

# Urban Search and Rescue and Rapid Field Assessment of Damaged and Collapsed Building Structures

**Professor. Abid Abu-Tair<sup>1</sup>, Eng. Gavin Wilde<sup>2</sup>, Dr Maher Amro<sup>3</sup>, Dr Munther Ibrahim<sup>4</sup>**

- |   |                                   |
|---|-----------------------------------|
| 1. Birzeit University, Palestine.               | 2. South Wales University, UK.    |
| 3. Palestine Polytechnic University, Palestine. | 4. Al-Najah University, Palestine |

**Corresponding Author:** Prof. Abid Abu-Tair, Birzeit University, Palestine; Email: [aabutair@birzeit.edu](mailto:aabutair@birzeit.edu)

## **Abstract:**

Urban Search and Rescue (USAR) is a functional capability that has been developed to allow the United Kingdom Fire and Rescue Service to deal with 'major incidents' primarily involving structural collapse. The nature of the work undertaken by USAR means that staying out of a damaged or collapsed building structure is not usually an option for search and rescue personnel, as a result there is always a risk that they themselves could become victims. For this paper a systematic and investigative review using desk research was undertaken to explore the role which structural engineering can play in assisting search and rescue personnel to conduct structural assessments when in the field. The main focus being how search and rescue personnel can assess damaged and collapsed building structures, not just in terms of structural damage that may be encountered, but in relation to structural stability. Natural disasters, accidental emergencies, acts of terrorism and other extreme events can vary significantly in nature and ferocity, and can cause a wide variety of damage to building structures. It is not possible or even realistic, to provide search and rescue personnel with definitive guidelines and procedures to assess damaged and collapsed building structures as there are too many variables to consider. However understanding what implications damage may have upon the structural stability of a building structure will enable search and rescue personnel to better judge and quantify risk from a life-safety standpoint. It is intended that this will allow search and rescue personnel to make informed decisions and ensure every effort is made to mitigate risk, so that they themselves do not become victims.

## **1.0 INTRODUCTION**

The search for the injured and rescue of those trapped are the most important activities in the immediate aftermath of any disaster, accidental emergency or act of terrorism, and should therefore be dealt with absolute urgency. Staying out of a damaged or collapsed building structure is not usually an option for search and rescue personnel, such as Urban Search and Rescue (USAR) and similar emergency services, as the urgent nature of the work means it is often necessary to gain entry as soon as possible.

Search and rescue personnel operate in difficult circumstances, under pressure and against time, often having to make difficult decisions which have life and death consequences. An example being the decision to enter a damaged building structure to search for the injured and rescue those trapped, as Gallagher *et al.* (1999) states, entering a damaged building structure is ‘never risk free’ and because of this search and rescue personnel, by nature, ‘take higher risks’. Although attempts will be made to mitigate any risk, by keeping time spent in damaged building structures to a minimum and through the use of temporary support (e.g. shoring and bracing), there will always be a risk that search and rescue personnel could themselves become victims.

To understand what guidance is available to assist search and rescue personnel to assess the structural stability of damaged and collapsed building structures, it is necessary to investigate the material produced for search and rescue personnel, particularly those directly related to field operations such as any field and training manuals. In addition, it is also necessary to investigate what literature is available to structural engineers on the subject of structural investigation, assessment and appraisal and if, and how, any of this information could be used to assist search and rescue personnel.

## **2.0 EMERGENCY RESPONSE AND RELIEF OPERATIONS**

### **2.1 Field Operations**

There is a wide variety of published literature available on the subject of humanitarian response. These publications have been produced by various governmental and non-governmental organisations (including charitable agencies), which provide an invaluable resource for the co-ordination and management of emergency relief operations following a natural disaster or conflict<sup>1</sup>. Each publication is highly informative and offers comprehensive guidance on a wide variety of socio-economic factors, which range from the characteristics of human behaviour to minimum requirements for food, water, health and sanitation. The information within these publications is very useful as it gives emergency relief workers an insight into sensitive issues which need to be considered when working with people who have lost everything and outlines what can be done to help with the rebuilding process. From the perspective of search and rescue personnel, who are deployed in the immediate aftermath of a disaster, accidental emergency or act of terrorism, the information within these publications is of limited value. Although the information does help search and rescue personnel to understand the socio-economic factors associated with emergency response and relief operations, particularly human behaviour, no information is provided about the search for the injured and rescue of those who are trapped.

A number of field manuals have been produced in recent years to provide search and rescue personnel with concise and easy-to-use reference documents to be used during operations. These field manuals have been produced specifically for Urban Search and Rescue in the United Kingdom (USAR)<sup>2</sup> and Urban Search and Rescue in the United States (US&R)<sup>3</sup>. Each containing essential operational procedures and guidelines for locating and extricating injured and trapped victims in damaged and collapsed building structures, in addition to other information including: organisational structure, assessment and management techniques, as well as roles and responsibilities.

It is a reasonable assumption that field manuals would contain significantly more information about search and rescue activities compared to the various texts that have been produced about humanitarian response. However, even within these field manuals there

---

<sup>1</sup> Davis and Lambert (2002); Sphere Project (2011); UNHCR (2007); USAID (2005).

<sup>2</sup> Merchant and Ashford-Smith (2008).

<sup>3</sup> FEMA (2003); FEMA (2006a); USACE (2009).

appears to be an obvious lack of technical information relating to the structural stability and the assessment of damaged and collapsed building structures. Rather than providing valuable guidance for structural assessment, such as hints to identify the structural systems in different types of building structures and examples of commonly associated structural defects. Instead the field manuals only outline general sequences of procedures and safety considerations – as discussed later in Chapter 3 (Section 3.2). The reason can only be assumed that it is not practical for the field manuals to contain every aspect of search and rescue as the purpose of a field manual is to provide a clear, concise and easy-to-use reference document which can be used during operations.

## **2.2 Training**

In the United States the Federal Emergency Management Agency (FEMA) is responsible for the deployment of US&R to a wide variety of accidental emergencies, natural disasters and acts of terrorism. The multi-disciplined and demanding nature of work undertaken by US&R means that each member of the team must undertake hundreds of hours of extensive training in order to provide the necessary search, rescue and technical capabilities required to work in an emergency situation. In order to achieve this, FEMA have developed a specialist in-house training programme comprising of a ‘Structural Collapse Technician Course’ amongst others. The syllabus of the ‘Structural Collapse Technician Course’ covers a number of key modules for study, these include: structural engineering systems, shoring and bracing, breaching and breaking, and lifting and moving.

The *Structural Collapse Technician Manual*<sup>4</sup> has been produced as a companion document to the ‘Structural Collapse Technician Course’. This is a very comprehensive manual that covers all modules within the ‘Structural Collapse Technician Course’ with information, that is not only relevant to students who are training, but can also be used as an ongoing source of reference. Basic principles of structural mechanics are outlined in a clear and concise manner throughout the manual, as well as how knowledge of these principles can be used to help better understand damaged building structures. The section of the manual about structural engineering systems is of particular interest as this contains information which would be very useful for search and rescue when assessing a damaged building

---

<sup>4</sup> FEMA (2010).

structure. A summary of the format and content of the section about structural engineering systems from the manual can be seen as follows.

#### Part 1 – Building Materials and Structural Systems

- Types of forces, properties and behaviour of the most commonly used building materials (concrete, steel, masonry and timber) under normal loading conditions.
- The function of primary structural systems and how these contribute to the overall stability and robustness of a structure.

#### Part 2 – Collapse Patterns

- Types of forces that act upon a structure under extreme circumstances, such as: earthquakes, floods, wind storms, fire and vehicular impact loading conditions.
- Classification of different types of building structure with examples of commonly associated structural defects which can lead to failure.
- Basic collapse patterns to demonstrate the general effects of the collapse of different types of building structure. This provides the required background knowledge for assessing how stable a structure is in its damaged condition and to identify what additional collapse could occur.

#### Part 3 – Hazard Identification and Building Monitoring

- General guidance to identify hazards and safety concerns, detailing what to look for with different types of building structures.
- Procedures for hazard mitigation when entering into partially collapsed and collapsed building structures.
- The use of visual indicators to monitor damaged structures to act as a warning system of any change in stability.

#### Part 4 – US&R Strategy and Structural Size-Up

- Outlines involvement at a disaster site, from arrival and the gathering of information from first responders to procedures for gaining access to injured and trapped victims.
- The importance of having a strategy that considers all relevant structural hazards to minimise risk to injured and trapped victims as well as US&R personnel.

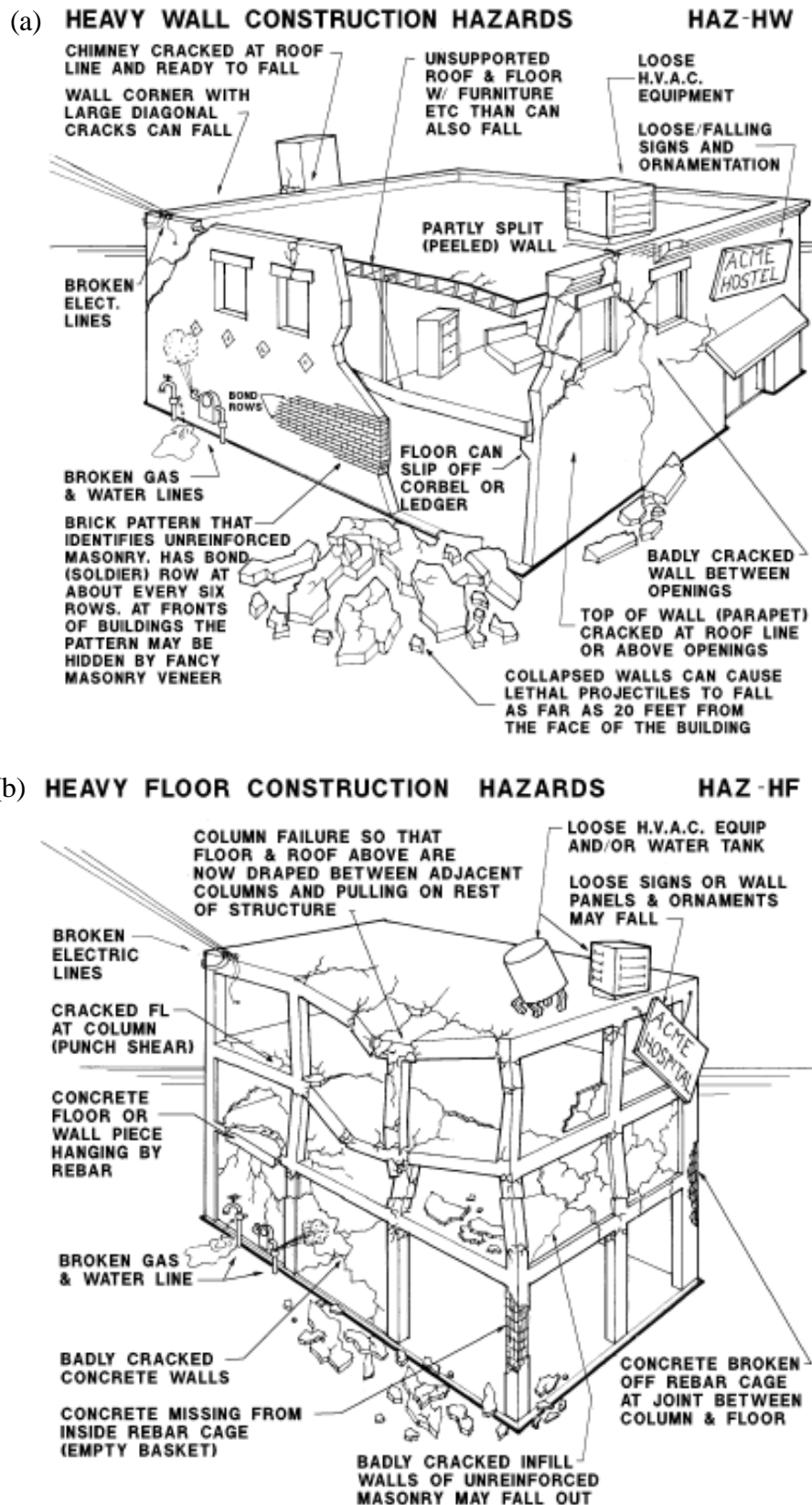
- Use of a “structural triage” as a means of prioritising search and rescue operations. The structural condition of building structures are assessed to evaluate what resources are required to gain access and if search and rescue operations could proceed with or without stabilisation.

The format and content of the manual indicates that the ability to understand and apply the basic principles of structural mechanics to a damaged building structure requires knowledge of many interlinked factors. This is supported by FEMA (1994) who emphasises the importance of providing a suitable education base for search and rescue personnel, not only to enable the structural assessment of damaged and collapsed building structures to be carried out, but also to recognise where it is necessary to obtain professional advice from a structural engineer. Although, a serious concern in the UK however, is that structural engineers rarely have suitable knowledge or experience of dealing with damaged and collapsed building structures and fewer understand the work that USAR does<sup>5</sup>.

A notable feature of the *Structural Collapse Technician Manual* is the use of diagrams as visual aids throughout the manual to demonstrate and reinforce the different points which are being made and how these can be applied in practice. An example of the type of diagrams that are included within the manual is displayed in Figure 1, illustrating typical construction details and safety concerns for the different types of building structures.

---

<sup>5</sup> Hampshire Fire and Rescue Service (2012); Lancashire Fire and Rescue Service (2007).



**Figure 1** – Example of diagrams contained within the *Structural Collapse Technician Manual* (a) a typical masonry building structure. (b) a typical reinforced concrete frame building structure.  
[Source: FEMA (2010).]

### 3.0 STRUCTURAL INVESTIGATION, ASSESSMENT AND APPRAISAL

There is a vast amount of published literature available on the subject of structural investigation, assessment and appraisal of building structures. Despite the availability of such literature, there is a distinct lack of material that is suitable and applicable for use by search and rescue personnel, when assessing to assess the structural stability of damaged and collapsed building structures. The reason for this is that the published literature that is available has been produced for structural engineers and other such professionals, to assess the general condition of a building structure under normal circumstances e.g. its ability to meet specific functional and durability requirements.

In the IStructE (1995) publication, *The Structural Engineer's Response to Bomb Damage*, it is stated that most structural engineers have experience of assessing the condition of building structures under normal circumstances, but many would be unfamiliar with how to assess a building structure where damage has been caused by explosion. Although this report focuses on explosion, damage caused by a range of disasters, accidental emergencies or acts of terrorism would also add new dimensions which must be considered during the assessment process – as discussed in the FEMA (1998) publication *Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings: Basic Procedures Manual*. When considering the fact that search and rescue personnel are not structural engineers and will be operating in difficult circumstances, under pressure and against time, this emphasises the challenges which are being faced when assessing the structural stability of damaged and collapsed building structures.

Both IStructE (1995) and FEMA (1998) publications express a similar view, that a competent structural engineer could, at least partially, assess the condition of a damaged building structure through the adaptation of assessment techniques by means of a knowledge about structural mechanics and understanding of building structures. Although these reports are discussing the ability of structural engineers to assess the condition of damaged building structures outside of normal circumstances, it suggests that the published literature about structural investigation, assessment and appraisal could potentially be adapted to assist search and rescue personnel. However, this would require a suitable education base to be provided in order to give search and rescue personnel a basic knowledge about structural

mechanics and understanding of building structures so that this could be applied a damaged building structure in the field<sup>6</sup>.

### **3.1 Techniques used for Structural Assessment and Appraisal**

A structural assessment or appraisal will usually be carried out on all types of structure, at some point during its service life, for many different reasons. The most common reasons for carrying out a structural assessment or appraisal are as follows:

- Evidence of deterioration, structural weakness or distress.
- Part of a routine maintenance programme.
- Accidental damage e.g. fire or impact.
- Change of use or structural alterations.
- Suspected defect in design or construction.
- Legal purposes e.g. change of ownership or insurance.

Kay (1992) states that irrespective of the underlying reason for a structural assessment or appraisal, some form of inspection or survey will be required. The purpose of any inspection or survey is to gather as much information as possible from a structure that is readily available; this is to allow for an accurate structural assessment or appraisal to be carried out. A highly effective method of gathering information is a visual inspection, which is the most widely used technique and is often regarded as one of, if not the most, valuable part of any inspection or survey programme<sup>7</sup>.

A visual inspection, sometimes known as a walk-over survey, involves the systematic examination of a structure to identify the location, nature and extent of any damage, deterioration or distress. Kay (1992) advises that a staged approach should be adopted for the visual inspection of a building structure or other structure, which has been unoccupied for many years or has been damaged. Stating that at first, a careful external reconnaissance should be carried out from a safe distance to determine whether it is safe to approach the structure, followed by a closer external examination. If visual inspections of the exterior of the structure indicate that it is stable, the structure can then be entered with caution. Within

---

<sup>6</sup> FEMA (1994); FEMA (2010).

<sup>7</sup> Concrete Society (2000); Concrete Society (2008); Hoxley (2009); Houghton-Evan (2005); IStructE (2008); IStructE (2010a); Kay (1992); Mays (1992).

this text, Kay (1992) suggests that the structural stability of a building structure can be established simply by checking the alignment of structural elements e.g. the verticality of columns and walls, and the horizontality of beams and floors. Although simple checks like this would be ideal for assisting search and rescue personnel to assess the condition of a damaged building structure, suitable guidance would still be required to help quantify risk.

To ensure that a visual inspection is successful, it is important that it is carried out systematically by trained and experienced personnel who are capable of making careful observations and recording findings accurately. Attention should be paid not only to areas with evidence of damage, deterioration or distress but also to areas which are visually sound for comparison. A visual inspection normally forms the basis for the rest of the inspection or survey, as any observations and recorded findings often allows for a preliminary diagnosis to be developed. Based on this information a more detailed inspection can be planned, if required, which may include on-site testing, non-destructive testing and selected sampling to further assess the condition of the structure. It is therefore critical that an open-minded approach is taken to the visual inspection to ensure that any judgement made is based on observations and recorded findings rather than preconceptions.

In the IStructE (2008) report, it explains that when inspecting structures it is virtually impossible for a structural engineer, no matter how competent, to cover everything that could possibly be checked. Although it is possible to suggest broad guidelines for inspecting structures, every inspection is different because every structure is unique and because of this, the use of survey forms is recommended<sup>8</sup>. There are many practical advantages for using survey forms during inspections as these can help speed-up the inspection process and helps to ensure all relevant information is recorded. Figure 2 shows an example of a survey form which has been developed to record the results of a visual survey for a concrete structure. In this instance the survey form has a simple format and acts like a checklist by listing typical defects which are associated with the deterioration of concrete which includes a basic rating system and section for addition comments.

Time spent pre-planning a visual inspection, or any other form of inspection or survey, is recommended<sup>9</sup>. Pre-planning generally involves obtaining and studying existing records relating to a structure, such as: drawings, calculations and other construction details. This is

---

<sup>8</sup> Concrete Society (2000); Mays (1992).

<sup>9</sup> Concrete Society (2000); Hoxley (2009); IStructE (2008); IStructE (2010a); Kay (1992); Mays (1992).

a useful exercise as it allows structural systems and the location of structurally relevant components of the structure to be identified which, in theory, should allow more information to be recorded when on-site. Search and rescue personnel do not have the luxury of being able to obtain and study any existing records, what typically is available is basic information from first response emergency services and possibly people with a knowledge of a building structure e.g. locals, occupants. It is therefore critical that search and rescue personnel are able to gain the maximum amount of information possible during a visual inspection and have a suitable education base to make judgements based on observations.

<b>Structure</b> ..... <b>Part of structure</b> ..... <b>Date of inspection</b> .....	<b>Rating</b>					
	<b>0</b> None	<b>1</b> Very slight	<b>2</b> Slight	<b>3</b> Moderate	<b>4</b> Severe	<b>5</b> Very severe
<b>Defects</b>						
Cracking	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Plastic shrinkage/settlement	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Thermal contraction	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Structural	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Crazing	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Rust staining	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Water leakage	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Pop-outs	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Spalling	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Loss of surface	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Abrasion	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Chemical attack	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Efflorescence	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Others (specify below)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
<b>Existing repairs (if any)</b>						
Delamination/debonding	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Cracking	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Others (specify below)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
<b>Supplementary documentation</b>	<b>Details (including reference numbers etc)</b>					
Sketches	.....					
Photographs	.....					
Others (specify below)	.....					
<b>Additional comments</b> (general condition of structure, local effects that may influence performance, such as damp areas).						

**Figure 1** – Example of survey form used for visual inspections as part of typical structural assessment and appraisal. [Source: Concrete Society (2000).]

#### 4.0 DAMAGE ASSESSMENT SYSTEMS AND TECHNIQUES

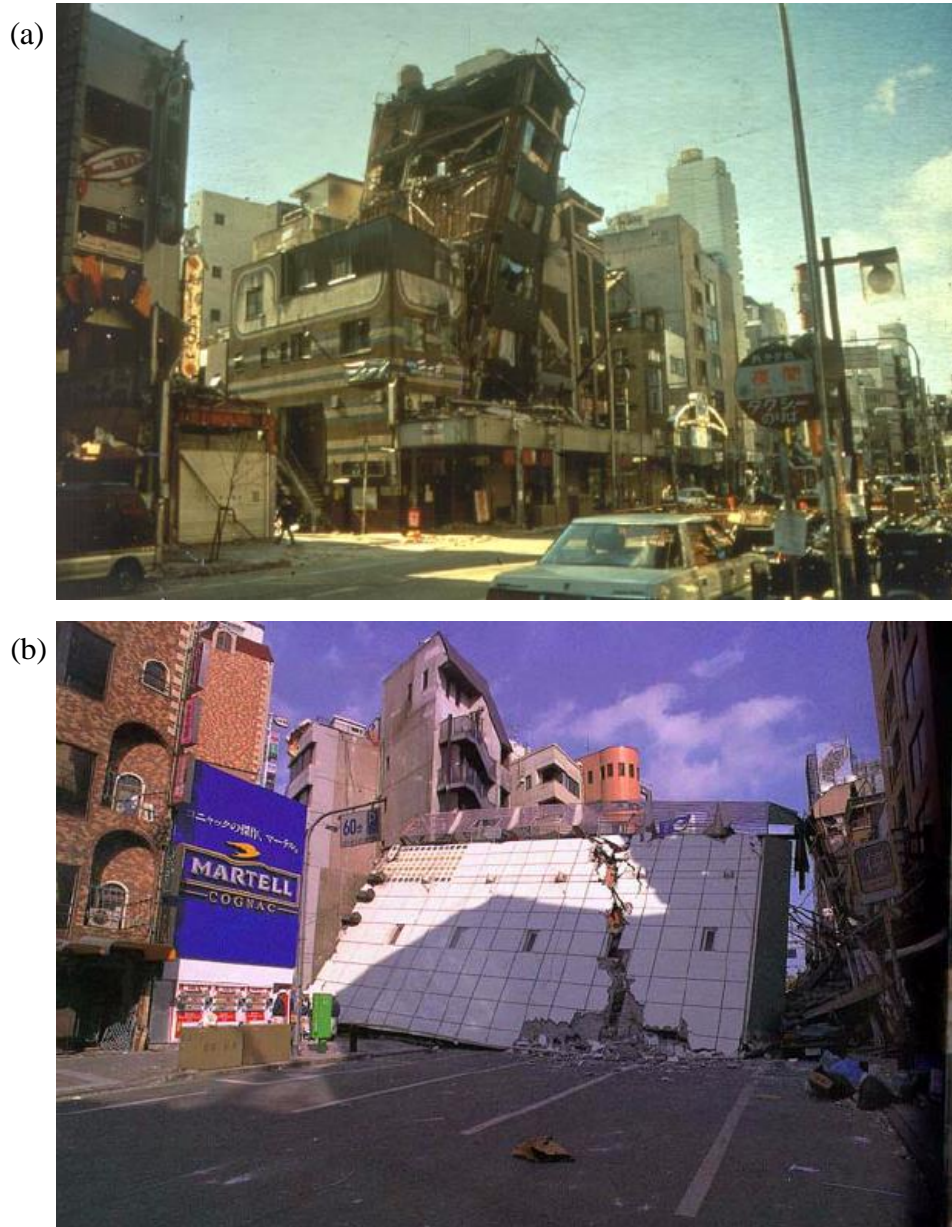
The importance of using quick damage assessment methods in the post-disaster period is identified by De Pauw and Lauritzen (1994) as being an integral part of the overall disaster emergency relief plan. Within this report it is recognised that in the short term (days, weeks) quick damage assessment is very important from both an emergency and life-safety standpoint. Not only does a quick damage assessment prove to be an invaluable tool for search and rescue activities but it can also be used to prohibit entry into and the uncontrolled reuse of severely damaged and hazardous building structures – it is anticipated this would prevent additional injuries and loss of life caused by the additional collapse.

An interesting point made by De Pauw and Lauritzen (1994) is that the majority of publications concerning damage assessment methods after large scale disasters focus upon post-earthquake relief. The reason for this is that earthquakes are one of nature's greatest hazards which can have catastrophic effects as these are responsible for massive levels of destruction and thousands of deaths each year – it is estimated that 17,000 people were killed globally as a result of earthquakes each year during the twentieth century<sup>10</sup>. Many countries around the world are situated in seismically active regions, including the United States and Japan, who often have to deal with earthquakes. The destructive effects of earthquakes are often widespread and can vary significantly, from ground shaking and liquefaction causing building structures and other types of structures to collapse, to even causing landslides and tsunamis which can completely destroy all existing infrastructure. Damage assessment methods for post-earthquake relief must therefore be diverse, meaning that in theory, these methods could be used for all post-disaster relief following natural disasters, accidental emergencies and acts of terrorism.

Gallagher *et al.* (1999) have produced guidelines and procedures to be used under emergency conditions following an earthquake, to minimise the risks associated with entering damaged building structures. The report explains that after an earthquake a state of suspended animation may exist; where some building structures may have collapsed and others may have become unstable which could collapse at any time, see Figure 3.

---

<sup>10</sup> Chen and Scawthorn (2003).



**Figure 2** – Example of damage following 1995 Kobe, Japan earthquake (a) unstable building structure. (b) an unstable building structure which collapsed less than 24 hours after the original earthquake. [Source: Gallagher *et al.* (1999).]

Within the Gallagher *et al.* (1999) report it states that assessing the structural stability of a damaged building structure may be a difficult task and is best judged by an engineer, but goes on to state that a level of acceptable risk must be established that considers the urgency of the need to enter. It is therefore advised that the decision to permit entry into any damaged building structure must not only consider the level of initial damage but also the possibility of aftershocks which could further aggravate existing damage. Although the focus of this report relates to earthquakes, these guidelines are also applicable to the period which follows any other form of disaster, accidental emergency or act of terrorism. The effects of strong

wind, additional explosions, collapse of nearby building structures or even the activities of search and rescue personnel themselves, could potentially aggravate any existing damage. Similarly, further collapse may occur as a result of weakened structural elements. Search and rescue personnel must therefore understand the necessity to consider the possibility and effects of any additional damage when assessing damaged and collapsed building structures.

#### **4.1 ATC-20**

A definitive guide on the subject of damage assessment and classification of building structures following an earthquake is the ATC-20 publication series produced by the Applied Technology Council (ATC)<sup>11</sup>. This is often regarded as the ‘best English publication’<sup>12</sup> as it contains practical guidelines and procedures for the assessment and classification of damage to the most common types of building structures found in the United States.

To promote consistent assessment and classification, the safety evaluation strategy employs a three-tier structure, so that if independent assessments of damage to a particular building structure were to take place, these would all arrive at the same conclusion as to the posting classification for that particular building structure. A summary of the safety evaluation strategy is as follows:

##### **1) Rapid Evaluation**

The first level of the evaluation strategy which is intended to be carried out quickly and with minimum manpower in about 10 to 20 minutes per building structure. Based on this evaluation it is possible to classify building structures as apparently safe (posted ‘INSPECTED’), obviously unsafe (posted ‘UNSAFE’) and others where uncertainty exists, the so-called grey area structures (posted ‘RESTRICTED USE’).

At this point the evaluation process involves a visual inspection of only the exterior of the building structure, unless there is a reported problem or the building structure cannot be adequately viewed from the outside. Obvious signs of structural distress are to be noted during the visual inspection include: partial collapse, leaning building structures, partial chimney collapse and detrimental geotechnical conditions e.g. ground movement.

---

<sup>11</sup> ATC (1989); ATC (1995); ATC (2005); ATC (1996).

<sup>12</sup> De Pauw and Lauritzen (1994); FEMA (2010); Gallagher *et al.* (1999).

**Table 1** – Basic inspection procedures for Rapid Evaluation. [Source: ATC (1989).]

1.	Examine the entire outside of the structure.
2.	Examine the ground in the general area of the structure.
3.	Enter a building only when the structure cannot be viewed sufficiently from the outside. Do not enter obviously unsafe structures.

## 2) Detailed Evaluation

The second level of evaluation strategy which is primarily used for the classification of building structures posted ‘RESTRICTED USE’ during the Rapid Evaluation. It is assumed that this evaluation will be carried out by at least two structural engineers, who have a good understanding of seismic design and experience of structural investigations, in about 1 to 4 hours.

The evaluation process involves thorough visual inspections of the entire building structure, both inside and out, where the primary focus is the structural system. Reasonable assurance is required that a building’s structural systems are sufficiently safe to allow the building structure to be put back into service and reposted ‘INSPECTED’. If any uncertainty exists as to whether the structural system is sufficiently safe then the posting classification will remain posted ‘RESTRICTED USE’.

It is recognised that the Detailed Evaluation will require considerable use of judgement as it is expected that much of the structural systems will be not be visible. At this point the use of destructive exploration is not recommended e.g. removal of plaster, studwork or false ceilings.

**Table 2** – Basic inspection procedures for Detailed Evaluation. [Source: ATC (1989).]

1.	Examine the entire outside of the structure.
2.	Examine the site for geotechnical hazards.
3.	Inspect structural systems from inside the building.
4.	Inspect for non-structural hazards e.g. cladding, ceilings, partitions, etc.
5.	Inspect for other hazards e.g. elevators, stairs, fire protection equipment, stored chemicals, etc.

## 3) Engineering Evaluation

This is the third and final level of the evaluation strategy and therefore the most thorough. It is used whenever a building structure has been damaged to such an extent

that it is not possible to assess its safety with the use of visual inspection alone. After this level of evaluation, all building structures previously posted ‘RESTRICTED USE’ (during both the Rapid Evaluation and Detailed Evaluation) will be reposted as either ‘INSPECTED’ or ‘UNSAFE’.

A structural engineering consultancy would take approximately 1 to 7 days (or more) per building structure and would produce detailed records of the damage, new structural calculations and a quantitative assessment of the strength of the damaged structure.

Despite the ATC-20 series offering practical guidelines and procedures for the assessment and classification of damaged building structures, as well as an effective safety evaluation strategy, De Pauw and Lauritzen (1994) advises that these not be used by search and rescue personnel. A reason for this is that the ATC-20 series has been developed so that the guidelines, procedures and safety evaluation strategy are for use of structural engineers and other such professionals with at least 5 years of experience in general structural design, construction or inspection. Another reason being, that it has been developed for the assessment and classification of building structures in order to prohibit entry and to prevent the uncontrolled reuse of into severely damaged and hazardous building structures in regards to occupancy. The terms ‘safe’ and ‘unsafe’ are very different when used in the context of assessing a damaged building structure for search and rescue to when used for occupancy<sup>13</sup>.

Although the ATC-20 series has been developed for use by structural engineers and other such professionals, it is an excellent example of how visual inspection can be tailored for the specific purpose of assessing damaged building structures. The fact that visual inspection is used within the three-tier structure of the safety evaluation strategy, confirms that it is a very valuable tool which can be adapted and applied to assess the condition of damaged building structures following all types of disasters. Two different practical survey forms have been developed specifically for the assessment of damaged building structures following an earthquake, for use during the Rapid Evaluation and Detailed Evaluation stages of the safety evaluation strategy, as shown in Figures 4 to 6. In addition to the survey forms, the pocket-sized *Field Manual: Procedures for Post-Earthquake Safety Evaluation of Building*<sup>14</sup>, has also been produced to summarise important guidelines, procedures and

---

<sup>13</sup> De Pauw and Lauritzen (1994); FEMA (2010); Gallagher *et al.* (1999).

<sup>14</sup> ATC (2005).

technical information to assist with the assessment and classification of damaged building structures.

Another excellent feature of the publications series as a whole is the inclusion of *Case Studies in Rapid Post-Earthquake Safety Evaluation of Buildings*<sup>15</sup>, which has been produced to demonstrate how to inspect and evaluate building structures for safety. Each case study includes photographs to display the extent of the damage and also specific examples of how to fill in the survey forms correctly and what extent of damage would correspond to each posting classification e.g. ‘INSPECTED’, ‘UNSAFE’ or ‘RESTRICTED USE’.

---

<sup>15</sup> ATC (1996).

ATC-20 Rapid Evaluation Safety Assessment Form																																												
<b>Inspection</b> Inspector ID: _____ Inspection date and time: _____ <input type="checkbox"/> AM <input type="checkbox"/> PM Affiliation: _____ Areas inspected: <input type="checkbox"/> Exterior only <input type="checkbox"/> Exterior and interior																																												
<div style="display: flex; justify-content: space-between;"> <div style="width: 48%;"> <b>Building Description</b>            Building name: _____            Address: _____            Building contact/phone: _____            Number of stories above ground: _____ below ground: _____            Approx. "Footprint area" (square feet): _____            Number of residential units: _____            Number of residential units not habitable: _____         </div> <div style="width: 48%;"> <b>Type of Construction</b>  <input type="checkbox"/> Wood frame <input type="checkbox"/> Concrete shear wall  <input type="checkbox"/> Steel frame <input type="checkbox"/> Unreinforced masonry  <input type="checkbox"/> Tilt-up concrete <input type="checkbox"/> Reinforced masonry  <input type="checkbox"/> Concrete frame <input type="checkbox"/> Other: _____   <b>Primary Occupancy</b>  <input type="checkbox"/> Dwelling <input type="checkbox"/> Commercial <input type="checkbox"/> Government  <input type="checkbox"/> Other residential <input type="checkbox"/> Offices <input type="checkbox"/> Historic  <input type="checkbox"/> Public assembly <input type="checkbox"/> Industrial <input type="checkbox"/> School  <input type="checkbox"/> Emergency services <input type="checkbox"/> Other: _____         </div> </div>																																												
<b>Evaluation</b> Investigate the building for the conditions below and check the appropriate column. <table style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="text-align: left; width: 45%;">Observed Conditions:</th> <th style="text-align: center; width: 10%;">Minor/None</th> <th style="text-align: center; width: 10%;">Moderate</th> <th style="text-align: center; width: 10%;">Severe</th> <th style="text-align: center; width: 25%;">Estimated Building Damage (excluding contents)</th> </tr> </thead> <tbody> <tr> <td>Collapse, partial collapse, or building off foundation</td> <td style="text-align: center;"><input type="checkbox"/></td> <td style="text-align: center;"><input type="checkbox"/></td> <td style="text-align: center;"><input type="checkbox"/></td> <td style="text-align: center;"><input type="checkbox"/> None</td> </tr> <tr> <td>Building or story leaning</td> <td style="text-align: center;"><input type="checkbox"/></td> <td style="text-align: center;"><input type="checkbox"/></td> <td style="text-align: center;"><input type="checkbox"/></td> <td style="text-align: center;"><input type="checkbox"/> 0-1%</td> </tr> <tr> <td>Racking damage to walls, other structural damage</td> <td style="text-align: center;"><input type="checkbox"/></td> <td style="text-align: center;"><input type="checkbox"/></td> <td style="text-align: center;"><input type="checkbox"/></td> <td style="text-align: center;"><input type="checkbox"/> 1-10%</td> </tr> <tr> <td>Chimney, parapet, or other falling hazard</td> <td style="text-align: center;"><input type="checkbox"/></td> <td style="text-align: center;"><input type="checkbox"/></td> <td style="text-align: center;"><input type="checkbox"/></td> <td style="text-align: center;"><input type="checkbox"/> 10-30%</td> </tr> <tr> <td>Ground slope movement or cracking</td> <td style="text-align: center;"><input type="checkbox"/></td> <td style="text-align: center;"><input type="checkbox"/></td> <td style="text-align: center;"><input type="checkbox"/></td> <td style="text-align: center;"><input type="checkbox"/> 30-60%</td> </tr> <tr> <td>Other (specify) _____</td> <td style="text-align: center;"><input type="checkbox"/></td> <td style="text-align: center;"><input type="checkbox"/></td> <td style="text-align: center;"><input type="checkbox"/></td> <td style="text-align: center;"><input type="checkbox"/> 60-100%</td> </tr> <tr> <td></td> <td></td> <td></td> <td></td> <td style="text-align: center;"><input type="checkbox"/> 100%</td> </tr> </tbody> </table> Comments: _____					Observed Conditions:	Minor/None	Moderate	Severe	Estimated Building Damage (excluding contents)	Collapse, partial collapse, or building off foundation	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> None	Building or story leaning	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> 0-1%	Racking damage to walls, other structural damage	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> 1-10%	Chimney, parapet, or other falling hazard	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> 10-30%	Ground slope movement or cracking	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> 30-60%	Other (specify) _____	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> 60-100%					<input type="checkbox"/> 100%
Observed Conditions:	Minor/None	Moderate	Severe	Estimated Building Damage (excluding contents)																																								
Collapse, partial collapse, or building off foundation	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> None																																								
Building or story leaning	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> 0-1%																																								
Racking damage to walls, other structural damage	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> 1-10%																																								
Chimney, parapet, or other falling hazard	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> 10-30%																																								
Ground slope movement or cracking	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> 30-60%																																								
Other (specify) _____	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/> 60-100%																																								
				<input type="checkbox"/> 100%																																								
<b>Posting</b> Choose a posting based on the evaluation and team judgment. <i>Severe</i> conditions endangering the overall building are grounds for an Unsafe posting. Localized <i>Severe</i> and overall <i>Moderate</i> conditions may allow a Restricted Use posting. Post INSPECTED placard at main entrance. Post RESTRICTED USE and UNSAFE placards at all entrances. <input type="checkbox"/> INSPECTED (Green placard) <input type="checkbox"/> RESTRICTED USE (Yellow placard) <input type="checkbox"/> UNSAFE (Red placard) Record any use and entry restrictions exactly as written on placard: _____																																												
<b>Further Actions</b> Check the boxes below only if further actions are needed. <input type="checkbox"/> Barricades needed in the following areas: _____ <input type="checkbox"/> Detailed Evaluation recommended: <input type="checkbox"/> Structural <input type="checkbox"/> Geotechnical <input type="checkbox"/> Other: _____ <input type="checkbox"/> Other recommendations: _____ Comments: _____																																												

© Copyright 1995-07, Applied Technology Council.  
 Permission is granted for unlimited, non-exclusive, non-commercial use and distribution of ATC evaluation forms, provided that this Copyright Notice appears on all copies and the Applied Technology Council name shall not be used in any advertising or publicity of Licensee product. Permission is further subject to the following conditions: (1) Licensee does not reprint, repackaging or offer this form for sale or license; and (2) no material gain or financial profit is to be made from any sale or license of this form. Placards may be used without restrictions for their intended use as building postings. All rights not specifically granted to Licensee are herein reserved by ATC.

**Figure 3** – The survey form for the safety assessment to be used during the Rapid Evaluation.  
 [Source: ATC: (1995).]

## ATC-20 Detailed Evaluation Safety Assessment Form

### Inspection

Inspector ID: \_\_\_\_\_

Affiliation: \_\_\_\_\_

Inspection date and time: \_\_\_\_\_ ☐ AM ☐ PM

### Final Posting from page 2

- ☐ Inspected  
☐ Restricted Use  
☐ Unsafe

### Building Description

Building name: \_\_\_\_\_

Address: \_\_\_\_\_

Building contact/phone: \_\_\_\_\_

Number of stories above ground: \_\_\_\_\_ below ground: \_\_\_\_\_

Approx. "Footprint area" (square feet): \_\_\_\_\_

Number of residential units: \_\_\_\_\_

Number of residential units not habitable: \_\_\_\_\_

### Type of Construction

- ☐ Wood frame ☐ Concrete shear wall  
☐ Steel frame ☐ Unreinforced masonry  
☐ Tilt-up concrete ☐ Reinforced masonry  
☐ Concrete frame ☐ Other: \_\_\_\_\_

### Primary Occupancy

- ☐ Dwelling ☐ Commercial ☐ Government  
☐ Other residential ☐ Offices ☐ Historic  
☐ Public assembly ☐ Industrial ☐ School  
☐ Emergency services ☐ Other: \_\_\_\_\_

### Evaluation

Investigate the building for the conditions below and check the appropriate column. There is room on the second page for a sketch.

	Minor/None	Moderate	Severe	Comments
<b>Overall hazards:</b>				
Collapse or partial collapse	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Building or story leaning	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Other _____	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
<b>Structural hazards:</b>				
Foundations	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Roofs, floors (vertical loads)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Columns, pilasters, corbels	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Diaphragms, horizontal bracing	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Walls, vertical bracing	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Precast connections	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Other _____	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
<b>Nonstructural hazards:</b>				
Parapets, ornamentation	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Cladding, glazing	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Ceilings, light fixtures	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Interior walls, partitions	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Elevators	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Stairs, exits	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Electric, gas	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Other _____	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
<b>Geotechnical hazards:</b>				
Slope failure, debris	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Ground movement, fissures	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____
Other _____	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	_____

General Comments: \_\_\_\_\_

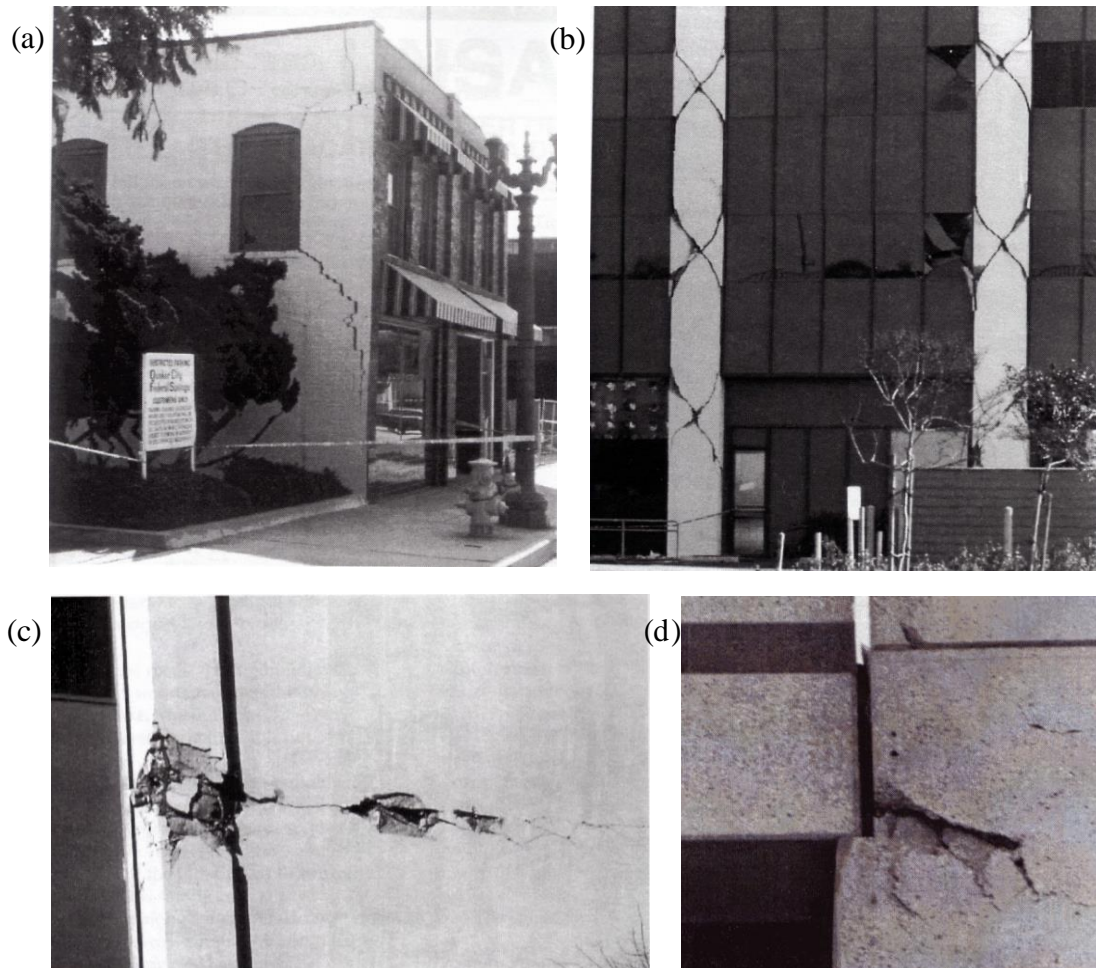
Continue on page 2

**Figure 4** – Page 1 of the survey form for the safety assessment to be used during the Detailed Evaluation. [Source: ATC: (1995).]



## 4.2 Documented Damage of Building Structures

A notable feature of the ATC-20 series is the frequent use of diagrams and photographs as visual aids to emphasise the guidelines and procedures and to illustrate what to look for during visual inspections. Throughout the ATC-20 series it states that a considerable amount of judgement is required to assess damaged building structures and it is very difficult, if not impossible to develop damage evaluation procedures and guidelines that can be used without judgement. To help those undertaking the tasks of assessing and classifying damage to building structures following an earthquake, photographs have been included throughout the ATC-20 series to document the different types and varying extent of damage, see Figure 7.



**Figure 6** – Examples of the documented damage to building structures caused by earthquakes in the ATC-20 series (a) crack pattern in side wall of masonry building. (b) Failed concrete piers (x-cracks) of multi-storey building. (c) Damage to shear wall along horizontal construction joint. (d) Cracking of precast concrete support of parking structure. [Source: ATC (1996).]

The main advantage of studying detailed analysis and photographs of different types of damage and collapse of building structures which has occurred in the past, is so that valuable

lessons can be learnt for the future, primarily to the design and construction of resilient building structures<sup>16</sup>. The ATC-20 series has used photographs throughout to great effect in order to demonstrate the different types and varying degrees of damage which can be caused by earthquakes. The reason for this is not to learn lessons for future design or construction but to assist those undertaking the tasks of assessing and classifying damage to building structures to make accurate judgements and to promote consistency.

There are a number of publications and reports that are available which provide information about damage to building structures, one such example being the field reports produced by the Earthquake Engineering Field Investigation Team (EEFIT). These are a group of British earthquake engineers, architects and academics who conduct field investigations following major earthquakes around the world. The primary purpose of the EEFIT field investigations is to assess current design practices and regulations by collecting detailed technical evaluations of the performance of structures, foundations and civil engineering works and to analyse the behaviour of structures when subjected to seismic loading. These field reports include nearly all of the major earthquakes which have occurred in the past ten years, such as: 2004 Indian Ocean Tsunami, 2008 China Earthquake, 2010 Haiti Earthquake, 2010 Chile Earthquake and most recently, 2011 Japanese Earthquake and Tsunami<sup>17</sup>. Similarly, numerous other reports and publications have also been produced which document damage to building structures caused by earthquakes, particularly on the 2011 New Zealand Earthquake in Christchurch<sup>18</sup>.

After reviewing the many different publications and reports which are available and contain information about damage to building structures caused by earthquakes, it is evident that damage to building structures can vary significantly, as shown in Figure 8. However, the problem remains that the information that is available about damage to building structures is aimed at structural engineers and other such professionals. There is very little published material, if any, that has been produced specifically for search and rescue personnel which provides suitable information about damage to building structures, and explains what impact damage has on structural stability.

---

<sup>16</sup> IStructE (1981).

<sup>17</sup> EEFIT (2006); EEFIT (2008); EEFIT (2010a); EEFIT (2010b); EEFIT (2011).

<sup>18</sup> Clifton *et al.* (2011); Kam (2011); Kam and Pampanin (2011a); NZSEE and RSNZ (2011).

The ATC-20 series<sup>19</sup> is an excellent example of a publication series that contain a range of important guidelines, procedures, technical information and visual aids, both diagrams and photographs, to assist with the assessment and classification of damaged building structures. In particular, the *Case Studies in Rapid Post-Earthquake Safety Evaluation of Buildings*<sup>20</sup> publication has been produced to demonstrate how to inspect and evaluate building structures for safety. Each case study includes photographs to display the extent of the damage and also specific examples of how to fill in the survey forms correctly and what extent of damage would correspond to each posting classification e.g. ‘INSPECTED’, ‘UNSAFE’ or ‘RESTRICTED USE’. Although, De Pauw and Lauritzen (1994) advise that the ATC-20 series not be used by search and rescue personnel, lessons should be learnt from it. For example, similar information needs to be available to search and rescue personnel which demonstrates what to look for during visual inspections, by documenting damage and also explaining what implication this may have on structural stability. Based on this type of information search and rescue personnel will be better equipped to make more accurate and consistent judgements when assessing damaged building structures and help to better quantify risk.

---

<sup>19</sup> ATC (1989); ATC (1995); ATC (2005); ATC (1996).

<sup>20</sup> ATC (1996).



**Figure 7** – Examples of the type of damaged and collapsed building structures documented in reports (a) a residential building in Kalutara, Sri Lanka. (b) a school building in Talcahuano, Chile. (c) a traditional residential building in San Gregorio, Italy. (d) an office building in Oroshi, Japan. (e) an apartment block in L'Aquila, Italy. (f) a warehouse in Christchurch, New Zealand.

Sources: (a) EEFIT (2006). (b) EEFIT (2010b). (c) EEFIT (2009). (d) EEFIT (2011). (e) Kam and Pampanin (2011a).

## 5.0 SUMMARY AND OVERVIEW

The fact that there is such little published literature available to assist search and rescue personnel to assess the condition of a damaged building structure, indicates that this is a subject that would greatly benefit from research in the forthcoming years. After reviewing the literature that is available to search and rescue personnel, in addition to general structural investigation techniques and damage assessment methods, the following observations have been made:

- Field manuals produced for search and rescue personnel lack technical information and guidance which would help considerably when assessing the structural condition of damaged building structures.
- Search and rescue personnel must be equipped with a suitable education base, including the basic principles of structural mechanics and knowledge of construction would ensure a better understanding of the different types of damaged and collapsed building structures.
- It is very difficult task to determine as to what constitutes as ‘safe’ and ‘unsafe’ in the context of search and rescue – search and rescue personnel must be able to quantify risk.
- The majority of literature available about structural investigations, assessment and appraisal are not suitable for search and rescue personnel. Although the use of visual inspection could be highly effective and a valuable tool, which could be adapted to assist search and rescue personnel to assess damaged building structures if appropriate training and guidance were provided.
- Diagrams and photographs are important visual aids which can be used to demonstrate what to look for during visual inspections, such as commonly associated structural and non-structural defects. The use of diagrams and photographs to display the different types and varying degrees of damage which can be caused to building structures will help search and rescue personnel to make more accurate and consistent judgements when assessing damaged building structures in regards to structural stability.

## REFERENCES

- ATC (1989) *Procedures for Post-Earthquake Safety Evaluation of Building*, ATC-20 Report, Redwood City, CA: Applied Technology Council (ATC).
- ATC (1995) *Addendum to the ATC-20 Post-Earthquake Building Safety Evaluation Procedures*, ATC-20-2 Report, Redwood City, CA: Applied Technology Council (ATC).
- ATC (1996) *Case Studies in Rapid Post-Earthquake Safety Evaluation of Buildings*, ATC-20-3 Report, Redwood City, CA: Applied Technology Council (ATC).
- ATC (2005) *Field Manual: Procedures for Post-Earthquake Safety Evaluation of Building*, ATC-20-1 Report, 2<sup>nd</sup> Edition, Redwood City, CA: Applied Technology Council (ATC).
- Campbell, P. (Ed.) (2001) *Learning from Construction Failures: Applied Forensic Engineering*, Caithness: Whittles Publishing.
- Ceci, A.M., Contento, A., Fanale, L., Faleta, D., Gattulli, V., Leipidi, M. and Potenza, F. (2010) 'Structural Performance of the Historic and Modern Buildings of the University of L'Aquila during the Seismic Events of April 2009,' *Engineering Structures*, Volume 32 (Issue 7) Pages 1899-1924.
- CERA (2011) *Photo Gallery*, Canterbury Earthquake Recovery Authority (CERA) Library [Online] Available at: <http://cera.govt.nz/photo-gallery> (Accessed: 6 March 2012).
- Chen, W. and Scawthorn, C. (2003) *Earthquake Engineering Handbook*, London: CRC Press.
- Clifton, C., Bruneau, M., Fussell, A., Leon and MacRae, G. (2011) *Steel Building Damage from the Christchurch Earthquake Series of 2010 and 2011: Technical Report*, Canterbury Earthquakes Royal Commission Document Library [Online] Available at: <http://canterbury.royalcommission.govt.nz/documents-by-key/20111104.759> (Accessed: 6 March 2012).
- Concrete Society (2000) *Diagnosis of Deterioration in Concrete Structures: Identification of Defects, Evaluation and Development of Remedial Action*, Technical Report 54, Camberley: Concrete Society.
- Concrete Society (2008) *Assessment, Design and Repair of Fire-Damaged Concrete Structures*, Technical Report 68, Camberley: Concrete Society.
- Davis, J. and Lambert, R. (2002) *Engineering in Emergencies: A Practical Guide for Relief Workers*, 2<sup>nd</sup> Edition, Rugby: Practical Action Publishing.
- De Pauw, C. and Lauritzen E.K. (Eds.) (1994) *Disaster Planning, Structural Assessment, Demolition and Recycling*, RILEM Report 9, London: E. & F.N. Spon.
- EEFIT (2006) *The Indian Ocean Tsunami of 26 December 2004: Mission Findings in Sri Lanka and Thailand*, Earthquake Engineering Field Investigation Team (EEFIT) Reports [Online] Available at: [http://www.istructe.org/knowledge/EEFIT/Documents/Indian\\_Ocean\\_Tsunami.pdf](http://www.istructe.org/knowledge/EEFIT/Documents/Indian_Ocean_Tsunami.pdf) (Accessed: 9 November 2011).

EEFIT (2008) *The Wenchuan, China Earthquake of 12 May 2008: A Preliminary Field Report by EEFIT*, Earthquake Engineering Field Investigation Team (EEFIT) Reports [Online] Available at: [http://www.istructe.org/knowledge/EEFIT/Documents/Wenchuan\\_Preliminary\\_Report.pdf](http://www.istructe.org/knowledge/EEFIT/Documents/Wenchuan_Preliminary_Report.pdf) (Accessed: 9 November 2011).

EEFIT (2010a) *The Haiti Earthquake of 12 January 2010: A Field Report by EEFIT*, Earthquake Engineering Field Investigation Team (EEFIT) Reports [Online] Available at: <http://www.istructe.org/knowledge/EEFIT/Documents/field-report-12-jan-2010.pdf> (Accessed: 9 November 2011).

EEFIT (2010b) *The  $M_w$ 8.8 Maule Chile Earthquake of 27<sup>th</sup> February 2010: A Preliminary Field Report by EEFIT*, Earthquake Engineering Field Investigation Team (EEFIT) Reports [Online] Available at: <http://www.istructe.org/knowledge/EEFIT/Documents/eeffit-chile-report.pdf> (Accessed: 9 November 2011).

EEFIT (2011) *The  $M_w$ 9.0 Tohoku Earthquake and Tsunami of 11<sup>th</sup> March 2011: A Field Report by EEFIT*, Earthquake Engineering Field Investigation Team (EEFIT) Reports [Online] Available at: <http://www.istructe.org/knowledge/EEFIT/Documents/field-report-tohoku-japan-11-march-2011.pdf> (Accessed: 13 December 2011).

Ekenel, M. and Myers, J.J. (2007) 'Durability Performance of RC Beams Strengthened with Epoxy Injection and CFRP Fabrics,' *Construction and Building Materials*, Volume 21 (Issue 6): Pages 1182-1190.

FEMA (1994) *Reducing the Risks of Non-Structural Earthquake Damage: A Practical Guide*, 3<sup>rd</sup> Edition, FEMA 74, FEMA Library [Online] Available at: <http://www.fema.gov/library/viewRecord.do?id=3843> (Accessed: 9 November 2011).

FEMA (1998) *Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings: Basic Procedures Manual*, FEMA 306, FEMA Library [Online] Available at: <http://www.fema.gov/library/viewRecord.do?id=1651> (Accessed: 9 November 2011).

FEMA (2003) *National Urban Search & Rescue (US&R) Response System: Field Operations Guide*, US&R-2-FG, US&R Resources [Online] Available at: <http://www.fema.gov/emergency/usr/resources.shtm> (Accessed: 16 November 2011).

FEMA (2006a) *National Urban Search & Rescue (US&R) Response System: Rescue Field Operations Guide*, US&R-23-FG, US&R Resources [Online] Available at: <http://www.fema.gov/emergency/usr/resources.shtm> (Accessed: 16 November 2011).

FEMA (2010) *National US&R Response System: Structural Collapse Technician Training Manual*, Structural Collapse Technician Course: Student Manual - Module 1c Structural Engineering Systems [Online] Available at: <http://www.fema.gov/emergency/usr/sctc.shtm> (Accessed: 16 November 2011).

Hampshire Fire and Rescue Service (2012) *Urban Search and Rescue*. Available at: <http://www.hantsfire.gov.uk/theservice/specialistresponse/specialistrescues/usar.htm> (Accessed: 15 February 2012).

Houghton-Evan R.W. (2005) *Well Built? A Forensic Approach to the Prevention, Diagnosis and Cure of Building Defects*, London: RIBA Publishing.

- Hoxley, M. (2009) *Building Condition Surveys*, Good Practice Guide, London: RIBA Publishing.
- IStructE (1981) *Structural Failures in Buildings*, London: Institution of Structural Engineers (IStructE).
- IStructE (1995) *Structural Engineer's Response to Explosion Damage*, London: Institution of Structural Engineers (IStructE).
- IStructE (2010a) *Appraisal of Existing Structures*, 3<sup>rd</sup> Edition, London: Institution of Structural Engineers (IStructE).
- Kam, W.Y. (2011) *Preliminary Report from the Christchurch 22 Feb. 2011 6.3M<sub>w</sub> Earthquake: Pre-1970s RC and RCM Buildings, and Precast Staircase Damage*, NZSEE Structural Database, [Online] Available at:  
<http://db.nzsee.org.nz:8080/documents/43301/b274721e-d91a-424c-b8bb-fd51a99d0954>  
 (Accessed: 6 March 2012).
- Kam, W.Y. and Pampanin, S. (2011a) 'The Seismic Performance of RC Buildings in the 22 February 2011 Christchurch Earthquake,' *Structural Concrete*, Volume 12 (Issue 4): Pages 223-233.
- Kay, T. (1992) *Assessment and Renovation of Concrete Structures*, Harlow: Longman Scientific & Technical.
- Lancashire Fire and Rescue Service (2007) *UK Urban Search and Rescue*. Available at: <http://www.usar.org.uk/> (Accessed: 15 February 2012).
- Mays, G. (Eds.) (1992) *Durability of Concrete Structures: Investigation, Repair, Protection*, London: E & FN Spon.
- NZSEE and RSNZ (2011) *The Canterbury Earthquakes: Scientific Answers to Critical Questions*, New Zealand Society for Earthquake Engineering (NZSEE) and Royal Society of New Zealand (RSNZ) [Online] Available at: <http://www.nzsee.org.nz/> (Accessed: 6 March 2012).
- Sphere Project (2011) *Humanitarian Charter and Minimum Standards in Humanitarian Response*, 3<sup>rd</sup> Edition, Rugby: Practical Action Publishing.
- UNHCR (2007) *Handbook for Emergencies*, 3<sup>rd</sup> Edition, Geneva: United Nations High Commissioner for Refugee (UNCHR).
- USAID (2005) *Field Operations Guide: For Disaster Assessment and Response*, Version 4.0, Washington, DC: U.S. Agency for International Development (USAID).