

StS2-1-3 Failure Mode Analysis – Student Questionnaire

Additional Comments:

StS2-1-3 FAILURE MODE ANALYSIS

Objectives

The objectives of this module are to systematically summarize:

- the various types of events that may lead to a US&R deployment,
- the failure modes that may be expected from those events for common building types,
- the practical significance of those failure modes for US&R operations.

Key Learning Points

1. Three characteristics of a collapse that must be assessed by the StS are viable void potential, structural hazards, and mitigation strategies.
2. Three major factors that influence hazard assessment and mitigation strategies are: the cause of the collapse, the nature and extent of damage (damage zone), and the construction type.
3. Many triggering events, each with unique characteristics, may lead to US&R deployment. While each triggering event has unique characteristics, a common element of all US&R deployments will be progressive or disproportionate collapse driven by gravity.
4. There are five damage zones, each with unique characteristics: close-in, complete collapse, partial collapse, structural damage, and non-structural damage.
5. Characteristics to be considered in the StS's assessment include total energy released in the collapse, remaining potential energy, stability of remaining structure and debris, and changing conditions.
6. Failure modes of damaged structures include falling of loose debris, shifting of debris pile, shifting/sliding/dropping of elevated failed components, shear/flexural failure of beams/slabs, crushing/buckling of walls/columns, story mechanism, and overturning.
7. There are many construction types, and combinations of construction types, each with unique characteristic regarding response to extreme loads, damage patterns, and hazards. This information is summarized in the Failure Modes Summary Table at the end of this module.

Topics

- Objectives / Key Learning Points
- Failure Modes - Key US&R characteristics
- Causes and characteristics of structural collapse
- Damage zones
- Damage by construction type

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Module Objectives

- Understanding of the types of events which may lead to a US&R deployment
- Understanding the failure modes in common building types which result from the different events
- Understanding of the practical significance of the failure modes for US&R operations

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5 Minute Case Study

- What information needed from building manager?
- What information does the TFL need from StS at the outset?
- What will you do to size up the situation when you initially arrive on scene?



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StS2-1-3 FAILURE MODE ANALYSIS

Introduction

The US&R program was initially developed to respond to a major urban earthquake disaster. Much of the early StS training therefore focused on expected earthquake damage patterns. However, the short history of the program has demonstrated that US&R resources may be called upon to respond to structural collapses triggered by a wide variety of causes. Each of the US&R deployments to date has presented unique challenges to the StSs that went well beyond what had been covered in early StS training. The intent of this module is to increase the experienced StS's understanding of both the commonalities and unique aspects of this wide variety of potential events so that they are better prepared to respond effectively to the unique circumstances of the next event.

Some of the material in this module may repeat material covered in StS1 training, specifically modules StS1-1.1, 1.2, 1.3, and 1.4. However, there is much pertinent information in those modules that is not repeated here and students are urged to review their StS1 student manuals.

Three major factors that influence risk assessment and mitigation strategies are:

- Cause of the collapse,
- Nature and extent of damage (damage zone),
and
- Construction type.

For example, the partial collapse of an unreinforced masonry building due to earthquake will present very much different hazards and require different mitigation strategies than the partial collapse of a steel framed structure due to a tornado.

Thus, the StS must consider those three major factors, as discussed in the balance of this module, in their ongoing assessment of failed structures and reevaluation of the risk/reward balance. as rescue operations proceed and circumstances change.

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FAILURE MODES – KEY US&R CHARACTERISTICS

Regardless of the type of triggering event, the StS has three essential responsibilities:

- Identification of viable voids
- Assessment of structural hazards
- Recommendation of mitigation measures

Discussion in this module of the various failure modes will be in the context of these three responsibilities.

Viable Void Potential

In rescue mode, the primary interest is finding and accessing voids in which live victims are entombed – viable voids. In assessing the potential for viable voids, there are two aspects (beyond the initial evaluation of the probability of occupants in the building prior to the event) that must be considered: the physical potential for voids and the viability of any victims in those voids.

In recovery mode the focus is on identifying the locations victims regardless of their condition and the issue of viable voids is of little interest.

Void Potential

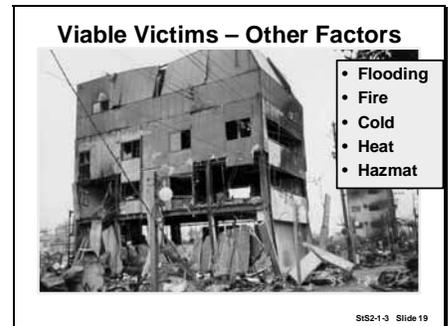
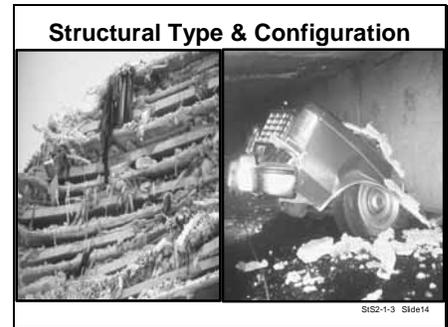
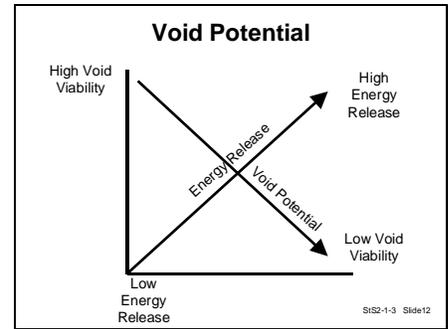
Void potential is a function of:

- Total energy released (during the initial event and any secondary events),
- Structural Type & Configuration
- Collapse pattern, Building contents & other factors.

Though the relative contribution of each element varies with the specific circumstances of the event. For example, in low- energy release events such as the soft story collapses of low-rise, woodframe apartment buildings in San Francisco during the Loma Prieta Earthquake in 1989, the size and location of voids was primarily a function of the structural configuration of the buildings – lightweight, flexible, woodframe construction with many partitions, and to a lesser degree, the presence of furniture and automobiles in the garages. At the other end of the spectrum, the enormous potential energy released during the collapse of the WTC towers largely overwhelmed any beneficial effects of structural configuration or building contents, leaving few viable voids.

Victim Viability

In addition to the physical presence of voids, the viability of potential victims in those voids must also be considered. A physical void that initially protects a victim from crushing may become non-viable due to various secondary events such as fire, smoke, temperature extremes, flooding, chemical exposure, and time.



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Structural Hazards

While the focus of most US&R personnel is the potential victims in viable voids, the focus of the StSs work is the assessment of structural hazards which may impact the safety of the rescue personnel. As discussed in StS1-1.4, there are two types of structural hazards to be considered: falling and collapse. There are three key factors that the StS must consider in assessing these hazards:

- Remaining potential energy,
- Stability,
- Potential failure modes of the damaged structure
- Changing conditions

Remaining Potential Energy

While it may sound obvious and trivial, the common enemy of the StS in all scenarios is gravity. Potential energy stored in a damaged building or in hanging debris presents the greatest threat to rescuers, a point driven home by the events at the WTC on 9/11.

As we all know, the two key characteristics of concern are mass and velocity. A fist sized piece of concrete falling four stories can kill; on the ground, it is merely a nuisance. The higher up a hanging hazard is located, the greater the potential energy and thus the greater the hazard to rescuers below.

StSs must assess the potential energy of surrounding overhead hazards. These include individual falling hazards as well as remaining structures above and to the sides of operational areas.

Stability

Even if an overhead hazard has much potential energy, if it is reasonably stable, it may represent less hazard than one with less potential energy but less stability.

To assess the hazard, the StS must assess the stability (i.e. the ability to resist the constant effects of gravity and external destabilizing influences) of the remaining structure and debris falling hazards:

- What is the condition of the load path? Are the key structural elements and connections intact and reliable or has the load path in the remaining structure been compromised to some degree? Are there redundant load paths, or could failure of a single connection or component result in failure? Are potential falling hazards securely attached or have the connections been compromised?

Structural Hazards



- Remaining potential energy
- Stability
- Changing Conditions

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Remaining Potential Energy = m*g*h

Masonry Reinforced concrete Post-tensioned concrete Precast concrete Structural steel Woodframe Light steel frame	↑ ↓	High Mass Low Mass
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Remaining Potential Energy = m*g*h

High-rise Mid-rise Low-rise Debris Pile	↑ ↓	Higher Potential Energy Lower Potential Energy
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Stability



- Load path:
 - Redundancy?
 - Connections?
- Failure mode
 - Brittle?
 - Ductile?
- Susceptibility to likely external influences
 - Vulnerable?
 - Resistant?
 - Destabilizing influences unlikely

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Potential Energy and Stability



Debris Pile vs Remaining Structure

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KEY US&R CHARACTERISTICS (continued)

Stability (continued)

- Are potential failure modes ductile or brittle? Steel yielding in flexure in an aftershock is unlikely to fail without ample warning. An unstable masonry parapet may topple with no warning.
- What is the vulnerability to foreseeable changing conditions? A damaged URM parapet is highly vulnerable to earthquake aftershocks and represents an extreme hazard in a seismic environment. In the aftermath of a hurricane or tornado, that same condition would be a benign nuisance.

Failure Modes of Damaged Structures

An essential element of structural hazard assessment is evaluation of the potential failure modes of the remaining structure/debris pile and the likelihood of their occurrence. Failure modes to be considered include:

- Falling of loose debris
- Shifting debris pile
- Shifting/sliding/dropping of elevated failed components
- Shear/flexural failure of beams/slabs
- Crushing/buckling of walls/columns
- Story mechanism
- Overturning or toppling

Proper prioritization of potential failure modes and their likelihood of occurrence will greatly assist the IC with development of a safe and effective rescue plan and form the basis development of a hazard mitigation plan.

Potential Energy and Stability



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Potential Energy and Stability



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Potential Energy and Stability



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Potential Energy and Stability



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KEY US&R CHARACTERISTICS (continued)

Changing Conditions

Hazard assessment is an ongoing process. While most structures and debris piles will be marginally stable following a major event, they can be destabilized by changing conditions.

US&R Activities

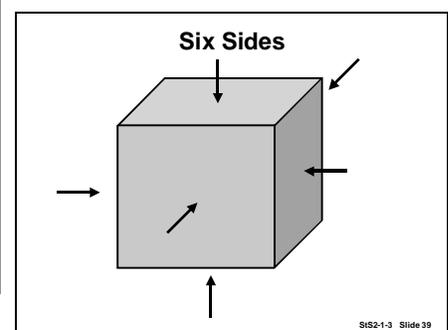
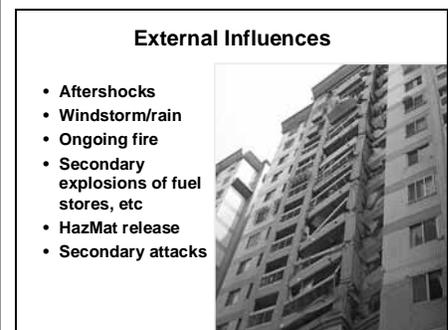
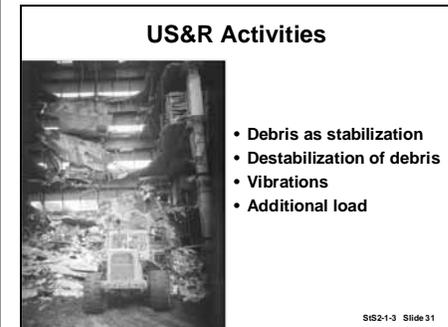
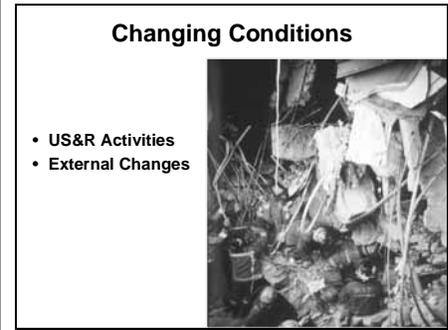
While much attention is paid to external changes, the most significant influences on stability are US&R activities themselves. The effect of debris removal on both the stability of the debris pile as well as the stability of the remaining structure as a whole must be continually re-assessed as operations proceed.

Shifting of debris was triggered by debris removal at both the Pentagon and in Oklahoma City. Columns in the Murrah building that had become laterally unsupported due to collapse of floor slabs were braced by the debris “tented” around the columns. As the debris was removed, bracing of the columns was necessary to prevent further progressive collapse. Weight and equipment vibrations led to a secondary collapse under a small track excavator during the recovery phase of the efforts at the World Trade Center. All of these incidents illustrate the potential negative effects of the work which we perform once we get to a collapse site. The StS must be aware of these issues and be diligent in predicting and preventing them as much as possible.

External Changes

In addition to US&R activities, the effect of external changes must also be evaluated on an ongoing basis. External changes to be considered include such secondary events as earthquake aftershocks, high winds, ongoing fires, heavy rains (e.g. debris clogging roof drains leading to ponding overload). For malicious events, the possibility of secondary devices must also be considered.

The StS should remember that these changes can take place on any of the six sides of their area of operations (four sides and above and below.)



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KEY US&R CHARACTERISTICS (continued)

Mitigation of Structural Hazards

Methods of mitigating hazards, which are covered elsewhere include:

- Avoidance of the hazard
- Minimization of exposure of personnel to the hazard
- Removal of the hazard
- Stabilization of hazard(shore, brace, tie, or anchor)
- Monitoring of the hazard

Given enough time and resources, virtually any structural hazard can be mitigated to zero risk. Given the incredibly short life expectancy of entombed victims, time and resources available for mitigation are scarce. Thus, in evaluating hazards and recommending mitigation measures, the StS must carefully consider the risks, rewards, and time involved. This assessment should be re-evaluated and revised as operations proceed.

Early in the operation when speed is essential to locate and extract trapped victims, higher risks are justified and a collapse hazard may be mitigated by sending in a small number of rescue personnel for a short period of time . However, as operations transition from rescue to recovery higher risks are no longer justified and more aggressive mitigation measures are appropriate such as removal or shoring of the hazard. For example, search and rescue operations were pursued at the Murrah Building for six days in the shadow of nine stories of overhead debris. While there was potential for recovering live victims, this risk was acceptable. As the potential for live victims declined, so did the tolerance for risk and the hanging debris was removed during the night between days six and seven.

It is essential that the StS not become complacent. Rather, the StS must be constantly re-evaluating the risks, rewards, and mitigation measures in light of changing conditions and the objective of supporting rescue operations while minimizing risks to the TF.

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KEY US&R CHARACTERISTICS (continued)

Mitigation of Structural Hazards

While methods of monitoring are covered elsewhere, it is important to note that only certain modes of failure lend themselves to effective monitoring. Monitoring of a condition is only effective if the monitoring can identify precursors of foreseeable failure modes with sufficient lead time to sound the alarm and evacuate the area. Thus monitoring is only effective for foreseeable ductile modes of failure where the structure (or some component) undergoes significant, gradual displacement prior to collapse. Racking of a soft story in a wood frame building is an excellent candidate for monitoring, as are flexural failure and overturning of ductile elements. Dislodged masonry veneer which could fall suddenly is not a candidate for monitoring. Monitoring can also be effective for evaluation of changing conditions, such as effects of removal of stabilizing debris, the effects of aftershocks, or movement of a retaining wall or landslide mass. While not encouraged, monitoring may be appropriate where a hazardous condition is mistakenly perceived by rescue personnel. Data that establish a stable condition will be much more effective at dispelling unjustified concerns than mere verbal assurances from the StS.

POTENTIAL CAUSES & UNIQUE CHARACTERISTICS OF US&R STRUCTURAL FAILURES

Many US&R events involve an initial or triggering event in combination with one or more secondary events. It is important to note that while there are a multitude of initial events, the most common secondary event is progressive collapse. Thus, while the initial damage to a structure caused by an earthquake will look much different from the damage caused by a natural gas explosion, if both initiating events lead to progressive collapse of the structure, the resulting collapse patterns will not be significantly different. The effects of the triggering event will dominate outside the area of progressive collapse and in adjacent buildings, but not in the area of progressive collapse. The cause or causes of collapse will influence the potential rewards, the risks, and the mitigation strategies.

Monitoring

- Only viable for
 - warning of foreseeable, ductile failure modes, e.g.
 - Overturning, story mechanism, flexural failure
 - monitoring effect of changing conditions
 - Aftershocks, landslide, debris removal
- Reassurance wrt components of hazardous appearance

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Failure Causes

- Progressive/Disproportionate Collapse
- Natural Hazards
- Explosions
- High Energy Impacts
- Fire
- Structural Defects & Overload
- Industrial Facility Accidents

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POTENTIAL CAUSES & UNIQUE CHARACTERISTICS OF US&R STRUCTURAL FAILURES (continued)

Progressive Collapse

While progressive collapse is, by definition, a secondary event, it is placed first in this list because it is the dominant failure mode in all scenarios which will require US&R support.

Progressive collapse occurs when an event or series of events destroys an essential link in the load path of a structure and a viable alternative load path does not exist. Most of the destruction at the WTC was the result of progressive collapse, not the high-energy impacts. As with the relative hazards from overhead debris and remaining portions of buildings, potential energy plays a key role in progressive collapse damage patterns. With greater potential energy release in the collapse, fewer viable are likely to be found in the debris. An example of this can be found by comparing the collapse of the WTC and the portion of the Pentagon which collapsed. The WTC, with its 110 stories, had a huge amount of potential energy and the resulting collapse pattern was of dense, highly compacted structural material (within and adjacent to the footprint of the towers). The Pentagon, with the same triggering event, released relatively little potential energy and the collapse pattern was therefore characterized by large, survivable voids. Had fire not followed the collapse, the potential for finding viable victims at the Pentagon would have been much greater.

Natural Hazards

Earthquake was the primary hazard for which the US&R program was initially developed. Hurricanes were soon added to the list. Other natural hazards that might lead to a US&R response include mass movement of soil (or snow) such as landslide, mudslide, debris flow or avalanche; and mass movement of water, such as flood, tidal surge, or tsunami.

Progressive Collapse

Progressive (or disproportionate) collapse occurs when local structural damage causes a chain reaction of structural element failures disproportionate to the initial damage, resulting in partial or full collapse of the structure. The local damage that triggers progressive collapse is called the initiating damage.

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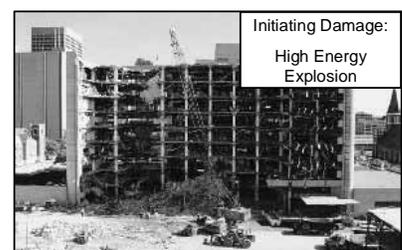


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Ronan Point Tower



Alfred P. Murrah Federal Building



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World Trade Center



Initiating Damage:
High Energy
Impact

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POTENTIAL CAUSES & UNIQUE CHARACTERISTICS OF US&R STRUCTURAL FAILURES(continued)

Earthquake

Earthquake damage is covered extensively in StS1-1.3 and 1.4. Therefore it is not discussed in this module in detail, but summarized as follows.

Earthquake damage results from inertial dynamic lateral forces generated in the structure by ground borne vibrations. Structures most affected are heavy, stiff, brittle, and often irregular. Vertical elements and components of the lateral load path, such as columns, braces, and walls sustain major damage while horizontal elements such as beams and floors typically sustain only minor damage. While shaking affects the entire structure, damage will typically be concentrated in areas that are more vulnerable due to structural irregularities. While most damaged structures will be marginally or completely stable once the ground shaking stops, strong aftershocks are a constant threat during US&R operations.

By virtue of this initial damage pattern, if collapse ensues, there will typically be numerous viable voids. However, as the energy released in a collapse increase, the probability of viable voids decreases. Thus, partial collapse of a low-rise woodframe building is much more likely to result in survivable voids than complete collapse of a mid- or high-rise concrete structure. Aftershocks will remain a serious threat through the US&R deployment.

Wind

Damage due to hurricanes and tornados is covered extensively in StS1-1.3. Therefore it is not discussed in this module in detail, but summarized as follows.

Forces are generated on the exterior surface of the building based on height (wind speed increases with height above the ground) and the square of the wind velocity. Unless the structure is penetrated, all the forces are applied to the exterior surfaces of the building. Wind pressures act inward on the windward side of a building and outward on most other sides and most roof surfaces. Special concentrations of outward force, due to aerodynamic lift, occur at building corners and roof edges, especially overhangs. Forces are also generated on structures by airborne missiles that vary in size from roofing gravel to entire sections of roofs.

Natural Hazards

- Earthquake
- Wind – hurricane & tornado
- Soil – landslide, mudslide, debris flow
 - Avalanche
- Water – flood, tidal surge, tsunami

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Earthquake



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Earthquake



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Vertical vs Horizontal Elements



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Wind – Tornado & Hurricane



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Wind (continued)

In stark contrast with earthquakes, wind forces are most damaging to light-weight elements with large surface areas such as windows, curtain walls, roofs. Heavy masonry and concrete structures that would be highly vulnerable to earthquake damage are not generally susceptible to serious structural damage from winds.

Because wind-induced collapse of heavy structures is rare, it is highly unusual for victims to be entombed in heavy structural debris. A wind-induced collapse requiring US&R assistance would most likely involve progressive collapse, where gravity and total energy release are going to dictate the potential for viable voids. Recurrence of damaging winds during the US&R deployment is unlikely.

Soil – Landslide, Mudslide, Debris Flow

Another group of natural hazards that could cause damage leading to a US&R response is mass movement of soil, including landslides, mudflows, and debris flows.

Avalanche is a closely related hazard involving frozen water rather than soil. Examples of landslide disasters are the Love Creek debris flows in Northern CA in 1982 and the La Conchita landslide of January 2005. In most circumstances, viable voids are unlikely, given the flowability and pressures of the material and the lack of oxygen within the material. The greatest concerns for StSs in these events would be dealing with potentially unstable soil masses and collapsed structures shifting under the pressures and movement of the debris. At higher water contents, the soil behaves as a very heavy (i.e. 120pcf) fluid. Trenches into the soil/debris mass should be shored/braced for twice the forces normal assumed in heavy trench rescue. The headscarp and upslope debris should be monitored for movement and potential growth of the landslide/mudslide/debris flow.

Water – Flood, Tidal Surge, Tsunami

Water in motion is powerful and can do considerable damage to even substantial structures. Events that may lead to a US&R deployment include floods¹ that may result from a swollen river or a failed dam; tidal surge associated with a hurricane (although evacuation of threatened areas generally minimizes or prevents victims); or a tsunami, of which the recent Indian Ocean tsunami was a sobering reminder.

Landslide, Mudslide, Debris Flow



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Landslide, Mudslide, Debris Flow



'Miracle' rescue: Buried 10 days, 4 still alive

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Flood, Tidal Surge, Tsunami



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¹ see StS1-1.3 for info on flood effects on structures

StS2-1-3 FAILURE MODE ANALYSIS

Explosion

While any rapid release of chemical energy is generally referred to as an explosion,² there are actually two distinct types of explosive energy sources to be considered: detonations and deflagrations. A second key aspect of explosions that must be considered is the location of the explosion: either within the building or external to the building.

As with wind-induced damage, explosions have their greatest effect on elements with large surface areas, such as windows, walls, floor, and roofs. In the 1993 WTC bombing for example, a portion of the floors of the parking garage were destroyed, but the columns survived. (albeit lacking lateral support)

Detonation

Detonations, result from high-energy explosives such as ANFO (ammonium nitrite fertilizer and fuel oil or diesel fuel) dynamite, TNT, C4, etc. All of the energy release comes from an exothermic reaction of the chemicals within the explosive material. These are either bombs or demolition charges (subsequently referred to as devices). The detonation is the rapid release of energy in the form of light, heat, sound and a supersonic shockwave.

The primary characteristic from a structural perspective is the shock wave which generates extremely high pressures (>10,000 psi) that last for milliseconds and decay roughly with the cube of the distance from the device. The effects of the blast diminish with distance in zones defined by concentric spheres. In the immediate vicinity of the device everything is destroyed: concrete is shattered and steel is sheared. For example, all that remained of the column nearest the device in Oklahoma City was bare reinforcing steel. In the next zone beams and columns may be laterally overloaded by the high blast pressures and fail in shear or bending. Further from the device, beam and columns survive as the blast wave washes around them, but wall and floor elements with larger surface areas, and relatively poor out-of-plane strength, are destroyed. Further out, all structural elements survive, but curtain walls and non-structural partitions are destroyed and propelled into the occupied areas of the building. Further still, damage is limited to glass breakage.

² The sudden rupture of a pipeline or pressure vessel storing compressed gas is also referred to as an explosion. Such events will generally not trigger a US&R response.

Explosions

- Detonations vs deflagrations
- Internal vs external
- Most significant effect is pressure on surfaces
- Victims may be displaced from original locations by blast pressures

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Detonations

- Light, heat, sound
- Supersonic shockwave
- High, rapidly decaying, pressure
- Multi-directional
- Factors



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Pressure Decrease with Distance

Weapon Size	Peak Reflected Air-Blast Pressure (psi)		
	5-Foot	20-Foot	100-Foot
500 pounds	18,979	1,183	14

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Localized Effects



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Detonation (continued)

Detonations may ignite fires, as occurred in many vehicles parked across the street from the Murrah Building, but not necessarily, as no fires were ignited within the Murrah Building despite the heavy fuel load of government paperwork.

Deflagration

A deflagration is the rapid release of energy from combustion of a flammable substance such as natural gas, propane, gasoline vapors, or dust with oxygen in the air. The primary characteristic of deflagrations from a structural perspective is a subsonic pressure wave which generates relatively low pressures (<10 psi) that may build up over several seconds within a large volume. Pressures from deflagrations are not high enough to damage bare beams and columns directly but can easily destroy elements with larger surface areas, such as structural walls, floors, curtain walls, and windows. While a deflagration can cause extensive damage in any type of building, they generally lead to progressive collapse only in bearing wall structures.

In addition to physical damage to the structure, deflagrations may ignite fires in other combustible material.

Internal/External

Confinement enhances the destructive effects of both detonations and deflagrations. Thus internal explosions cause much greater damage than external explosions for the same energy release.

High-energy Impacts

High-energy impacts include all manner of damage done by objects with kinetic energy, such as aircraft, trucks, ships, falling debris, or meteors impacting a structure. Examples of high-energy impacts include aircraft flying into the Pentagon and the WTC towers (9/11/2001), structural debris from the WTC towers falling on surrounding buildings, the semi tractor collision with the California State Capital (1/17/01), the NYC ferry accident (10/15/03), and the train derailment in California (1989). Generally, direct structural damage from high energy impacts is localized to the immediate vicinity of the impact, but it often results in fire and can trigger progressive collapse of the structure, either as a result of the direct impact damage or as a result of the combined effects of impact damage and fire.

Deflagration

- Rapid chemical reaction
- Combustion of flammable substance
- Subsonic shockwave
- Low pressures (<10 psi)
- Damage to large surface area members
- Fire in combustible materials



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Deflagration



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External v. Internal Detonations

<ul style="list-style-type: none"> • External <ul style="list-style-type: none"> - Most common mode of terrorist attack - Unconfined or only partially confined - Extremely short duration - Limited reflections 	<ul style="list-style-type: none"> • Internal <ul style="list-style-type: none"> - 1993 World Trade Center attack - Confined - Extended duration - Reflections <ul style="list-style-type: none"> • Floors • Ceilings • Walls
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High Energy Impacts

<ul style="list-style-type: none"> • Accident or attack • Truck • Boat • Airplane • Falling Debris 	<ul style="list-style-type: none"> • Local damage to structural members at point of impact • Potential for fuel tank leakage • Potential for additional collapse
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Fire

See also StS1-1.3 for discussion of fire effects on structures.

Fire is rarely the initial cause of a US&R deployment, with the Worcester fire being a partial exception. Rather, fire may be a secondary event, such as at the Pentagon and WTC. While secondary in causation, fire may do significant structural damage, as at the WTC where the effects of the fire ultimately caused the progressive collapse of both towers.

Fire is generally going to be more damaging in steel framed structures than in concrete or masonry structures due primarily to steel's rapid thermal expansion and rapid deterioration in the strength and stiffness of steel at temperatures above 1100°F. Lighter built-up steel members, such as bar joists, cold formed sections, and built-up plate girders in pre-engineered metal buildings are more vulnerable than rolled sections given their higher surface area to mass ratio, susceptible to buckling, and the lower likelihood of being fireproofed. Short of collapse, fire exposure may distort members, and cause failures of connections, especially bolted connections.

For the most part, steel regains its strength and stiffness upon cooling, although the members may be deformed and connections may be damaged.

Due to potentially rapidly changing conditions, a fire in progress poses a greater risk than a fire that has been extinguished. Prior to 9/11 a modern, major, fireproofed, steel structure had never collapsed due to fire. While the WTC towers could be dismissed as being severely weakened by the aircraft impact damage and loss of fireproofing, the collapse of WTC 7 later that day solely as a result of fire justifies caution in future events.

Another aspect of fire is the potential for uncontrolled urban fires following a major earthquake that would greatly complicate US&R activities in collapsed structures. An additional potential hazard from fire is water from sprinkler systems and/or firefighting activities which has the potential to overload compromised portions of the structure.

Fire

- Rarely primary cause of US&R deployment
- Light frame & unprotected steel most vulnerable
 - Steel: loss of strength & stiffness >1100°F, thermal expansion high surface/mass ratio, connection integrity
 - Light frame rapid combustion
- Concrete, masonry, & protected steel
 - Good material performance, consider loss of lateral support in bearing wall bldgs.
- Firefighting water overload

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Post Earthquake Urban Fires



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Collapse From Fire



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Loss of Structural Integrity From Fire



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StS2-1-3 FAILURE MODE ANALYSIS

POTENTIAL CAUSES & UNIQUE CHARACTERISTICS OF US&R STRUCTURAL FAILURES (continued)

Structural Defect and Overload

As Pogo said many years ago, in a different context, “We have met the enemy and he is us.” Even in the absence of natural disasters and terrorist attacks, throughout human history there have been a significant number structures that spontaneously collapse due to gravity overload or shortcomings in their design, construction, maintenance, or alteration. The collapse of a portion of the recently opened terminal at De Gaul Airport in France is the latest example. Many of these collapses occur during construction before all components of the structure are in place and tied together. Examples of this include the L’Ambiance Plaza apartment building in Bridgeport CT (April 23, 1987), and Tropicana Casino parking garage in Atlantic City NJ (2003).

Others occur later in the life of the building as a result of latent defects, such as the walkways at the Hyatt Regency in Kansas City MO (July 17, 1981) the Hartford Arena in Hartford CT (July 18, 1978), and the Save-On Supermarket in Canada. Still others occur as a result of deterioration or misguided demolition efforts.

Many smaller buildings collapse as a result of “overload” following heavy snow storms or due to ponding following heavy rain storms. Examples include the Ice Arena in Squaw Valley CA (1983) and Amigo Store in Brownsville TX (July 1988)

Collapses due to structural defect or overload are driven by gravity, thus they have all the same characteristics as progressive collapse failures. Where collapse is not complete, it must be remembered that the remaining portion of the structure may harbor the same defects or overloads that led to the collapse, thus the stability of the remaining structure should be viewed skeptically. Because structural defect and overload collapses result from unique defects in specific structures, these collapses tend to be isolated, single site events. Often the structure will provide early warning of impending collapse and most (or all) occupants will evacuate. Some events, especially higher energy events, occur without warning.

Generally there will be numerous viable voids. Any of the collapse or falling hazards associated with the type structure involved may be present and all standard mitigation measures are applicable

Structural Defect Failures

- Construction
- Latent defects
- Overload



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Latent Defect Hartford Arena



SIS2-1-3 Slide 85

Latent Defect Hyatt Regency, Kansas City



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Construction Defect Amigo Store



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StS2-1-3 FAILURE MODE ANALYSIS

Industrial Storage Facility Failures

Failures of industrial storage facilities that store granular materials such as grains pose the unique hazards of dealing with large volumes of flowable material that has come to rest at its angle of repose. In most circumstances, viable voids are unlikely, given the flowability and pressures of the material and the lack of oxygen within the material. Excavation, tunneling, or other localized removal of material will destabilize the material resulting in small slides. Standard US&R mitigation measures are generally not applicable to this type of failure.

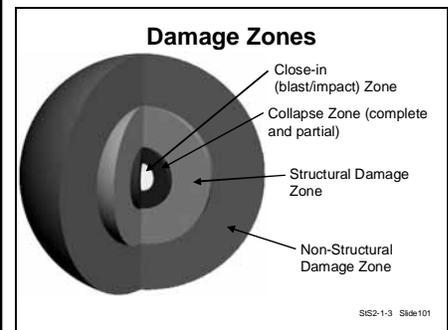
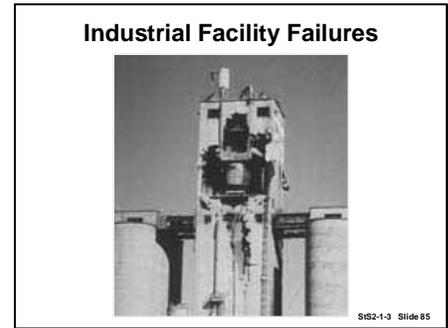
DAMAGE ZONES

Despite significant differences in the basic mechanism of damage and collapse, the resulting problems that a StS will have to deal with can be characterized into five zones, which are generally a function of distance from the initial event:

- Close-in zone (blast/impact only)
- Complete Collapse zone
- Partial Collapse zone
- Structural Damage zone
- Non-Structural Damage zone

These zones may be thought of as rough, concentric spheres centered on the most heavily damaged area. Often, and especially for low-rise buildings, these concentric spheres are reduced to concentric circles and the relationship between zones need be considered only in two dimensions. However, and most challenging for US&R work, is the situation where the damage zones extend in three dimensions. For example, imagine the challenge of the WTC if the towers had not collapsed, with damage zones extending outward in three dimensions from the point of impact. Worse, imagine the scenario where only one of the towers collapsed and US&R activities were necessary in the other. Many floors of the building had no damage prior to the collapse. Or consider the Vista Hotel before the collapses – a building completely undamaged by the aircraft impact that was ultimately crushed by falling debris. Thus, the StS need consider not only the hazards and challenges associated with each damage zone, but also the potential hazards associated with events in other damage zones.

The key US&R StS concerns in each of these zones is discussed in the following paragraphs.



StS2-1-3 FAILURE MODE ANALYSIS

Close-in Zone (Blast/Impact)

This damage zone is unique to high-energy explosions (detonations) and high-energy impacts. In this zone, all structural and non-structural material is destroyed and there are no viable voids. The debris in the immediate vicinity of the blast/impact zone should be inherently stable and pose no structural hazard, however there could be overhead falling hazards or stability concerns. The size of this zone will have a direct dependence on the energy imparted to the structure. For explosions this is determined by the net explosive weight of the bomb and for high energy impacts, it is determined by the mass and speed of the impacting object. StSs should be aware of this when deploying to a US&R scene, and should attempt to determine this information prior to arrival.

Typically no immediate mitigation would be needed in this zone, as there is no need for US&R activity in the close-in zone. Mitigation measures, such as excavating the debris pile, may be required as conditions change.

Complete Collapse Zone

In the zone of complete collapse, the building, or a portion of the building has collapsed into a marginally stable configuration with none of the vertical components of the building intact. The collapse pattern may be an orderly pancake collapse where the floor slabs are relatively intact and neatly stacked (although often offset), or a chaotic debris pile. In either event, the key characteristic is that there is little potential energy remaining in the collapsed portion of the building and the debris is marginally stable overall, at least until it is disturbed. There may however be considerable stored strain energy in elastic members, such as structural steel elements, prestressing cables, ductile concrete, and mechanical piping. Extreme caution should be used when cutting members with stored strain energy. The StS should carefully evaluate the situation and provide guidance as to the direction and amount of potential movement when the member is cut. There was at least one injury and several close calls at the WTC when strained members were cut without engineering oversight. Viable voids will be a function of the energy release, structural configuration, and contents. While the debris pile will be marginally stable overall, the void spaces may be highly vulnerable to minor shifting and consolidation due external influences such as aftershocks or wind or due to US&R activities elsewhere in the pile.

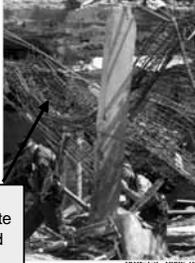
Close-in Zone

- Complete destruction of structural elements
- Detonations
 - Extremely high pressures cause fracture of building materials (brissance). (Oklahoma City, Ball)
- High Energy Impacts
 - Structural members in path of vehicle
- Area of greatest potential damage and injury and least likelihood of viable victims and voids

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Close-in Zone

- No survivable voids
- No viable victims



Rebar/
Concrete
stripped
away

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Complete Collapse Zone

- Debris pile
 - All potential energy dissipated
 - Marginal stability
- Void size and number based on potential energy released, structural configuration and contents
- Voids vulnerable to shifting
- Adjacent partial collapse and structural damage zones are a danger

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Complete Collapse Zone



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Stored Strain Energy

- Actions and Reactions
- Be aware that debris removal and partial demolition will release stored strain energy
- Ductile failures

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StS2-1-3 FAILURE MODE ANALYSIS

DAMAGE ZONES (continued)

Complete Collapse Zone (continued)

In many cases the complete collapse zone will border a partial collapse zone and be in the potential collapse shadow of unstable remaining portions of the structure or adjacent structures. There will likely be falling hazards to consider as well.

Partial Collapse Zone

The partial collapse zone falls between the zone of complete collapse and the structural damage zone. This is the most challenging zone from the US&R perspective – it is the area with potentially the greatest number of viable voids as well as the area possessing the greatest number of difficult to mitigate hazards to rescuers.

This zone is considered to be high risk because

- The debris most likely contains a high level of potential and/or strain energy
- The marginally stable debris can be quickly destabilized by changing conditions
- There may be significant vertical elements which have lost their lateral support systems
- There are likely many smaller falling hazards

Partial collapse patterns include:

- Lean-to, such as corner buildings or portions of the Pentagon and Murrah Building
- Catenary, such as the slab system at the Taiwan high rise building after the 1999 Chichi earthquake
- Mid-story, such as many buildings in Kobe Japan

Mitigation measure implementation in the partial collapse zone is difficult and very much time dependent. In most cases the debris will be sufficiently stable for K9 searches (if the slope of the floors is not too steep) without mitigation. Monitoring of critical structural elements should begin as soon as possible. If extended operations are to take place (i.e. removal of an entombed victim) mitigation measures should be instituted. The level of mitigation (crib as you go, speed shores, laced posts, etc) should be weighed against the remaining hazards (potential energy, falling hazards, stability) and the expected duration of the operation.

The StS must remember that they are acting as an advisor to the TFL/RM/IC and that their recommendations for mitigation may not be adopted. Under those

Partial Collapse Zone

- Between complete collapse and structurally damaged zones
- High potential for voids
- Difficult-to-mitigate hazards
- High risk area
- Mitigation likely required

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Partial Collapse Zone

- Collapse Patterns:
 - Lean-to
 - “V”
 - Cantilever
- Catenary action
- Mid-story collapses

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Mid-story Collapse



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Partial Collapse



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Partial Collapse Zone - Mitigation

- Time dependent
- K-9 vs. human access
- Monitoring
- Weigh sophistication of mitigation measures against duration of extrication operations

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StS2-1-3 FAILURE MODE ANALYSIS

circumstances, structural monitoring takes on added importance.

DAMAGE ZONES (continued)

Structural Damage Zone

The structural damage zone is that part of the building that has generally maintained its original structural configuration. The structure is essentially intact but, severely damaged. Structural elements and connections have been damaged to the extent that their remaining capacity is uncertain. In the case of a blast, special consideration should be given to floor systems as they will have been loaded in the upward direction and may be severely damaged on their underside.

Herein lies the crux of the problem for the StS. The building retains all of its original potential energy, and thus has the potential for both local and global collapse, depending upon the extent of structural damage, perhaps quite subtle. Initially the building will be at least marginally stable, but can be destabilized by changing conditions.

Interior spaces will be littered with contents and architectural elements. Where the initial event was a blast, interior spaces may also be littered with exterior elements that have been thrown into occupied spaces. There will likely be hanging structural debris at the perimeter of this zone where it abuts the partial or complete collapse zones.

Victims may be trapped or have been injured by fallen debris in this zone, but will not be entombed. Thus, it is probable that all victims will have been removed from this zone by local responders.

US&R activities in this zone may include systematic searches (including elevators) and use as a staging area or an access route to the total or partial collapse zones.

Mitigation measures are exposure dependent. Search activities may proceed under the guidance of the StS without mitigation. However, for extended operations, localized areas should be shored if necessary and the overall building stability monitored. See StS1-1.4 for detailed discussion of evaluation of damaged structural elements.

Structural Damage Zone

- Intact, but severely damaged
- Uncertain residual capacity
- Large "sail" elements (explosions)
- Trapped, but not entombed victims
- Internal disarray and debris
- Areas may be used for access to partial collapse zone or as staging areas

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Structural Damage



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Structural Damage Zone - Mitigation

- Exposure dependent
- Search – no mitigation
- Extended operations – localized shoring, and monitoring

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StS2-1-3 FAILURE MODE ANALYSIS

DAMAGE ZONES (continued)

Non-Structural Damage Zone

In the non-structural damage zone there is only contents and architectural damage. Primary hazards are overhead architectural debris such as glass, curtain walls, signs, and light fixtures. While structurally safe, the area may be adjacent to hanging structural debris and may be within the fall zone of unstable portions of structurally damaged or partially collapsed areas.

Victims in this zone will either be self-extracting removed by local responders.

US&R activities in this zone may include search, access route, staging areas, or forward BOO.

Mitigation measures are either to avoid, restrain, or remove the hazards.

EXPECTED DAMAGE BY CONSTRUCTION TYPE

Damages will be highly dependent upon the causative events and the construction type. For example, structural damage resulting from blast loading and wind storm will be largely a function of pressures, surface areas, and out-of-plane structural capacity while damage from earthquake loading will be largely a function of structural mass and lateral load path. Damage patterns in ductile, cast-in-place reinforced concrete will differ significantly from damage patterns in precast concrete structures. In short, each building type is going to have its own set of “weak links” that may sustain damage and pose a threat to the safety of US&R activities. In addition, mitigation strategies will vary by building type. Be aware however that many buildings are made up of a combination of structural systems (cast-in-place concrete combined with precast concrete for example). Thus, the StS may have to consider hazards and mitigation strategies associated with several basic construction types.

Non-structural Damage Zone

- Damage to non-load bearing elements of building
- Exterior envelope (detonation)
- Glass shards and debris thrown about
- Primary hazards are overhead falling debris
- Incipient failure of gravity connections possible in some structural types

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Non-Structural Damage



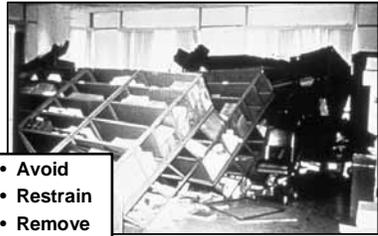
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Non-Structural Damage



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Non-Structural Damage



- Avoid
- Restrain
- Remove

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Mixed Construction Types



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Damage by Construction Type	Structural System
<ul style="list-style-type: none"> • Structural System <ul style="list-style-type: none"> – Frame – Bearing Wall • Structural Materials <ul style="list-style-type: none"> – Concrete – Masonry – Steel – Wood • Building Envelope (non-structural) <p><small>StS2-1-3 Slide 139</small></p>	<ul style="list-style-type: none"> • Frame <ul style="list-style-type: none"> – 3D Moment frame most robust – 2D Frames w/o continuity most vulnerable – Lateral and vertical systems generally independent • Bearing Wall <ul style="list-style-type: none"> – Lateral and vertical systems combined – Wall failure leads to collapse <p><small>StS2-1-3 Slide 140</small></p>

StS2-1-3 FAILURE MODE ANALYSIS

EXPECTED DAMAGE BY CONSTRUCTION TYPE (cont.)

Cast-in-place (CIP) concrete comes in three flavors: ductile, non-ductile, and post-tensioned. All three utilize concrete that is cast into its final position, although they differ in their reinforcing. CIP concrete frame structures are referred to as “heavy floor” buildings in the StS FOG. CIP concrete structures will typically be frame structures, some of which also have shear walls to resist lateral loads. Failure modes of concrete frame buildings include tilting or toppling of taller structures as widely observed in Taiwan in 1999, pancaking as widely observed in Mexico City in 1999, and partial collapse as observed in the Murrah Building in 1995.

CIP ductile concrete utilizes mild steel reinforcing (conventional rebar) detailed with sufficient laps, splices, and confinement to produce structural elements with significant ductility – the ability to sustain large deformations without loss of strength. The columns of the Pentagon and California State University - Northridge parking garage are excellent examples of good ductile concrete behavior. Ductile concrete is typically found only in structures built on the west coast since the mid 1970s. Because ductile concrete members generally deform rather than fracturing, a damaged ductile concrete frame structure is of the least concern to an StS. Cracks in ductile concrete members should not be of concern. However, beware that not all elements in a ductile concrete structure may be detailed for ductile behavior, the Royal Palm Resort Hotel in Guam and the Northridge University parking garage being excellent examples.

CIP non-ductile concrete also utilizes mild steel reinforcing, although it is detailed only for elastic behavior and is highly dependent upon the integrity of the concrete. Once a non-ductile element is loaded beyond its capacity, it will suddenly lose virtually all of its strength. The double-decker Cypress freeway structure in Oakland CA and the Murrah Building in Oklahoma City are excellent examples of non-ductile concrete behavior under extreme loading. Cracks in non-ductile concrete buildings may indicate a serious loss of strength and must be carefully evaluated. Even fine hairline cracks can indicate considerable strength loss as illustrated by this photo sequence taken during the attempted removal of a floor beam at the Murrah Building.

Concrete

- Types
 - Cast-in-Place:
 - Ductile – frame
 - Non-ductile – frame or bearing wall
 - Post-tensioned – frame or bearing wall
 - Pre-cast – frame or bearing wall
 - Tilt-up – bearing wall
 - Lift-slab – frame

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Ductile Concrete

- Higher potential for survivable voids
- Generally – west coast post-1970
- Cracks not a large concern
- Some residual load capacity
- Stored strain energy

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CSN Parking Structure



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Non-Ductile (brittle)

- Lower potential for survivable voids
- Catastrophic (brittle) failure
- No residual load capacity
- Cracks may indicate loss of capacity

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I-880 Freeway - 1989



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StS2-1-3 FAILURE MODE ANALYSIS

CIP post-tensioned concrete is primarily reinforced with high strength steel cables (tendons) encased in plastic sheaths. Once the concrete has cured, the cables are stretched, placing the concrete in compression and storing a great deal of strain energy in the tendons. The tendons are anchored at their ends, but are not bonded to the concrete. Thus failure of the concrete anywhere along length of a tendon will result in loss of strength over the entire length of the tendon.

As for non-ductile concrete, post-tensioned concrete depends upon the integrity of the concrete to maintain its strength, thus cracking post-tensioned elements needs to be examined carefully for its structural implications. Post-tensioned members should be examined for evidence of shear cracking, as well as damage in the vicinity of the tendon anchorages. Also, since the tendons are “draped” over multiple structural bays, slab damage in one bay may indicate loss of structural integrity in bays farther away. As observed in the L’Ambiance Plaza collapse, the post-tensioned floor slabs crumbled. It is important that the StS note this early in an event and inform other rescuers as to areas of potential secondary failures.

While post-tensioning may be used for beams as well as floor slabs, it is most commonly used for floor slabs. Post-tensioned floor slabs may be much thinner than conventionally reinforced slabs. The combination of thin cross-section and draped tendons (which are applying an upward thrust on the slab to counteract the dead weight of the slab) results in floors that are particularly vulnerable to damage from blast loading.

Precast concrete consists of pre-stressed members that are generally fabricated off-site and reinforced with steel tendons that are stretched prior to placement of the concrete. The tendons are bonded to the concrete and their strength depends upon the integrity of the concrete. Unlike post-tensioned members however, tension in the entire tendon is not lost if the concrete or tendon are locally damaged or cut. When precast members are assembled into a structure, the connections between members are often simple bearing seats with no connection or lightly welded embedded plates. The weak links in precast concrete are generally the connections, which are either non-existent or brittle. Precast structures have performed poorly in past earthquakes and blast events, falling apart like stacked building blocks. They collapse into a jumbled mass of pick-up-sticks, with many voids.

Post Tensioned Concrete

- Minimal resistance to upwards forces (blast)
- Unbonded tendons
- Behaves as unreinforced concrete once tendons are broken
- Cracks may indicate loss of capacity
- Multiple bays may be affected
- Stored strain energy

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Post-Tensioned Slabs



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Pre-Cast Concrete

- Pre-stressed concrete
- Tendons bonded to concrete
- Connections are weak links
 - Generally bearing connections
 - Connections exhibit catastrophic failures
- Potential for survivable voids (large element debris pile)

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Pre-cast Structure –Armenia 1988



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Pre-Cast Structure - Khobar Towers 1996



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StS2-1-3 FAILURE MODE ANALYSIS

Tilt-up construction is a variant of CIP and precast concrete, where wall panels are cast on-site, flat on the ground then lifted into position. While the panels themselves are generally well reinforced, the interconnections between the panels may be weak and brittle. The pilasters between panels often provide vertical support for the roof structure, which is typically of either woodframe or bar joist construction. The roof structure in turn provides lateral support to the top of the wall panels. The weak links in tilt-up buildings are the connections between panels and the connections between the panels/pilasters and the roof structure. When the connection between roof and wall fails, the wall tilts outward and the roof collapses, at least at the perimeter.

Lift-slab construction is an innovative system developed in the 1950s for construction of multi-story buildings. All floor slabs (usually post-tensioned) are cast in a stack on grade, then jacked up into position on steel columns. Once in place, a steel collar embedded in the slab is welded to the column. The slab-column connection is the weak link in lift-slab construction and is very sensitive to punching shear failure under lateral loading. Collapse is merely reversal of the construction process – the slabs pancake back down to the ground. The collapse of the L’Ambiance Plaza during construction is a chilling example of the failure mode of this type of construction.

Masonry construction comes in many flavors, although the most common are unreinforced brick masonry (URM), unreinforced concrete masonry, and reinforced concrete masonry. Masonry construction is characterized as “heavy wall” construction in the StS FOG.

Unreinforced masonry is simply red brick held together (or apart) by low strength mortar. URM wall construction is widespread in older urban areas in the eastern U.S. and less common, but still prevalent in older areas of the western U.S. In most cases, the URM walls are load bearing – they support the upper floors and roof. The floor and roof diaphragms in turn may provide out-of-plane lateral support to the URM walls. Generally the connections between the walls and floors/roof are wood beams and joists simply sitting in pockets in the masonry. Some buildings were built with iron ties and many buildings in the western U.S. have been retrofit with steel ties to strengthen this critical connection.

Tilt-up Concrete

- Large, heavy wall panels
- Connections of panels to floors and roof and between panels are weak links
- Generally, panels fall outwards and roof/floors collapse

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Tilt-up Concrete



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Lift-slab Construction

- Cast in a stack
- Jacked to final floor height
- Slab-column connection is weak link
 - Punching shear
- Susceptible to failure during construction
- Few viable voids

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L’Ambiance Plaza Slabs



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Masonry

- Unreinforced masonry (URM)
- Unreinforced concrete masonry
- Reinforced concrete masonry

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StS2-1-3 FAILURE MODE ANALYSIS

Unreinforced masonry (contin.) URM is quite brittle and has little capacity to resist out-of-plane loads. A caveat to this discussion is the fact that mass plays a large role in determining a structural element's resistance to blast effects. Older URM buildings tend to have thick, massive walls which increase their resistance to blast loads. An example of this relatively non-intuitive phenomena is the Journal Records Building near the Oklahoma City bomb site. The building had approximately 18 inch thick URM walls and the face of the building was estimated to have experienced approximately 12 psi pressure. Photos of the building show little damage to the vertical walls beyond window breakage. The roof however was blown off.

Out-of-plane movement and connection to the diaphragms are the weak links in URM buildings. In-plane shear cracks should be examined, but are generally not of great concern for US&R activities. The greatest threat of URM buildings is the falling hazard outside the building footprint, ranging from single bricks to entire walls and parapets which can crush adjacent buildings.

Unreinforced concrete masonry consists of concrete masonry units (CMU) held together (or apart) with mortar. Horizontal (bed) mortar joints may be lightly reinforced with heavy gage wire reinforcing. The cells of the block are left empty. This type of construction is widely used in the eastern U.S. for both load bearing and non-load bearing walls, including exterior infill walls in steel and concrete frame buildings.

Unlike the URM buildings noted above, Unreinforced CMU walls do not generally have a lot of mass and therefore have no increased resistance to blast effects. Infill walls may be poorly attached to the structural frame.

Out-of-plane movement and connection to the diaphragms are the weak links in unreinforced concrete masonry buildings. In-plane shear cracks should be examined, but are generally not of great concern for US&R activities.

URM

- Very poor in earthquakes
- Shear cracks generally not a concern for US&R
- Falling debris hazards



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URM – Journal Records Building



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URM Infill Walls



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Unreinforced Concrete Masonry



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Unreinforced Concrete Masonry

- CMU block and mortar
- Cells not grouted
- Load bearing, non-load bearing and infill walls
- Out-of-plane loading and connections are the weak links
- Shear cracks generally not a concern for US&R
- Falling debris hazards

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StS2-1-3 FAILURE MODE ANALYSIS

EXPECTED DAMAGE BY CONSTRUCTION TYPE (cont)

Reinforced concrete masonry consists of CMU with a portion of the cells filled with horizontal and vertical reinforcing and grout. This type of construction is widely used in the western U.S. and in hurricane prone areas of the eastern U.S. for both load bearing and non-load bearing walls.

Generally reinforced CMU walls have sufficient strength and some ductility to remain reasonably safe despite considerable damage. Connections to diaphragms should be examined and the presence of reinforcing and grout verified.

Steel structures come in two general flavors: heavy steel structures composed of hot-rolled wide flange sections and light steel structures composed of built-up plate members, cold formed sections, or open web steel joists. Generally light steel construction is confined to low-rise structures while heavy steel construction is used for mid- and high-rise construction. The World Trade Center towers were notable exceptions, where open web steel joists were used as primary structural members supporting the floors and tying the core to the perimeter structure.

Heavy steel frame structures generally consist of a three dimensional frame of beam and columns which are generally interconnected with bolted connections. Some structures, especially in the western U.S. may have a portion of the connections that are full penetration welds.

Connections and fire exposure are the weak links in heavy steel framed structures. Widespread cracking of welded connections was discovered in otherwise lightly damaged buildings following the Northridge Earthquake. Bolted connections are easily sheared by overloads. Exposure to temperatures above about 1200°F will cause steel framing to deform. Upon cooling, the material strength of the steel will return to normal, although the section capacity may be reduced due to flange buckling.

Reinforced Concrete Masonry

- CMU, mortar and reinforcing steel
- West coast and hurricane areas
- Load bearing and non-load bearing walls
- Tend to have residual capacity even though damaged
- Confirm presence of reinforcing steel

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Reinforced Concrete Masonry



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Heavy Steel

- Framed buildings
- Connections and fire exposure are weak links
- Welded connection cracks
- Bolted connection shear failures
- 1200 degrees F - deformation

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Heavy Steel



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StS2-1-3 FAILURE MODE ANALYSIS

EXPECTED DAMAGE BY CONSTRUCTION TYPE (cont)

Light steel construction is used in a wide variety of applications, ranging from pre-engineered metal buildings (generally single story) to open web steel joists widely used in combination with load bearing tilt-up or CMU walls.

Weak links in light steel construction are connections, lateral buckling in built-up plate girders, and weld failures in open web steel joists.

Wood construction comes in two basic flavors: conventional light woodframe construction and heavy timber construction.

Conventional woodframe construction consists primarily of framing members nominally two inches thick and is typically used for residential construction up to four stories. This type of construction is referred to as “light frame” in the StS FOG.

Weak links in conventional woodframe construction are the lateral bracing system (shear walls) and connections between the roof and walls. The seismic failure mode is racking of one or more stories. Wind load failure modes consist of loss of the roof or complete destruction. This type of construction is quite tough ductile, although stories racked significantly out-of-plumb present a danger of collapse.

Heavy timber construction consists of solid sawn or glulam members greater than two inches thick and is generally found in older commercial construction in the eastern U.S. (often in combination with load bearing masonry walls) and in floor and roof structures in commercial structures in the western U.S.

Weak links in heavy timber construction are connections between members and connections to perimeter load-bearing walls.

Light Steel

- Pre-engineered buildings
- Lightweight steel floor and roof joists
- Weak links are connections, lateral buckling and weld failures
- Building envelope easily disconnected

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Light Steel - Wind



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Light Frame Construction

- Typically up to 4 stories
- Lateral bracing (shear walls) and connections are the weak links
- Seismic failure – racking
- Wind load failure – loss of roof or total Blast – complete destruction

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Wind Failure



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Seismic Failure



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StS2-1-3 FAILURE MODE ANALYSIS

EXPECTED DAMAGE BY CONSTRUCTION TYPE (cont.)

The Building Envelope is the portion of the building which keeps the elements out of the building and the occupants and contents in the building. The envelope elements are usually non-load bearing perimeter wall elements (except in the case of bearing wall systems). Building envelope materials range from light-weight window wall systems of aluminum and glass to heavy masonry, stone, and precast concrete panels. The envelope can either be attached to the exterior face of the structural frame or installed as infill systems, between the framing members (i.e. light gage stud wall systems and masonry infill systems).

For all standard building envelope systems, the weak links are the window glass (which is typically not tempered, thus producing large sharp fragments), connections to the structure and the strength of the panels, resulting in potential falling hazards. Buildings which have been specifically designed for blast/ballistic/ or forced entry effects will have significantly stronger windows. Damage to connections may be subtle and not readily apparent. Examples include the precast panels over the south entrance to the Murrah Building and the stone façade panels on the east wall.

Building Envelope

- Non-load bearing wall elements
- Curtain-wall type systems
- Infill wall systems
- Glass, connections and out-of-plane strength are the weak links
- Failure can be obvious or subtle

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Building Envelope Failure



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Building Envelope Failure



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StS2-1-3 FAILURE MODE ANALYSIS

Summary

A US&R site must be evaluated in the context of three key factors: viable voids, stability, and mitigation. Viable voids are a function of the energy released in the initial and any secondary collapse as well as structural configuration and contents. Of the five collapse zones, the partial collapse zones and the structural damage zones are the most challenging for the US&R StS. The remaining structure and debris will be marginally stable initially, but are susceptible to destabilization due to changing conditions. Thus, the StS must continually reassess hazards and mitigations considering changing conditions as well as changes in the risk/reward balance.

Module Key Learning Points

- Many events may trigger collapse but common characteristic of USAR events is progressive or disproportionate collapse driven by gravity
- Five damage zones to be considered
 - Close-in
 - Total collapse
 - Partial collapse
 - Structural damage
 - Non-structural damage

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Module Key Learning Points

- Characteristics to be considered by StS
 - Total energy released in the collapse
 - Remaining potential energy
 - Stability of remaining structure and debris
 - Changing conditions

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Module Key Learning Points

- Many construction types and combinations of types, each with unique response to extreme loads, collapse patterns, and structural hazards – see [Failure Modes Summary Table](#)

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Module Key Learning Points

- Three characteristics of a collapse that must be assessed by the StS are
 - Viable void potential
 - Structural hazards
 - Hazard mitigation strategies
- Three major factors which influence hazard assessment and mitigation strategies are
 - Cause of collapse
 - Failure mode
 - Construction type

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Module Key Learning Points

- Three characteristics of a collapse that must be assessed by the StS are
 - Viable void potential
 - Structural hazards
 - Hazard mitigation strategies
- Three major factors which influence hazard assessment and mitigation strategies are
 - Cause of collapse
 - Failure mode
 - Construction type

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Module Key Learning Points

- Failure Modes of Damaged Structures
 - Falling of loose debris
 - Shifting debris pile
 - Shifting/sliding/dropping of elevated failed components
 - Shear/flexural failure of beams/slabs
 - Crushing/buckling of walls/columns
 - Story mechanism
 - Overturning

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5 Minute Case Study

- What information needed from building manager?
- What information does the TFL need from StS at the outset?
- What will you do to size up the situation when you initially arrive on scene?



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StS2-1-3 FAILURE MODE ANALYSIS—FAILURE MODES SUMMARY TABLE

		Frame Systems				Bearing Wall Systems				
Characteristics	Heavy Structural Steel (hot rolled sections)	Light-gage Steel (pre-fab metal buildings)	Heavy Floor Structure - CIP Ductile Reinforced Concrete	Heavy Floor Structure - CIP Non-ductile Reinforced Concrete	Heavy Floor Structure CIP Post-tensioned Concrete slabs & beams only; includes Lift Slab	Precast Concrete	Tilt-up	Heavy Wall Structure Unreinforced Masonry (includes unreinforced brick and CMU)	Heavy Wall Structure Reinforced Masonry	Light Frame (2X wood framing or light gage steel framing)
Type	Commercial, some Industrial, Highway bridges	Office, Industrial & Commercial	Office & Commercial, Highway bridges (W. US)	Office & Commercial, Highway bridges	Parking garages Office, Residential,	Various	Office, commercial, light industrial	Residential, commercial, institutional and industrial	Residential, commercial, institutional and industrial	Residential, light commercial
Typical Occupancies	Office & Commercial, some Industrial, Highway bridges	Office, Industrial & Commercial	Office & Commercial, Highway bridges (W. US)	Office & Commercial, Highway bridges	Parking garages Office, Residential,	Various	Office, commercial, light industrial	Residential, commercial, institutional and industrial	Residential, commercial, institutional and industrial	Residential, light commercial
Distinguishing Characteristics	Heavy wideflange (W) beams and columns; Two to 100+ stories	Low-rise up to 3 stories; Most industrial/commercial are single story	Mid-rise - Western US post 1975	Eastern US, Western US pre 1975; Up to 12 stories.	Larger span/depth ratios than for R/C	Modular structural components, up to 14 stories; may be frame or bearing wall structure	Modern low-rise, typically single story but up to four stories. Long span roof (50ft+) and floors (25ft+).	Older "red brick" with bond courses Lack of strap anchors & ties CMU used for many low-rise bldgs. Up to 8 stories	Modern low-rise typically single story but up to four stories.	Up to 4 stories
Key Performance aspects	Normally well-engineered; Members very ductile. Overall performance dependent upon connections – welds may be brittle.	Highly engineered – little redundancy or overstrength; very flexible	Robust structural system can absorb considerable energy and sustain considerable cracking w/o loss of integrity;	Brittle failure modes when loaded beyond capacity; Cracking generally means significant loss of strength	Highly engineered with little capacity to resist unanticipated loads	Highly engineered prestressed systems. Brittle connections between elements with no capacity for unanticipated loading	Robust wall panels dependent upon diaphragms for out-of-plane support. Wall/diaphragm connection vulnerable	Brittle with little capacity to resist unanticipated loads. Numerous interior walls may prevent floor collapse	Excellent fire resistance. Reinforcing provides ductility and improved ability to resist unanticipated loads	Many walls create redundant structures w/ significant overstrength, generally ductile failure modes, depending on sheathing type.
Common combinations	Precast or CIP concrete floors w/ or w/o metal deck; Masonry, precast or metal curtain walls; URM partitions	May have masonry, precast, tilt-up exterior walls; wood or light gage metal interior partitions and mezzanine	Structure may contain non-ductile elements; Curtain walls & URM partitions	Curtain walls & URM partitions	CIP Ductile or Non-ductile columns, Curtain walls & URM partitions	Precast panels used for floors and roofs of masonry and steel frame structures. Commonly used for curtain walls	Light frame or steel joist diaphragms, with concrete fill in multi story bldgs.	Heavy timber, light frame or steel joist diaphragms, with concrete floor fill in multi story bldgs.	Heavy timber, light frame or steel joist diaphragms, with concrete fill floor in multi story bldgs	May be built above R/C parking garage, frequently used for interior partitions in residential and commercial masonry structure

StS2-1-3 FAILURE MODE ANALYSIS—FAILURE MODES SUMMARY TABLE

Characteristics ▼ Type ►	Heavy Structural Steel	Light-gage Steel	CIP Ductile Reinforced Concrete	CIP Non-ductile Reinforced Concrete	CIP Post-tensioned Concrete	Precast Concrete	Tilt-up	Unreinforced Masonry	Reinforced Masonry	Conventional Woodframe
Typical Failure Modes	Member yielding, connection failure, buckling/fracture of bracing. Complete collapse is rare	Diagonal rod bracing elongation and connection failure; Buckling of slender built up beams and columns	Ductile failure of properly detailed elements; Brittle failure of non-ductile elements in structure	Shear failure in columns/joints or punching shear in slabs leading to partial or total collapse; Either pancake or side sway failure mode	Shear failure in columns/joints or punching shear in slabs leading to partial or total collapse; Either pancake or side sway failure mode	Failure of interconnections between parts leading to partial or total collapse.	Walls separate from roof/floors leading to falling walls and collapsed roof/floors. Long-span collapse is probable	Walls separate from roof/floors leading to falling walls and collapsed roof/floors; Cracked/pealed walls create brittle falling hazards	Walls separate from roof/floors leading to falling walls and collapsed roof/floors; Cracked/pealed walls create brittle falling hazards	Racking of walls in soft/weak stories; Failure typically slow and noisy
Check Points	Indications of movement – check plumbness, stairs, non-strl damage; Beam/column cons, diagonal bracing; Curtain wall attachment	Elongated, buckled, broken rod bracing & connections; Beam buckling; Bolted connections & anchor bolts	Attachment of infill; Cracks exposing fractured rebar	Attachment of infill; Cracking of cols, beams, slabs, joints; Cracks may indicate significant or total loss of strength	Attachment of infill; Cracking of cols, beams, slabs, joints; Cracks may indicate significant or total loss of strength	Beam/column connections, broken welds & cracked corbels; Column cracking @ top, bottom, & wall joints; Wall connections at floors, columns, and foundation	Connections between exterior walls and roof/floors; Beam to beam and other interior roof connections	Loose, broken parapets; Roof/wall & floor/wall connections; badly cracked walls; unsupported floors or roof	Loose, broken parapets; Roof/wall & floor/wall connections; badly cracked walls; unsupported floors or roof	Badly cracked and leaning walls; Leaning, loose veneer or chimney; Offset from foundation; Separated porches, split-levels.
Hazard Reduction	Avoid/remove/sec ure exterior skin; Monitor racking/leaning	Remove loose/lightly connected members; Shore/brace/monitor racking/leaning	Remove/secure wall infill; Monitor racking/leaning	Shore badly cracked slabs, beams, cols; Remove/secure wall infill; Monitor racking/leaning	Shore badly cracked slabs, beams, cols; Remove/secure wall infill; Monitor racking/leaning	Remove/avoid leaning/hanging elements; Shore roof/floor beams; Monitor racking/leaning	Raker shore or pull down leaning walls; Shore hazardous roof/floor/beams; Monitor racking/leaning	Shut off gas, elec; Diagonally shore, tie-back, avoid, or remove hazardous walls; Shore roof/floor; Monitor racking	Shut off gas, elec; Diagonally shore, tie-back, avoid, or remove hazardous walls; Shore roof/floor; Monitor racking	Shut off gas, elec; Avoid/pull down damaged veneer & chimneys; Vertical or diagonal shoring; Monitor racking
Victim Access	Vertical by cutting slabs from above; Horizontal through existing cavities & openings; Remove/shore hazards near victims	Vertical/horizontal by removal/cutting of sheathing; Horizontal through existing cavities & openings; Remove/shore hazards near victims	Vert. thru exist access shafts or cutting thru slabs from above; Horizontal thru existing cavities & openings; Cut infill walls after careful assmt; Remove pieces by crane after rebar has been cut	Vert. thru exist access shafts or cutting thru slabs from above; Horizontal thru existing cavities & openings; Cut infill walls after careful assmt; Remove pieces by crane after rebar has been cut	Vert. thru exist access shafts or cutting thru slabs from above; Horizontal thru existing cavities & openings; Beware of prestressing tendons – cutting may compromise member	Vertical through thin horizontal sections from above; Horizontal entry through existing cavities & openings; Cut holes in wall panels 2ft+ from joints; Remove roof/floor/wall panels by crane	Vertical through floor/roof from above collapsed area; Horizontal through existing cavities or openings; Cut holes in walls 2ft+ from joints; Remove wall, roof panels by crane	Vertical through floor/roof from above collapsed area; Horizontal through existing cavities or openings; Remove bricks by hand, excavator or clamshell; Remove or shore hazards near victims	Vertical through floor/roof from above collapsed area; Horizontal through existing cavities or openings; Remove or shore hazards near victims	Vertical through floor/roof from above collapsed area; Horizontal through existing cavities or walls; Remove or shore hazards near victims.

StS2-1-3 FAILURE MODE ANALYSIS—FAILURE MODES SUMMARY TABLE

Initiating Event ▼	Constr uction Type ▲	Heavy Structural Steel	Light-gage Steel	CIP Ductile Reinforced Concrete	CIP Non-ductile Reinforced Concrete	CIP Post- tensioned Concrete	Precast Concrete	Tilt-up	Unreinforced Masonry	Reinforced Masonry	Conventional Woodframe
Progressive / Gravity Collapse	Rare, except during erection; Members maintain integrity with failures at joints Joint failure or member buckling leading to partial or complete collapse	Members likely to retain strength & integrity	Members likely to break into smaller pieces of questionable integrity; Rubble pile may shift	Members likely to break into smaller pieces of questionable integrity; Rubble pile may shift; Failed single story cols have lead to progressive collapse	Heavy members & weak, brittle connections are critical issue;	Members likely to retain strength and integrity	Wall panels separate from diaphragm and lean outward, diaphragms collapse, interior structure may stand independently	Masonry walls likely to disintegrate, interior structure may stand independently	Likely to break into panels, interior structure may stand independently	Extensive connection failures, members and components likely to remain intact	
		Good performance; Failure of diagonal bracing and fracture of welded joints common, but collapse is rare; Curtainwall, esp. PC panels could fail and are hazard in aftershock	Good performance. Failure of rod bracing common, but collapse is rare; Minor aftershock response	Good performance. Members will maintain strength & integrity even with significant damage. Beware of non-ductile concrete elements within structure	Very poor performance. Brittle failures in columns, walls, beams, & slabs leading to partial or complete collapse; Punching shear failures common in structures with flat plate floors; Aftershocks cause added collapse, shifting, falling hazards	Brittle failures in walls and columns leading to partial or complete collapse. Punching shear failures common in structures with flat plate floors. Element failure results in loss of tendon tension leading to behavior as unreinforced concrete	Very poor performance; Failed connections lead to partial or total collapse; Members generally remaining intact. Debris pile vulnerable to shifting during aftershocks. Beware of loose wall panels, out-of-plumb columns. Check connections, bearings, and corbels.	Weak link is connection between perimeter wall panels & diaphragms resulting in out-of-plane failure of wall panels and collapse of diaphragms; Aftershock falling & collapse hazard	Very poor performance. Out-of-plane wall failures, loss of connection between walls & floors leading to partial or total collapse. Loose bricks pose lethal falling hazard. Aftershock collapse hazard	Shear failure of wall elements and failure of connections between walls and horizontal diaphragms most common.	Generally good performance. Failure mode is ductile racking of columns and wall elements, and loss of lateral strength in soft stories. Racked stories are subject to ratcheting and collapse in aftershocks
Earthquake	Good performance; Failure of diagonal bracing and fracture of welded joints common, but collapse is rare; Curtainwall, esp. PC panels could fail and are hazard in aftershock	Good performance. Failure of rod bracing common, but collapse is rare; Minor aftershock response	Good performance. Members will maintain strength & integrity even with significant damage. Beware of non-ductile concrete elements within structure	Very poor performance. Brittle failures in columns, walls, beams, & slabs leading to partial or complete collapse; Punching shear failures common in structures with flat plate floors; Aftershocks cause added collapse, shifting, falling hazards	Brittle failures in walls and columns leading to partial or complete collapse. Punching shear failures common in structures with flat plate floors. Element failure results in loss of tendon tension leading to behavior as unreinforced concrete	Very poor performance; Failed connections lead to partial or total collapse; Members generally remaining intact. Debris pile vulnerable to shifting during aftershocks. Beware of loose wall panels, out-of-plumb columns. Check connections, bearings, and corbels.	Weak link is connection between perimeter wall panels & diaphragms resulting in out-of-plane failure of wall panels and collapse of diaphragms; Aftershock falling & collapse hazard	Very poor performance. Out-of-plane wall failures, loss of connection between walls & floors leading to partial or total collapse. Loose bricks pose lethal falling hazard. Aftershock collapse hazard	Shear failure of wall elements and failure of connections between walls and horizontal diaphragms most common.	Generally good performance. Failure mode is ductile racking of columns and wall elements, and loss of lateral strength in soft stories. Racked stories are subject to ratcheting and collapse in aftershocks	

StS2-1-3 FAILURE MODE ANALYSIS—FAILURE MODES SUMMARY TABLE

Initiating Event ▼ Type ►	Constr uction	Heavy Structural Steel	Light-gage Steel	CIP Ductile Reinforced Concrete	CIP Non-ductile Reinforced Concrete	CIP Post-tensioned Concrete	Precast Concrete	Tilt-up	Unreinforced Masonry	Reinforced Masonry	Conventional Woodframe
Explosion	Good performance of frame; Wall and floor panels typically fail leaving structural frame intact; Frame collapse is unlikely	Skin blown away, frame may collapse; entire building blown away in some cases	Destruction of concrete in close-zone. Otherwise members retain strength with significant damage	Poor slab performance due to upward loading can lead to loss of column stability and collapse	Little resistance to upward loads. Brittle behavior when overloaded	Very poor performance. Connections are weak links, resulting in partial or complete collapse	Roof diaphragm and roof/wall connections fail at low pressures leading to partial or total collapse	Heavy URM walls may perform well. Lighter walls likely to disintegrate. Roof diaphragm and roof/wall connections fail at low pressures leading to partial or total collapse	Roof diaphragm and roof/wall connections fail at low pressures leading to partial or total collapse	Roof diaphragm and roof/wall connections fail at low pressures leading to partial or total collapse	Load bearing wall elements become disconnected from horizontal diaphragms leading to partial or total collapse
Fire	Plastic deformation of steel, connection failure. Strength regained upon cooling	Rapid loss of strength and collapse upon heating; Long span structures could collapse suddenly	Good structural performance; Non-structural spalling of concrete cover.	Good structural performance; Non-structural spalling of concrete cover	Annealing of tendons, loss of pre-stress possible; Spalling of concrete	Generally good performance but heat causes thermal expansion leading to cracked connections and can cause annealing of tendons, loss of pre-stress	Diaphragms of wood or bare steel joists have little fire resistance, leading to loss of out-of-plane lateral support for wall panels; Inward or outward thrust from collapsing roof or floor structures	Loss of diaphragm support to walls, inward or outward thrust from collapsing roof or floor structures	Destruction of interior wood or steel framing leading to loss of lateral support for exterior walls. Inward or outward thrust from collapsing roof or floor structures	Rapid combustion and collapse	
High-energy Impact	Impacted members severed/destroyed; Connection failures in vicinity of impact	Structure will provide little resistance to impact	Damage and possibly limited destruction of structural members in immediate vicinity of impact. Damaged members retain strength.	Damage and possibly limited destruction of structural members in immediate vicinity of impact; Damaged members of questionable strength	Damage and possibly limited destruction of structural members in immediate vicinity of impact; Damaged members of questionable strength	Impact damage likely to be localized but may fail or dislodge numerous connections. Requires careful inspection of connections	Impact damage to walls likely limited to localized collapse. Diaphragms have little impact resistance, resulting in localized collapse	Disintegrates upon impact, possible partial collapse. Loose bricks pose lethal falling hazard	Somewhat tougher than URM, but little resistance to impact beyond mass of wall.	Little resistance to impact. Destruction in immediate vicinity of impact – remaining structure generally stable.	

StS2-1-3 FAILURE MODE ANALYSIS—FAILURE MODES SUMMARY TABLE

Initiating Event ▼	Constr uction Type ▲	Heavy Structural Steel	Light-gage Steel	CIP Ductile Reinforced Concrete	CIP Non-ductile Reinforced Concrete	CIP Post- tensioned Concrete	Precast Concrete	Tilt-up	Unreinforced Masonry	Reinforced Masonry	Conventional Woodframe
Wind	▼	Frame unlikely to be damaged by wind; Curtainwalls and partitions may be destroyed.	Very poor performance; Skin blown away, frame may rack/buckle and collapse	Structure unlikely to be damaged by wind. Windows, exterior walls and partitions may be destroyed.	Structure unlikely to be damaged by wind. Windows, exterior walls and partitions may be destroyed.	Structure unlikely to be damaged by wind. Windows, exterior walls and partitions may be destroyed.	Structure unlikely to be damaged by wind. Curtainwalls and partitions may be destroyed	Roof diaphragm vulnerable to uplift, failure of roof/wall connection, leading to partial or complete collapse; Penetration through large doors can lead to critical uplift and blowout pressures	Roof diaphragm vulnerable to uplift, failure of roof/wall connection, leading to partial or complete collapse	Roof diaphragm vulnerable to uplift, failure of roof/wall connection, leading to partial or complete collapse	Damage is highly dependent on wind speed, building shape and detailing. Even well-constructed wood structures often destroyed by tornados
		Failures during erection and failure of long-span structures most common Members maintain integrity with failures at joints	Failure by lateral torsional buckling of built-up sections Joint failure and member buckling	Failure of falsework during construction most common Members likely to retain strength & integrity.	Failure of falsework during construction most common. Members likely to break into smaller pieces of questionable integrity	Failure of falsework during construction most common Members likely to break into smaller pieces of questionable integrity	Failure at connections most common, leading to cascading failures Members likely to retain strength and integrity	Failure of roof structures due to ponding (localized) and snow (global) loads, especially in older structures. Wood decay common in older structures. Walls likely to disintegrate.	Failure of roof structures due to ponding (localized) and snow (global) loads. Wood decay common in older structures. Extensive connection failures Wall panels likely to topple as units of questionable integrity	Failure of roof structures due to ponding (localized) and snow (global) loads. Wood decay common in older structures. Walls likely to disintegrate.	Failure of roof structures due to ponding (localized) and snow (global) loads. Wood decay common in older structures. Extensive connection failures Wall panels likely to topple as units of questionable integrity
Structural Defect / Overload	▼										

StS2-1-3 FAILURE MODE ANALYSIS—FAILURE MODES SUMMARY TABLE

Additional Notes

StS2-1-3 FAILURE MODE ANALYSIS – DAMAGE ZONES SUMMARY TABLE

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