny-filtered images. For each shrinkage scenario, an empirical approach was used to identify the optimum threshold level, involving a random subset of 74 building outlines. The actual damage state of these structures was determined through visual inspection of the satellite imagery, resulting in a count of 43 collapsed and 31 non-collapsed buildings.

The edge-based damage index was calculated according to Equation 4-1. The frequency of edge pixels falling within the outlines was computed (e). The total number of pixels (t) within the outline was also measured. b is the before image, a is the after image, and i represents each individual outline within the sub-sample of 74 ($1<i<74$).

$$E = \frac{e_{ai}}{t_{ai}} - \frac{e_{bi}}{t_{bi}} \qquad -1<E<1 \qquad (4\text{-}1)$$

A series of difference thresholds (D) spanning the range $-1<D<1$ were tested to find the optimum value that when applied to the 74 results for the damage state index, achieved the highest degree of correspondence between the predicted and actual damage state. If the magnitude of the actual value of the damage state index is below the threshold being tested, the result is set to 'non-collapsed'. If the actual magnitude is above the threshold, it is set to 'collapsed'. Results using the test threshold were compared with the actual damage state (collapsed versus non-collapsed) and the percentage of correctly classified outlines computed. Finally, a confusion matrix was constructed for each threshold and for each level of building shrinkage, and the results expressed graphically. Using the optimum threshold value, all building objects within the 'after' image were classified as collapsed or non-collapsed. Finally, the accuracy achieved by this threshold classification was evaluated using a set of 163 randomly selected buildings.

To understand the edge-based characteristics associated with building damage in further detail and their influence on threshold levels and accuracy, additional analysis of the relationship between edge pixel frequency and damage state was conducted. Figure 4-3 shows a sample area with the assessed damage levels color coded by severity using the validation dataset developed by Yamazaki *et al.* (2004). The frequency of edges within the 'before' and 'after' building outlines was evaluated for each EMS98 damage level for masonry structures, and statistical characteristics computed.

Figure 4-3 Example of Visually-Assessed EMS98 Damage Levels Overlaid with the 'After' Image

4.4 Counting the Number of Collapsed Buildings (Step 7)

After applying the optimum damage threshold, the occurrence of collapsed versus non-collapsed buildings was computed. The output frequency statistics were compared with the validation data developed by Yamazaki *et al.*, (2004)

SECTION 5
RESULTS 2: EDGE-BASED DAMAGE THRESHOLD

Results for Step 1 and Step 2, which are identical to those employed for Method 1, are described in Section 3.1

5.1 Shrinking the Building Outlines (Step 3)

Figure 5-1 illustrates the effect of imposing a shrinking routine on the edge detection process. In the 'before' image, the building outline corresponds precisely with the zero shrinkage limit. However, in the 'after' scene, the equivalent shrinkage limit appears offset in relation to the outline. For example, in the upper left corner (highlighted in red) pixels for the building outline now fall within the zero shrinkage boundary, and as such would contribute to a damage calculation based on edge pixel frequency. Shrinking helps to minimize this source of error. In the present example a shrinkage margin of 1.2 significantly reduces the occurrence of outline pixels in the 'after' boundary. However, accuracy results found a margin of shrinkage = 0.6 to produce the best results.

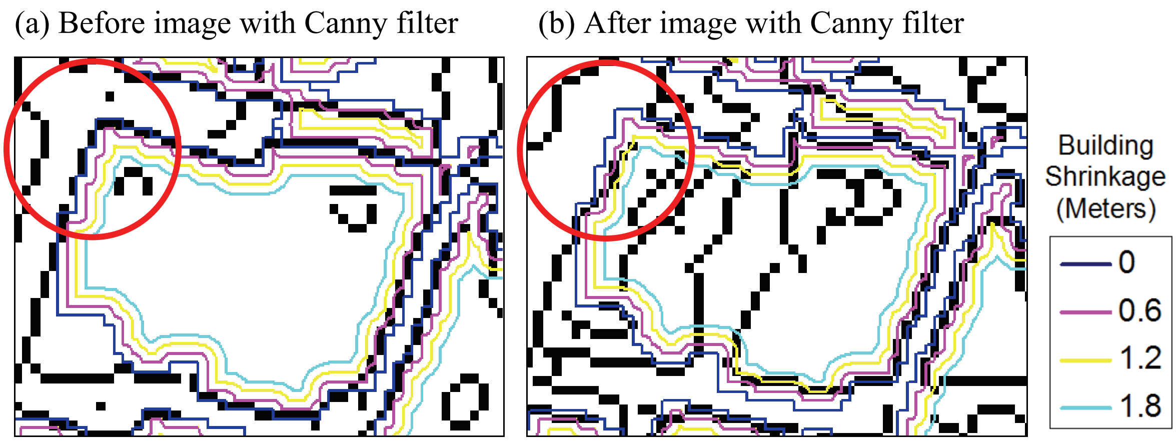


Figure 5-1 The Effect of Implementing Building Shrinkage by 0.6m, 1.2m and 1.8m when Computing the Frequency of Edge Pixels. This Example is for a Non-Collapsed Structure. The Red Annotation Highlights an Area of Discontinuity Between the Before and After Scenes where Pixels from the Building Outline Now Fall Within the Footprint, and as such would be Wrongly Included in a Damage Calculation.

5.2 Edge Detection Filtering (Step 4)

Within the before event image (figure 5-2a), the edges represent the building's boundary walls, coupled with minor details within the roof. In the 'after' event scene (figure 5-2b), collapsed structures are replaced by a chaotic jumble of edges corresponding with the debris pile. Buildings that are still standing remain delineated, often with some changes may be evident within the roof expanse, where minor damage has occurred. Comparing the Canny-filtered scenes, there is an increase in the density of edges within collapsed versus non-collapsed buildings (figure 5-2c and 5-2d).

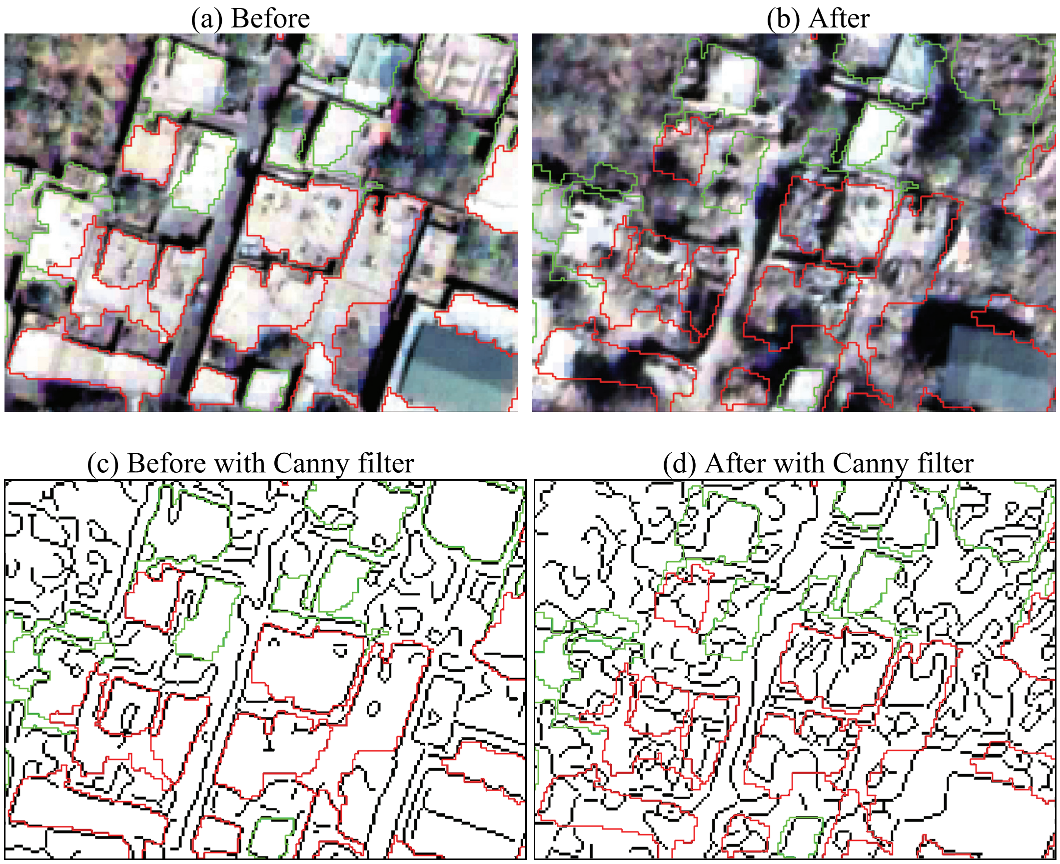


Figure 5-2 (a) Before Event Image; (b) After Event Image; c) 17x17 Canny Filtered Before Image; and d) 17x17 Canny Filtered After Image. Building Outlines are Superimposed, with Non-Collapsed in Green and Collapsed in Red.

5.3 Superimpose Shrunk Buildings and Compute Damage Threshold (Step 5 and Step 6)

Figure 5-3 shows the results obtained when assessing the optimum threshold for the edge-based damage index. Comparing the responses for shrinkage levels of $0 < \text{shrinkage} < 1.8$ suggests that pixels associated with the building outline exert a significant influence on the results obtained. Considerable variability is evident between the accuracies achieved because factors such as co-registration errors and differential shadowing and illumination between the 'before' and 'after' images play a role. By reducing the influence of border pixels in the edge-based damage index through shrinking, the maximum accuracy level achieved increased from 65% (for a threshold of D = -0.03, building shrinkage = 0m) to 75% (D = 0.04, building shrinkage = 0.6 m).

A value of D = 0 represents the situation of no change in the occurrence of edge pixels between the 'before' and 'after' scenes. In this instance, the optimum threshold was identified as D =

0.04. Positive values occur when the number of edge pixels is higher in the 'after' compared with the 'before' scene. This result therefore suggests that collapsed structures are often associated with a substantial increase in edge pixels. However, it is also true that all values in the range 0<*D*<0.04 are, to a degree, indicative of an increase in edges. It is theorized here that values of 0<*D*<0.04 may be indicative of lower damage states, which cause an increase in edge occurrence between the 'before' and 'after' images, but to a lesser degree than for collapsed buildings.

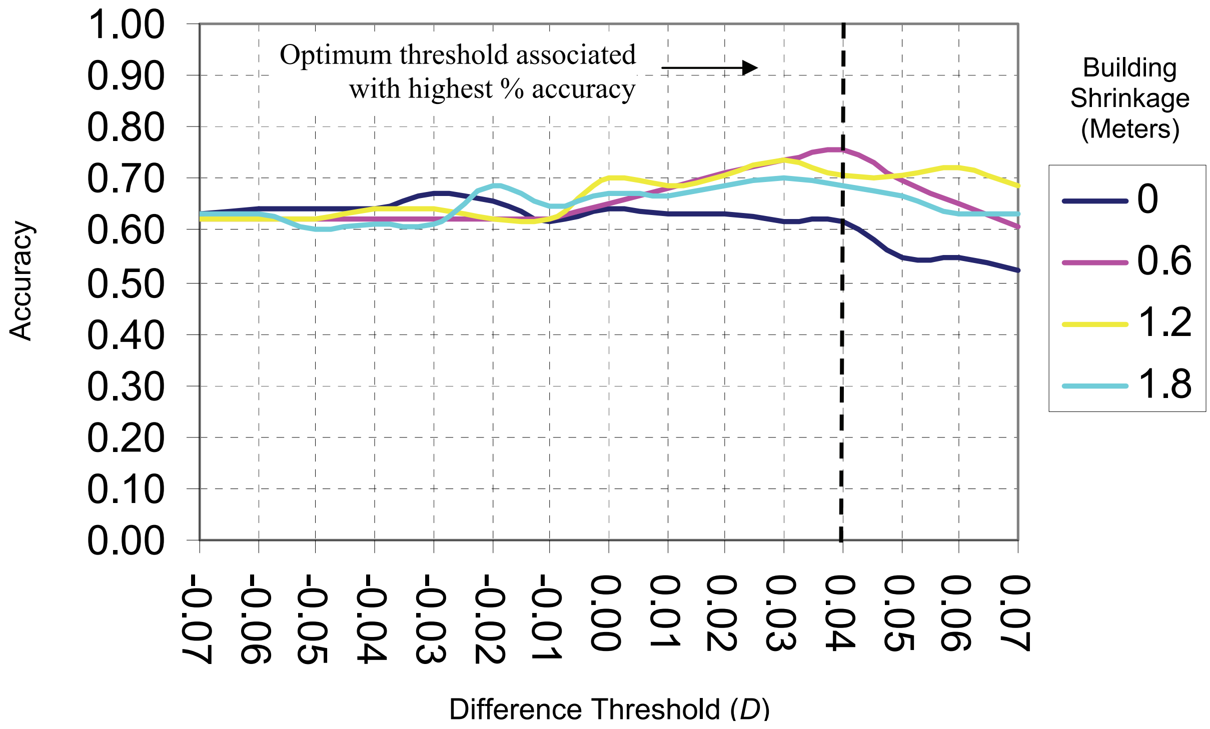
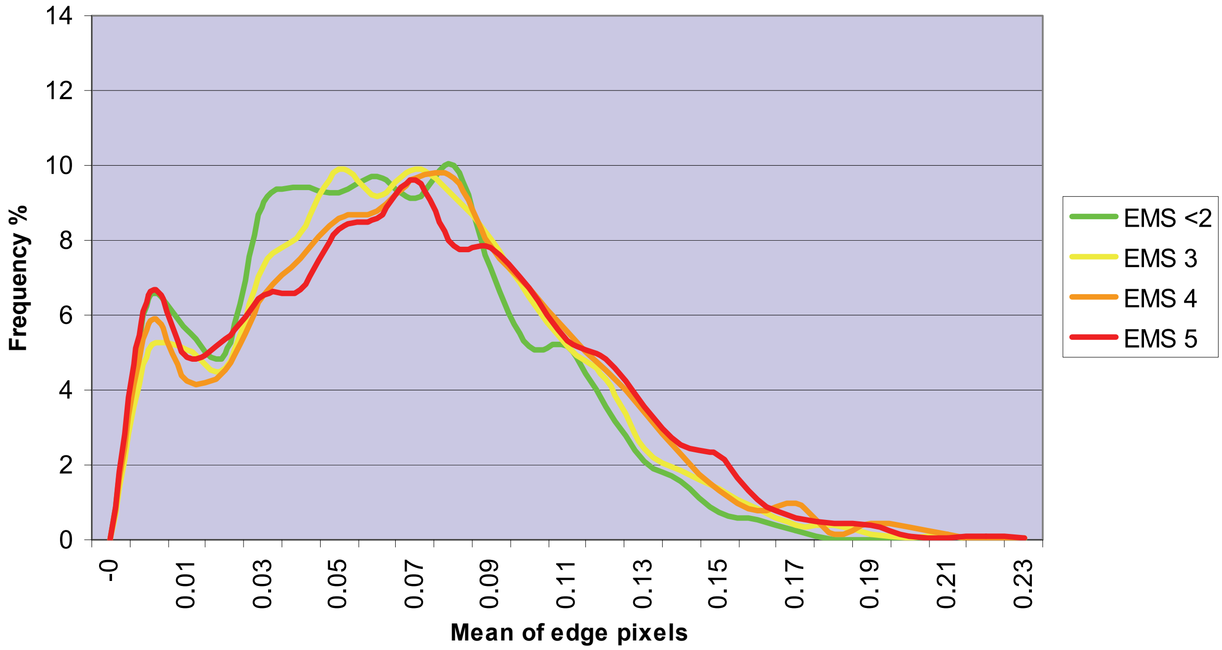


Figure 5-3 Threshold Evaluation for the Edge-Based Damage Index

In order to better understand the relationship between edge occurrence and intermediate damage levels, edge statistics were correlated with validation data classified according to the EMS98 damage scale, provided by Yamazaki *et al.* (2004). Figure 5-4 shows how the frequency of edge pixels changes with EMS98 damage severity. In the before image, edge frequency within the buildings is fairly consistent between all damage states. However, in the after scene, the % frequency of edge pixels consistently increases with damage state. Figure 5-5 goes on to demonstrate the differing responses within the before and after scenes for buildings sustaining a given damage state. For both damage states, the average occurrence of edge pixels is higher within the after compared with the before scene. However, the margin is wider for Level 5 versus Level 2, which results in higher difference values. This finding provides further support for the hypothesis that damage states EMS98 1-4 are associated with an increased number of edges, although their frequency is lower than for EMS98 level 5.

(a) 'Before' Image



(b) 'After' image

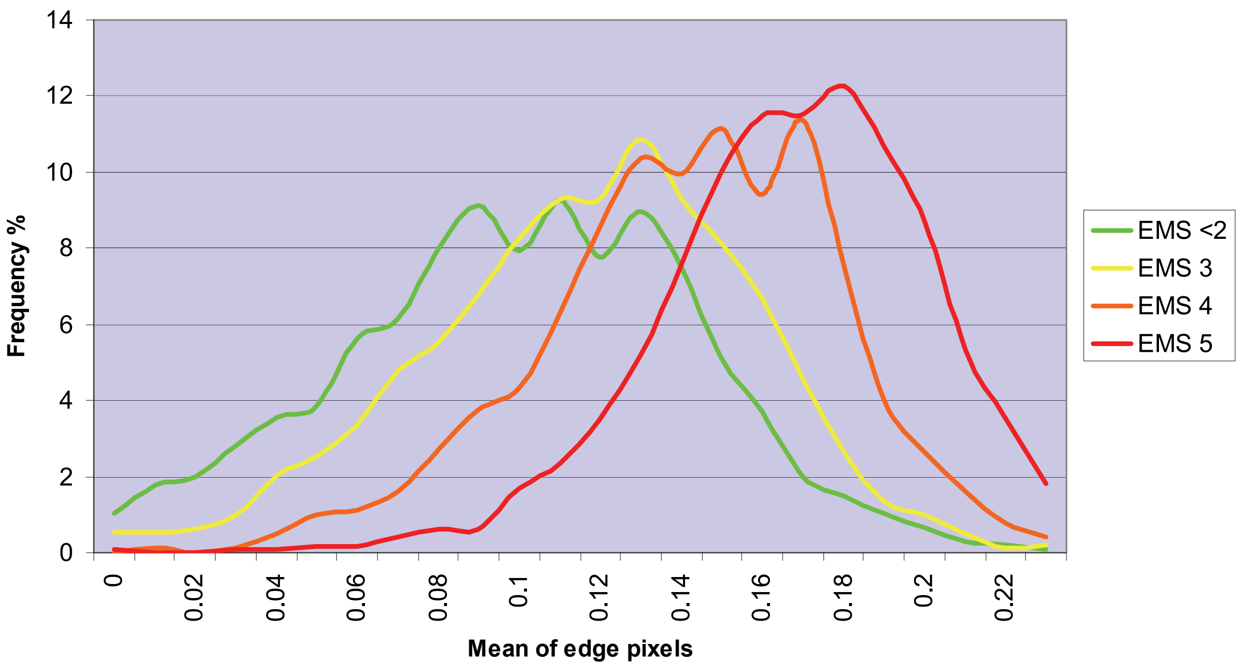
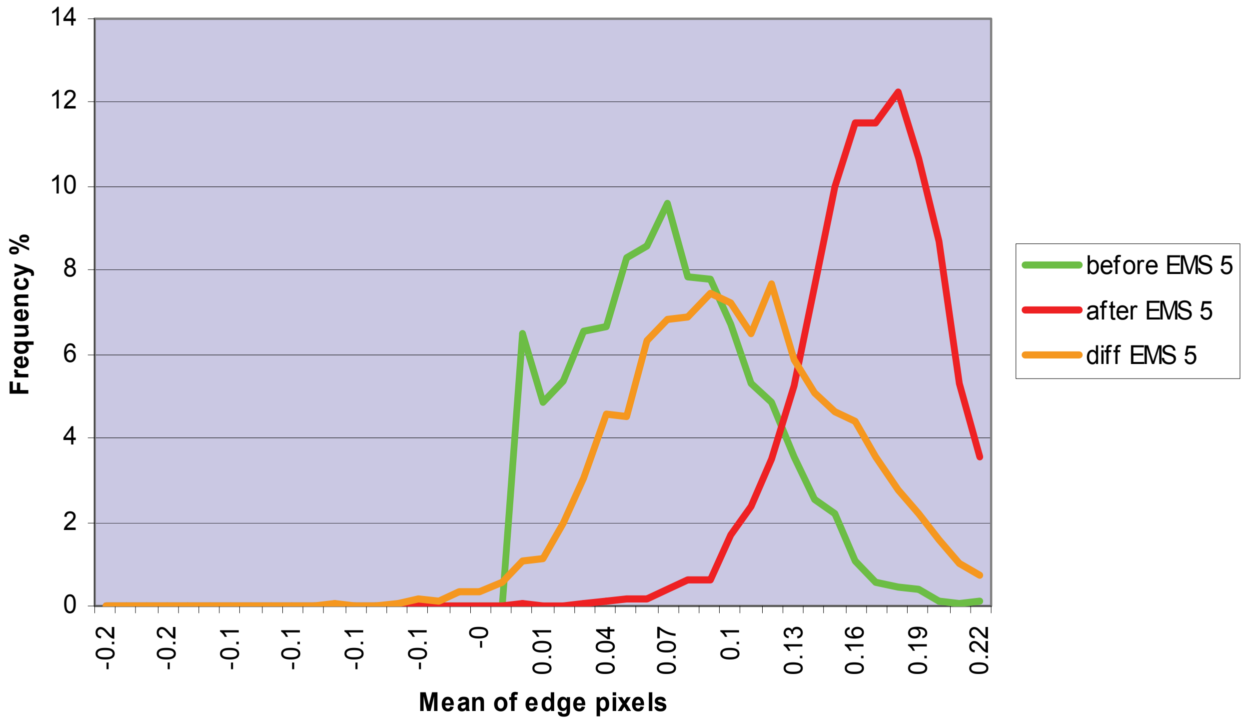


Figure 5-4 Frequency of Edge Pixels Occurring within (a) Before and (b) After Images for Buildings Classified According to the EMS98 Damage Scale (Validation Dataset Provided Courtesy of Yamazaki *et al.* (2004)).

(a) EMS98 damage level 5 (Destruction)



(b)EMS98 damage level 2 (Moderate Damage)

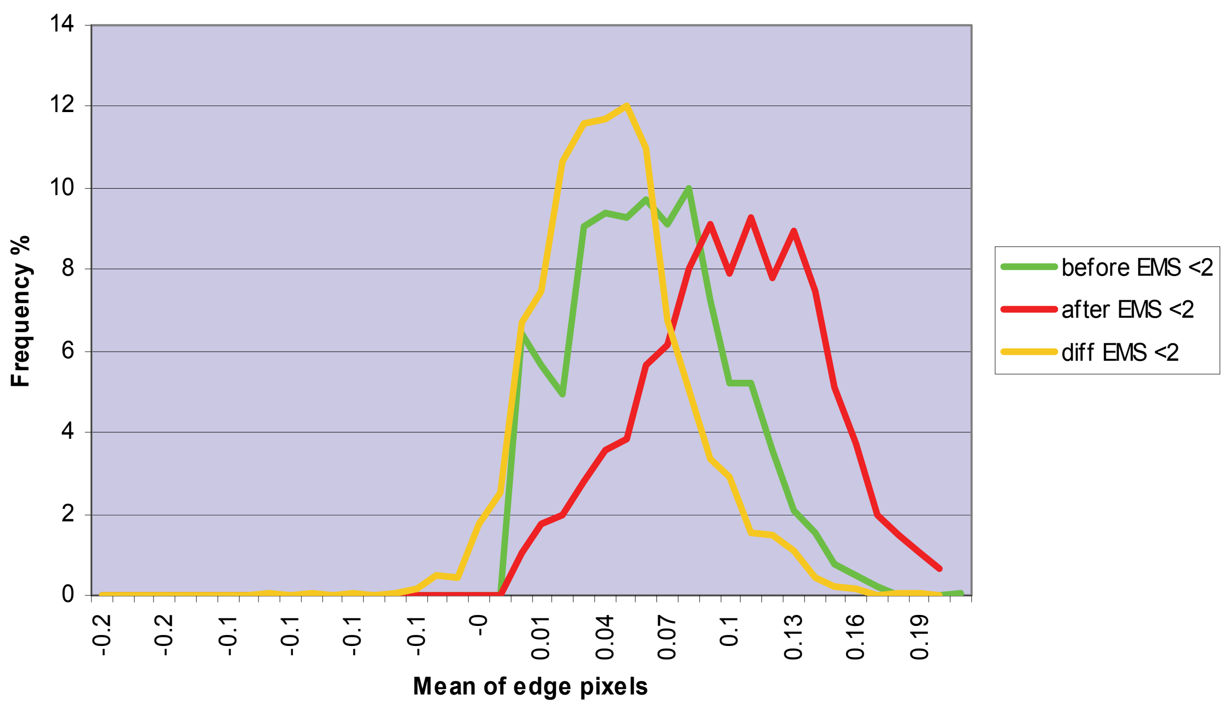


Figure 5-5 Variation in the Frequency of Edge Pixels Occurring within Buildings Classified as EMS98 Level 5 (Destruction) and Level 2 (Moderate Damage) for Non-Damaged (Before) and Damaged (After) Scenarios. The Difference Between the Before and After Results is also Shown.

5.4 Counting the Number of Collapsed Buildings (Step 7)

Using the optimum threshold value of $D = 0.04$ (see figure 5-3), a total of 7,390 (39.2%) buildings within Bam were classified as collapsed (table 5-1). On a city-wide scale, this total is 33% higher than the validation dataset developed by Yamazaki *et al.* (2004). As for the Method 1 results (Section 3), which overestimated the frequency of collapse by 17%, the higher frequency is likely linked to the building to object ratio output from the segmentation phase. Clearly, the accuracy of segmentation requires further refinement as input to the damage detection phase.

To explore performance in greater detail, a neighborhood level accuracy assessment was conducted which employed a total of 163 buildings. The results in table 5-2 found that using an edge-based change detection methodology, 68% of footprints were correctly classified.

Table 5-1 Number of Collapsed Buildings, Computed Using the Edge-Based Damage Classification. Area of Building Collapse is Expressed in M^2

Classification	Count	Object average area	Total area
Not damaged	11,482 (60.8%)	189	2,647,847
Damaged	7,390 (39.2%)	231	2,082,690
Total	18,872	205	4,730,537

Table 5-2 Confusion Matrix Relating to the Accuracy Assessment for the Edge-Based Damage Classification

Reference/ classified	Damaged	Non- damaged	total	
Damaged	70	34	104	
Non-damaged	18	41	59	
Total	88	75	163	**Accuracy = 68%**

SECTION 6
KEY FINDINGS AND FUTURE WORK

Two object-oriented methodologies are presented for quantifying the number of collapsed buildings in the aftermath of a major earthquake, using high-resolution optical satellite imagery captured before and soon after the event. This general theoretical approach has enormous potential to yield rapid urban damage estimates in the aftermath of future disasters.

The methodologies described here employ a two-phase process, comprising: (1) building inventory development; and (2) damage assessment. Building inventory development provides a count of the total number of structures (both damaged and non-damaged) based on analysis of the 'before' building stock. Damage assessment may employ a range of different theoretical techniques to identify the presence of collapsed structures. The techniques presented here explored both intra-scene variations between collapsed and non-collapsed buildings, and damage-based changes between the before and after images.

- Method 1 – Reclassification detected damaged buildings within the total building stock, based on characteristic spectral features within the 'after' image. In this instance, intact adobe buildings are characterized by homogenous and bright/white domed or flat rooftops. In contrast, the collapsed structures appear as chaotic piles of debris, of a subdued color that is similar to the surrounding soils.

- Method 2 – Edge-based damage thresholding detected damaged buildings based on differences between the occurrence of edge features within the before and after images. In this instance, intact adobe buildings are delineated around the margin, with limited texture on the domed roof. In contrast, irregular edges are prevalent within collapsed structures, associated with chaotic debris piles.

The results obtained here for Phase 1 of the methodology - building inventory development, suggest that eCognition object-oriented image processing software is a useful environment for extracting the footprints of non-damage structures, which provides a basis for classifying the damage state. However, the overestimation of building occurrence suggests that using a single set of parameters to extract all structures within a city introduces errors, particularly where there are differences in building structure size, orientation and density.

In order to optimize the delineation of building outlines by minimizing occurrences of building and object split, the exploration of techniques for intra-scene segmentation factor optimization is an important topic for future research. This evaluation should also investigate whether segmentation performance varies more widely with structural and occupancy type, urban setting, and geographic location, with the aim of establishing the robustness of this approach for different urban environments around the World, maximizing 1:1 correspondence between segmented objects and the full range of building stock within a given city, and ultimately streamlining the segmentation process.

The accuracy achieved when classifying segmented objects into classes of building versus non-building may be further improved through the investigation of more sophisticated processing options, including advanced nearest neighbor and fuzzy classification techniques.

The results obtained here for Phase 2 of the methodology – damage detection, suggest that both re-classification and edge-based damage thresholding are useful techniques for identifying building collapse. The number of collapsed buildings was overestimated by 17-33% compared with a validation dataset developed by Yamazaki et al. (2004). The reclassification performed better than the edge-based damage detection methodology. This overestimation is largely due to object split at the segmentation phase and reinforces the importance of further research to improve the accuracy of building inventory extraction prior to damage assessment.

SECTION 7
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University at Buffalo, The State University of New York
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Phone: (716) 645-3391 ▪ Fax: (716) 645-3399
E-mail: *mceer@buffalo.edu* ▪ WWW Site *http://mceer.buffalo.edu*
University at Buffalo *The State University of New York*

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