General Awareness Information

RAPID STRUCTURAL SAFETY ASSESSMENT & MONITORING for REINFORCED CONCRETE STRUCTURE

June 2003

U.S. Public Health Service
Engineer Professional Advisory Committee

Emergency Preparedness Subcommittee Disclaimer

This document provides guidance on the Engineering Professional Advisory Committees (EPAC) current thoughts on the subject. An alternative approach may be used if such approach satisfies the situation. Periodically, EPAC will review this document and modify it according to comments submitted.

Contributors

Members of the EPAC, Emergency Preparedness Subcommittee, produced this document. The Emergency Preparedness Subcommittee members that provided input to this document were:

LCDR Dan Beck
CAPT Jose Cuzme
CDR Nathan Gjovik, principal author
Mr. Brain Kong
LCDR Scott Lee
LCDR Nelson Mix
CDR Peter Pirillo, Jr.
CDR Kathy Poneleit
CAPT John Riegel
CAPT Sven Rodenbeck, Chairperson
CDR Jim Simpson
CDR Andy Smith
LCDR Mary Weber

Other USPHS engineers who provided significant contributions were:

CAPT Richard Melton
Mr. John Pavlides
Mr. Hank Payne

Any comments or questions concerning this document should be sent to Captain Sven Rodenbeck, Chairperson, Emergency Preparedness Subcommittee, EPAC at Srodenbeck@cdc.gov.

RAPID STRUCTURAL SAFETY ASSESSMENT & MONITORING
for
REINFORCED CONCRETE STRUCTURE

Purpose

During a disaster an engineer may be tasked with a variety of functions, some of which may not be within the purview of his/her expertise. One of these could be the assessment and monitoring of the structural stability of a reinforced concrete structure. It is the premise of this instruction that this can be performed in a cursory fashion by a non-structural engineer (in the absence of a competent structural engineer)[1], within a relatively static environment. Therefore, the purpose of this instruction is to provide a fundamental understanding that will allow a nonstructural engineer to perform a cursory safety assessment/monitoring of a reinforced concrete structure.[2]

This instruction has its roots in the procedures that were used in the hours and days following the bombing of the Alfred P. Murrah Federal building in Oklahoma City, Oklahoma, on April 19, 1995.

Reinforced Concrete Structures

Reinforced concrete is comprised of two basic materials, steel and concrete. The two materials work in a synergistic fashion when constructed properly to provide composite components which have very strong structural characteristics. Reinforced concrete is commonly used in structures designed for heavy use and long life, such as governmental and institutional buildings and public works structures.

Concrete has a great capacity to support compressive loads (i.e., loads that tend to force the "fibers" of the material together). However, concrete has only a limited capacity to support tensile loads (i.e., loads that tend to pull the "fibers" of the material apart). Steel has a great capacity to carry both compressive and tensile loads. However, it is expensive to use as a single structural element and is prone to degradation (e.g., rusting) in certain environments. Therefore, in order to construct structural elements which are long lasting, economical, and have both compressive and tensile capacity, steel is combined with concrete to harness the compressive strength of concrete and the tensile strength of steel.

Beams are horizontal structural components that support floors, ceilings, roofs, or decks (i.e., bridge and parking decks). The loads carried by a beam are primarily perpendicular to the longitudinal axis of the beam. As load is applied to a beam it generally tends to cause bending of the beam, with the center of the unsupported section being forced away from the applied load. This bending creates compressive forces (compression) in the upper depth of the beam and

[1] This instruction is intended to provide cursory guidance in the absence of a competent structural engineer within an emergency environment. If and when a competent structural engineer becomes available, he/she should be briefed on any emergency activities related to the structure performed by other engineers and other emergency personnel, if known, consulted before any additional activities are undertaken.
[2] This document contains a very basic discussion of building systems in an effort to keep the concepts readily comprehensible to persons lacking specialized training in structural engineering. For more thorough guidance on this topic, the reader is referred to the additional references provided at the end of this instruction.

tensile forces (tension) in the lower depth of the beam. A typical reinforced concrete beam is designed to allow the compressive forces to be carried by the concrete material and the tensile forces to be carried by the steel.

Columns are vertical structural components that support beams and other structural elements. The compressive loads carried by columns are primarily parallel to the vertical or longitudinal axis of the column. As a uniform concentric load is applied to a column, compressive loads occur within the column's cross-section, and are distributed between the concrete and longitudinal steel reinforcement. When an eccentric load is applied to a column (e.g., a corner column with beams connecting into the column which are 90^o apart) bending will occur in the column, with outer sections of the column being in tension and inner sections being in compression. The tension and compression loads within the column are carried by vertical reinforcement and concrete. Columns are usually designed with a ring of structural steel around the outer perimeter to provide confinement of the concrete in case of column failure.

Concrete structures are built using cast-in-place, precast, or a combination of either procedure. Structures built prior to the 1975 were built using non-ductile concrete methods and hence have more structural damage due to unforeseen events. Cast-in-place buildings are erected using temporary forms that concrete is placed into and then forms removed. Precast buildings elements are generally formed off-site and then shipped to be assembled on-site using some type of anchoring device. Cast-in-place structural failures will occur throughout the concrete member and/or its connections while failures in a precast building member will typically occur at the joints and/or connections.

Rapid Structural Safety Assessment

The objective for the rapid structural safety assessment is to quickly inspect and evaluate the concrete structure and determine if the damaged structure is unsafe for personnel within the building and rescue personnel accessing the building. Two primary concerns need to be considered when performing this assessment of the structure that has sustained structural damage. This includes a quick evaluation of the building "structural" components (e.g., beams, columns, decking, etc.) and of the building "nonstructural" components "(e.g., structural debris, partitions, ceilings, glass, pipe anchoring, electrical/mechanical equipment anchoring, etc.). If there are any visual signs of structural and/or nonstructural damage, then the specific building area needs to be isolated, secured, and marked as UNSAFE. The on-scene commander should be informed and the area remained in this UNSAFE condition, until a structural engineer proves otherwise.

The rapid structural damage assessment would note the major failures within the structure including the major structural elements of beams, columns, roof and floor decks. Typical failures would be found at the connections of the major structural elements, or at elements that no longer have adequate vertical support (e.g., unsupported roof and floor decks that are now cantilever elements.[3]) Indications would include cracking, spalling (i.e., loss of concrete from an

[3] Frequently, structural members are concealed by wall and ceiling finishes. Therefore, it may be advisable to perform selective demolition in order to allow adequate inspection of critical structural elements. However, such activities should be done only with the knowledge and support a structural engineer and the on-scene commander.

exterior surface), and/or complete loss of all or part of a structural element. The on-scene commander should be notified immediately of the risk, and the area secured and marked UNSAFE.

The rapid nonstructural damage assessment would note the major failures within the building structure envelope including such items as structural debris, partitions, ceilings, glass, piping, and electrical/mechanical equipment. Concrete is a brittle material and, therefore, has a tendency to fragment into small, dense, hard pieces with rough edges. Many of these fragments may be precariously lying near or hanging from the exposed building edges and some fragments may be barely attached to exposed reinforcement steel. Settlement or shifting of the damaged structure may cause fragments to fall resulting in serious harm to personnel[4] and/or additional damage to the remaining structure. The issue of potential harm to personnel from concrete fragments and other building materials (such as glass, and other items that may have been in and around the structure) is exacerbated by activities that may be occurring in and around the remaining structure by rescue personnel operating throughout the building, along with rescue and/or press rotary-wing aircraft operating around the building. These activities may tend to cause accidental (e.g., physical interaction with something causing debris to fall) or inadvertent (e.g., vibration or rotor wash from rotary-wing aircraft causing debris to fall) mishaps. Typical failures in other nonstructural elements would be found where they originally were attached and/or secured. Failures would include anchoring tensile or shear failure, nonstructural element damage, and potential of future damage due to gravity loads and/or inadequate support bracing. The on-site commander should be notified immediately of the risk, and the area secured and marked UNSAFE.

Depending on the structural and nonstructural elements within the building matrix and their relation to rescue/recovery activities, there may be varying importance on the ability of these elements to provide adequate support. For example, failure of a column at ground level may cause failure of the remaining structure above that column[5], or failure of a beam above an area where rescue/recovery workers are operating may at least cause collapse of a floor (and its contents) into the rescue/recovery area. Therefore, the rapid structural safety assessment should focus on those remaining structural elements of greatest importance to the remaining structure and the safety of rescue/recovery workers.

The ability to perform a rapid structural safety assessment is likely to require a good flashlight (or headlamp), because adequate lighting often is not available in[6] or around[7] the remaining

[4] The importance of using proper personal protective equipment when working within a compromised structure is paramount. One of the fatalities at the Alfred P. Murrah Federal building in Oklahoma City was not within close proximity of the building at the time of the bombing. This person was a rescuer who entered the remaining structure without wearing head protection and subsequently received a fatal blow to the head from falling debris.

[5] This is not to suggest that failure of a structural element in an upper floor or roof would be limited to the affected area of the building. Most structures are not designed to withstand the impact force of a heavy section of an upper floor or roof section landing on it. Consequently, a failure of a structural element in an upper floor of a remaining structure may manifest a progressive collapse below and around the failed element as the failed upper floor/roof sections progressively slam onto each lower floor section. An example of this concept is the collapse of the two World Trade Center towers following the terrorist attacks to the upper floors of the buildings, with the net result being a progressive collapse of both towers.

[6] Any entry into a compromised structure should only be attempted with the approval of a structural engineer and the permission of the on-scene commander.

structure. In addition, a notebook, pen or pencil, spray paint (for making annotations on or around the compromised structure) and a camera (if available) will be needed for the assessment.

The locations of any structural and nonstructural elements should be documented via a written description and an associated sketch or photograph (digital or Polaroid®) for use in more detailed assessment/analysis following the rapid structural safety assessment.

Personnel performing the rapid structural safety assessment in and around the remaining structure should wear appropriate personal protective equipment (PPE). At a minimum PPE should include a hardhat, steel-toed boots (with steel shanks), gloves, and respiratory protection from dust. The specific site conditions may dictate further PPE.

The rapid structural assessment should be performed in the following order:

1) Review the entire outside of the structure.
2) Enter the building <u>only</u> if necessary to determine extent of damage.
3) Determine what degree of damage found in the structural and nonstructural elements.
4) Secure all areas that need to be isolated and post UNSAFE signage.

<u>**Monitoring**</u>

A monitoring program can be established during the rapid assessment effort. Monitoring of potentially dangerous debris, unsecured equipment, structural cracks and failures until any mitigation/removal effort is complete may be simple periodic surveillance of the affected areas.

The primary mode of failure for nonstructural elements within a compromised structure is due to the potential future movement of these elements. All unsecured elements need to be documented and recorded so that any future movement of these elements can be clearly established.

Two primary modes of failure for structural elements within a compromised structure are shear and buckling[8]. Shear failure implies failure generally along a plane (e.g., the failure of a deck slab that is no longer properly supported, could fail in a clean shear break). Buckling failure is a compressive failure that results in the element collapsing (e.g., the lateral displacement of a column).

Failure events may occur suddenly (e.g., the clean break of a cantilevered floor or roof section with no structural steel in the upper depth) or could be subtle as remaining structural elements adjust to the loading from the remaining structure. This adjustment may be radically different from the original design loads of the structural elements, as well as their potentially different structural composition. For example, they may have cracking and/or spalling affecting the carrying capacity of the element and/or the characteristics of the materials comprising the remaining structural elements may have changed (e.g., steel loses strength rapidly at

---

[7] Assessment of the exterior of the remaining structure can be effectively accomplished via a man basket capable of reaching the upper floors.
[8] This should not be construed to imply that shear and buckling are mutually exclusive or that they are the only modes of failure.

temperatures over 800^{o} F and, if exposed to such temperatures, it may lose its ability to carry the original design loads, even after it has cooled). Therefore, monitoring is critical to expose subtle changes that may have the potential to result in structural failure.

Monitoring individual structural elements for possible shear failure[9] can be performed simply by marking a straight line perpendicularly across cracks of concern using a pencil or fine-tip permanent marker (see Figure 1). Any slippage along the crack (possible shear failure) would then be indicated by a disjunction of the straight line. The length of cracks also should be monitored by drawing an arrow on the affected structural element with the tip of the arrowhead placed at the clearest discernible termination point of the crack (see Figure 1). The date and time that the arrow was placed also should be clearly noted on the structural element such that its association with the arrow is unambiguous. This will document any extensions of cracks which may indicate possible weakening of the affected structural element with the potential end result being buckling failure. This data could then be utilized to make decisions on necessary shoring or bracing efforts by engineers with structural experience.

Monitoring of the overall structure can be accomplished by establishing a matrix of "witness marks" or survey marks on the exterior of the remaining structure (see Figure 2). A line of markings can be made vertically through a line of columns and/or horizontally through a line of beams. This can be accomplished with the use of a transit (or other optical device with vertical and horizontal crosshairs), and bright-colored (preferably fluorescent) spray paint. It is desirable to have clear visibility of all markings from a common transit station that can be permanently established, without having to be periodically broken down during the monitoring effort. The intent of the placement of the witness marks is to allow monitoring of the various sections of the remaining structure relative to the others. This allows a relatively easy, fast, and safe means of determining if a given section is moving relative to the rest of the remaining structure and may illuminate significant and possibly imminent structural issues.

The monitoring effort should be constant (i.e., around the clock unless ordered to suspend the effort by the on-scene commander) with data logging at regular time intervals. The interval will be dependent upon available resources, the stability of the remaining structure, and the dynamics of the environment and rescue/recovery efforts within and around the remaining structure.

Additional References

Case Studies in Rapid Safety Evaluation of Buildings was prepared with funding from the Applied Technology Council and R.P. Gallagher, and Associates, Inc. Available from the Applied Technology Council. (Published 1997, 295 pages)

Postearthquake Safety Evaluation of Buildings Training Manual. Developed under a contract with FEMA. Available from the Applied Technology Council. (Published 1993, 177 pages; 160 slides)

[9] Monitoring is especially important for those elements deemed critical (i.e., their loss would manifest a catastrophic loss of the remaining structure and/or place rescue/recovery workers at risk).

Rapid Visual Screening of Buildings for Potential Seismic Hazards: a Handbook was developed under a contract from FEMA. Available from the Applied Technology Council. (Published 1988, 185 pages)

Rapid Visual Screening of Buildings for Potential Seismic Hazards: Supporting Documentation was developed under a contract from FEMA. Available from the Applied Technology Council. (Published 1988, 137 pages)

Field Manual: Post earthquake Safety Evaluation of Buildings (ATC-20-1). Available from the Applied Technology Council (Published 1989, 114 pages)

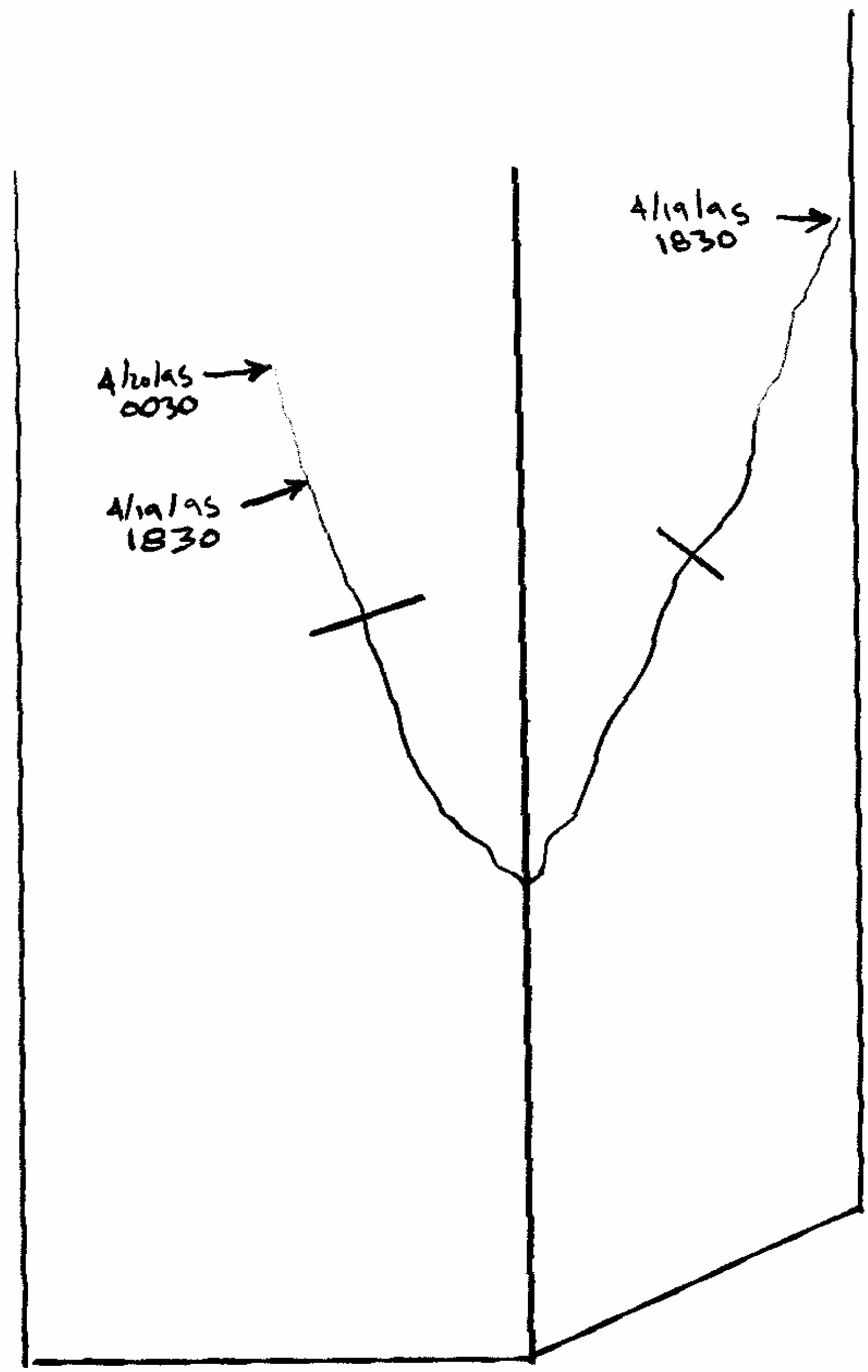

Figure 1. Depiction of examples of suggested markings along a column to monitor potential for shear (lines crossing and perpendicular to cracks) and/or buckling failure (arrows with arrowheads at discernable ends of cracks with dates and times that arrows were placed annotated).

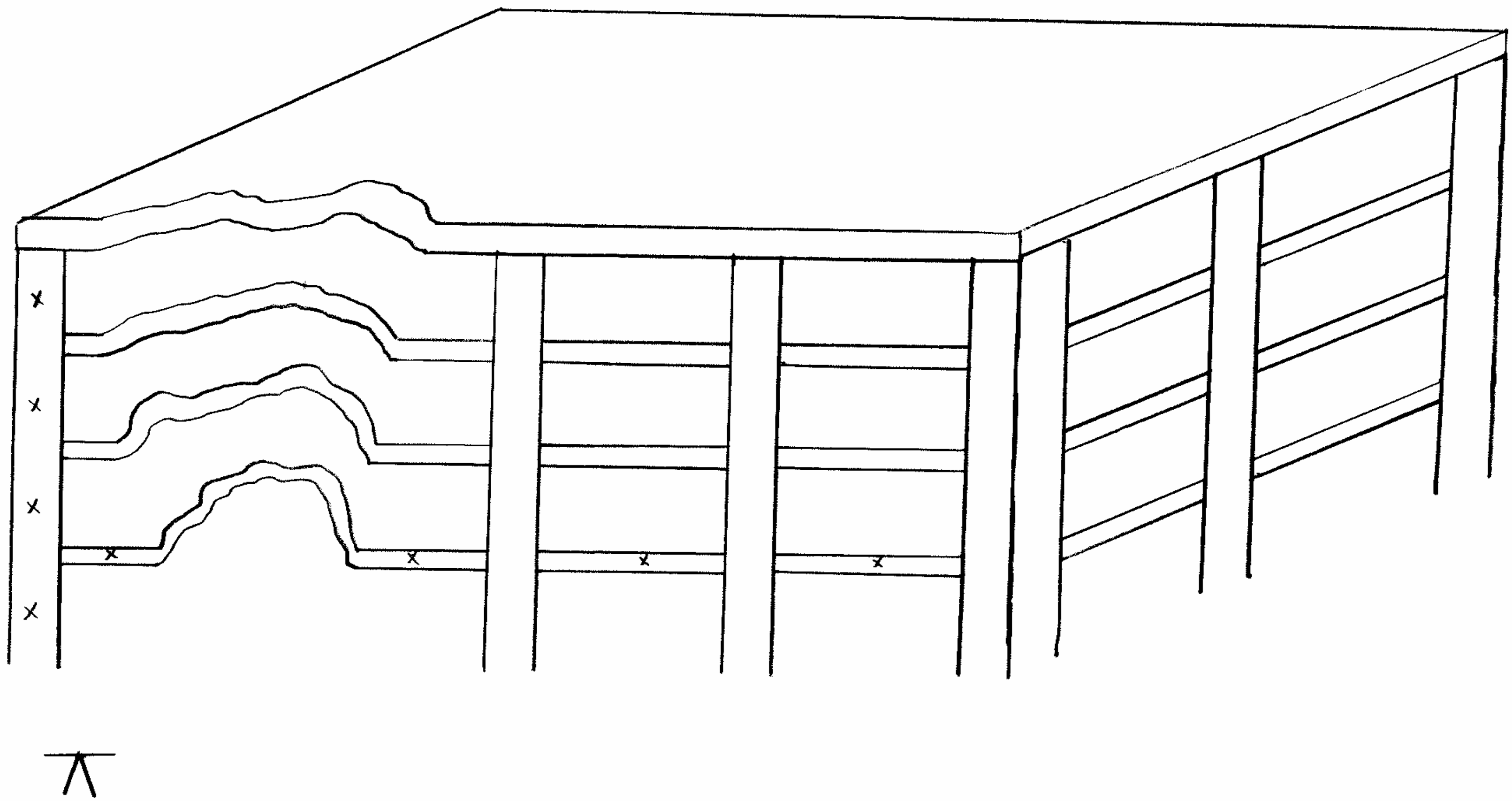

Figure 2. Depiction of examples of witness/survey marks (shown as X's) along column (vertical) and beam (horizontal) alignments around compromised section of remaining structure. Transit station is shown in front.