EXPEDIENT HAZARD MITIGATION FOR A STRUCTURALLY COMPROMISED TALL BUILDING: A DECISION MODEL FOR CRISIS MANAGERS

A Dissertation

by

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ABSTRACT

This study compares repair responses by individuals to a damaged high rise wind frame. Individuals are experienced high rise structural engineers and constructors. Solutions are indexed. Comparisons are made between individuals by experience levels and professionals.

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1. INTRODUCTION

1.1 The Problem

The progressive collapse of high-rise buildings is a theoretical issue that has evolved to urgent reality. The high-rise power symbolism that has permeated our culture in the last century has been co-opted by darker forces as a negative expression of their power. The reason that we build high-rises is the same reason that others will attempt to destroy them.

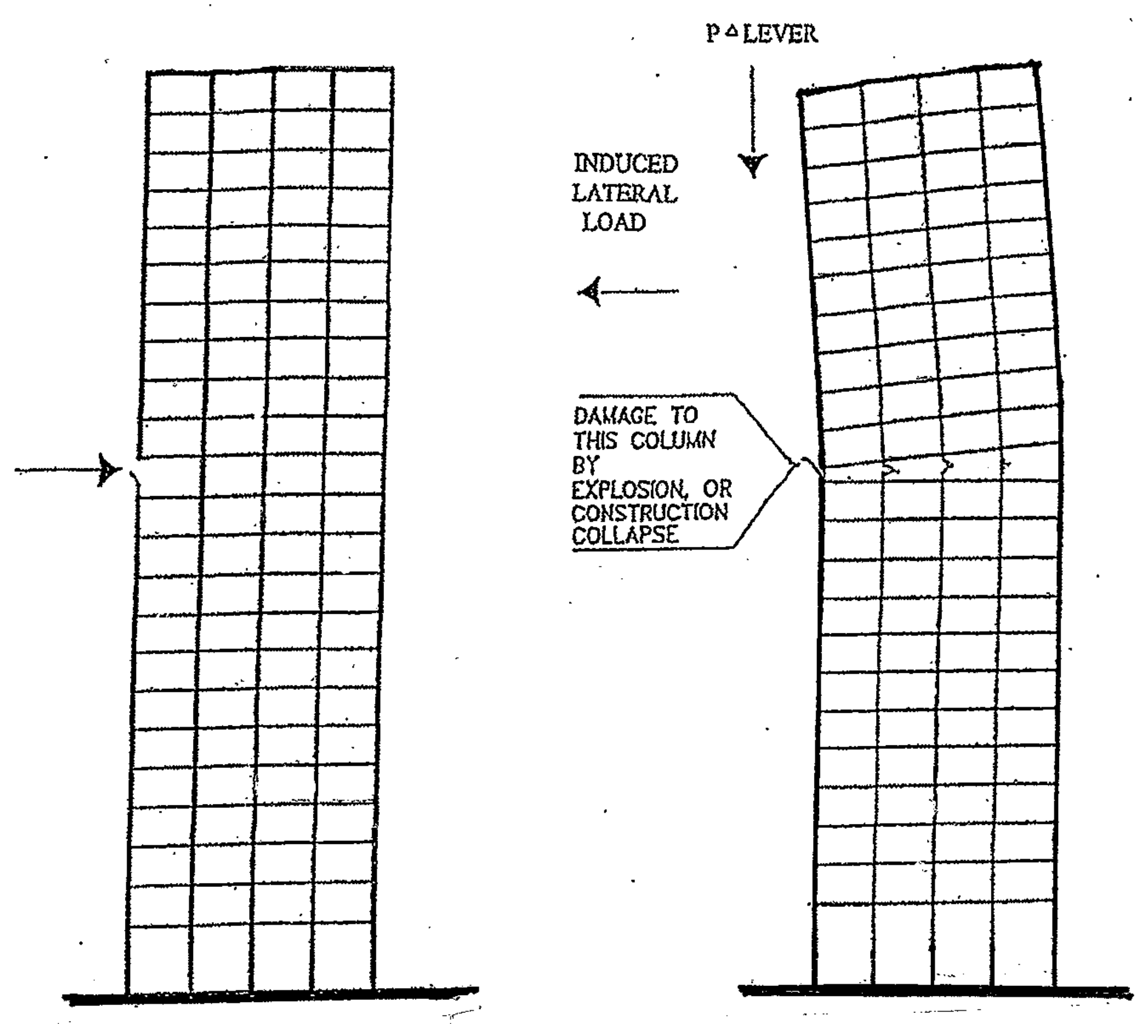
While local and national disaster management is prepared to deal with the aftermath of a total vertical collapse, there is no specific planning to deal with a structurally crippled tall building, poised to collapse under wind loading or additional damage. The World Trade Center ("WTC") on 9/11 had three buildings severely crippled. Two of the high-rises survived for an hour or more and the third survived a day.(1)

With viable technologies to deal with the fire and temporary repair of the structure, there is the possibility that all three buildings could have been saved. It has been well argued that WTC 7 should have been saved with existing technology (resulting in a lawsuit) and that only faulty decision making led to its collapse after fire weakened its foundations for a full day. The problem is by definition an engineering management issue, and this study will approach it from the initial key decisions that must be identified and solved to prevent a greater and perhaps catastrophic disaster.

The potentially progressive nature of this type of event introduces time as a critical component of the study. The stabilization or removal of the building must be accomplished before weather or other conditions can increase the damage to such a degree that overloading of the remaining structure results in total collapse.

At least seven high-rise buildings have collapsed in recent decades after weakening of their structural systems by fire or construction error. The failures at WTC (three) collapsed straight down as their structural frames provided a vertical channeling for the accordion-like collapse. A much greater theoretical risk, however, is posed by a *toppling* failure of a tall building. This type of collapse could be the result of (1) the building's being pushed over by external forces (wind or foundation failure), or (2) multiple column failures on one side of the building, or (3) a combination structural failure and overturning moment such as wind and foundation failure. In any of these events, the entire building would lean to an extreme degree in one direction, causing progressive overload of columns and eventual toppling of the building as a coherent unit, not unlike a tree being felled (Figure 1). To date, several smaller high-rises have toppled from various causes, including a 12-story in Selangor, Malaysia on December 11, 1993[(2)], a 13-story in Shanghai, China on June 27, 2009[(3)] and most recently, a 20-story on January 26, 2012 in Rio de Janeiro, Brazil. The 20-story building toppled into an adjacent 10-story building and collapsed it, as well as a 4-story building[(4)].

Figure 1 - Progressive Failure of Columns. The left profile shows a single column severed near the midpoint of a multi-story building. The weight previously carried by that column shifts to the immediately adjacent columns. If the addition of the shifted weight exceeds the capacity of any of the adjacent columns, then they will also fail. The combined weight from the two failed columns will then redistribute to adjacent columns and collapse a third column, etc. The building begins to lean and weight is shifted onto the remaining columns in what is referred to as the P-Delta lever.[5]



Initial Column Failure   Chain Reaction of Failures

For this exercise, the relevant theory is progressive failure of columns in a long span, rigid-frame, tall steel building: The initial failure of one or more columns of the exterior rigid "cage" results in load shifting to adjacent columns and their subsequent failure from the overload. The loading on the columns would be a combination of gravity loading from building and occupant weight, with concomitant building movement induced by wind loading. Once the building leans in a direction, it is pushed into toppling by a combination of what is referred to as the P-Delta lever of its off-centered weight and building sway from wind force. Initial progression of the column failures may be continuous or intermittent. More specifically, progressive failure of the rigid-frame of high rise columns will normally be dependent on several conditions.

First, the subject building's spans between columns must be large, probably 25 feet or more. Lesser distances increase the chance of the remaining beams and columns forming an impromptu truss over the damaged column, as occurred at WTC 1 and 2, thereby preventing the building from immediately collapsing.

Second, gravity-loading alone will normally not be sufficient to trigger a progressive collapse from a single severed column. Additional wind-loading will probably be required to cause the failure of the second, and perhaps, the third column. At that point, the transferred gravity-loading will be adequate to continue the sequence. If two or three columns are severed concurrently, however, then the wind loading would not be necessary. Once several columns have been severed or have collapsed, the P-Delta lever takes effect. The missing columns and the sagging structure above will cause the building to lean to the damaged side. This lean translates in engineering calculation to an overhang, and further increases the loading on the remaining columns under the lean (P-Delta lever).

Third, the most efficient point (considering effort and degree of damage) for triggering progressive failures is not near the top or bottom of the building. Rather, it will usually fall between the 1/4 and 1/2 point of the building and will vary with the height and design of the structure. Lower points will encounter much heavier structure to cut, while higher points will theoretically reduce the damage.

These variations in the failure analysis will normally require an experienced structural engineer to determine whether the severance of a particular column may produce progressive failures. The key issue is whether the exterior frame topples *before* the interior floors collapse downward. If so, the building will topple; if not, the building will collapse upon itself as did the WTC. If a single (or multiple) column failure(s) leads to progressive failure of columns and progressive collapse in a toppling mode, this can trigger a sequential collapse of multiple buildings. This domino model of sequential building collapse stems from the toppling failure of a single building: If a collapsing building applies lateral force to a neighboring building, the weights may be of such magnitude as to cause compression failure in the columns on the opposite side of the impacted structure or a lateral failure of bracing 90^o to the loading. If so, the neighboring building may topple with the first and possibly impact a third building in a similar manner (see Figure 2). This model appears account for to the multiple failures in Rio de Janeiro previously mentioned, although these buildings were relatively small.[(6)]

A variation of the domino model is that the collapsing building does not impact the second building high enough to push it over, but damages the base columns and delivers a "kick" to the base of the second structure, causing it to topple back toward the first building. (See Figure 3).

Because of the possibility of a domino reaction, a toppling failure poses a significant threat to neighboring buildings over a large radius. In an extreme example, it is theoretically possible that the failure of one or two columns in certain buildings could translate into the sequential failure of multiple high-rises.

Figure 2 - Domino Model Type I, Direct Topple. The primary building shown in Figure 1 topples against a neighbor and results in the failure of lateral bracing or overloading of columns on the opposite side.

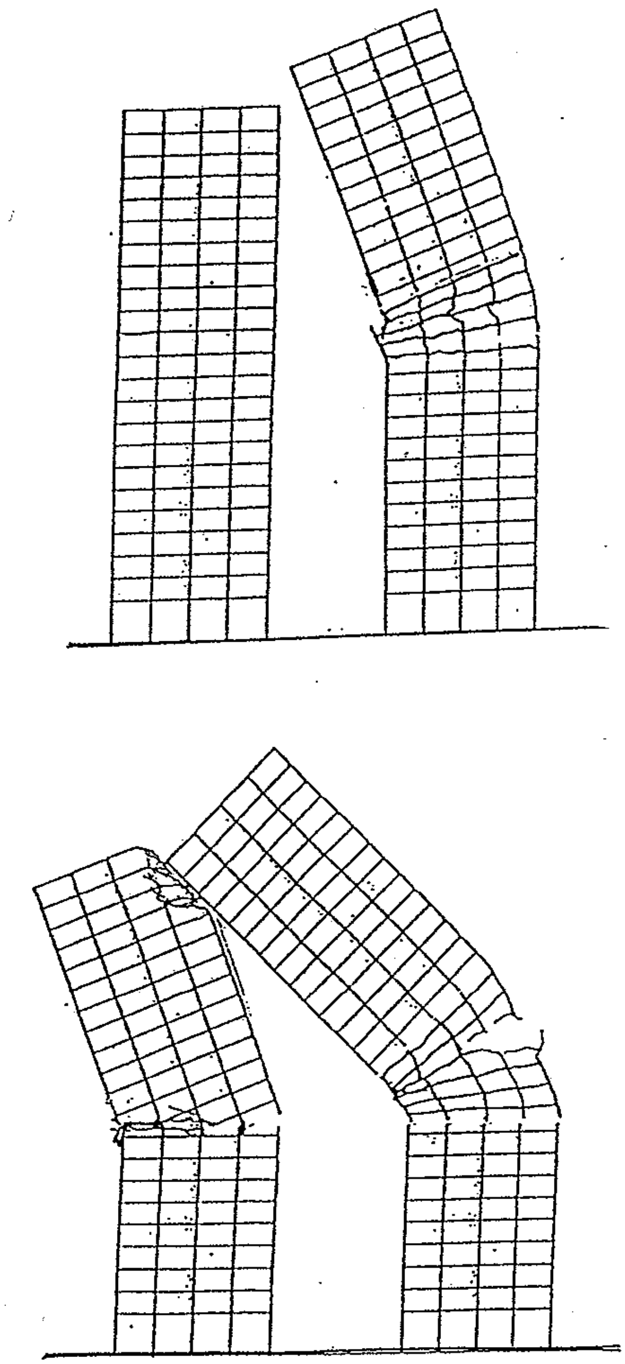
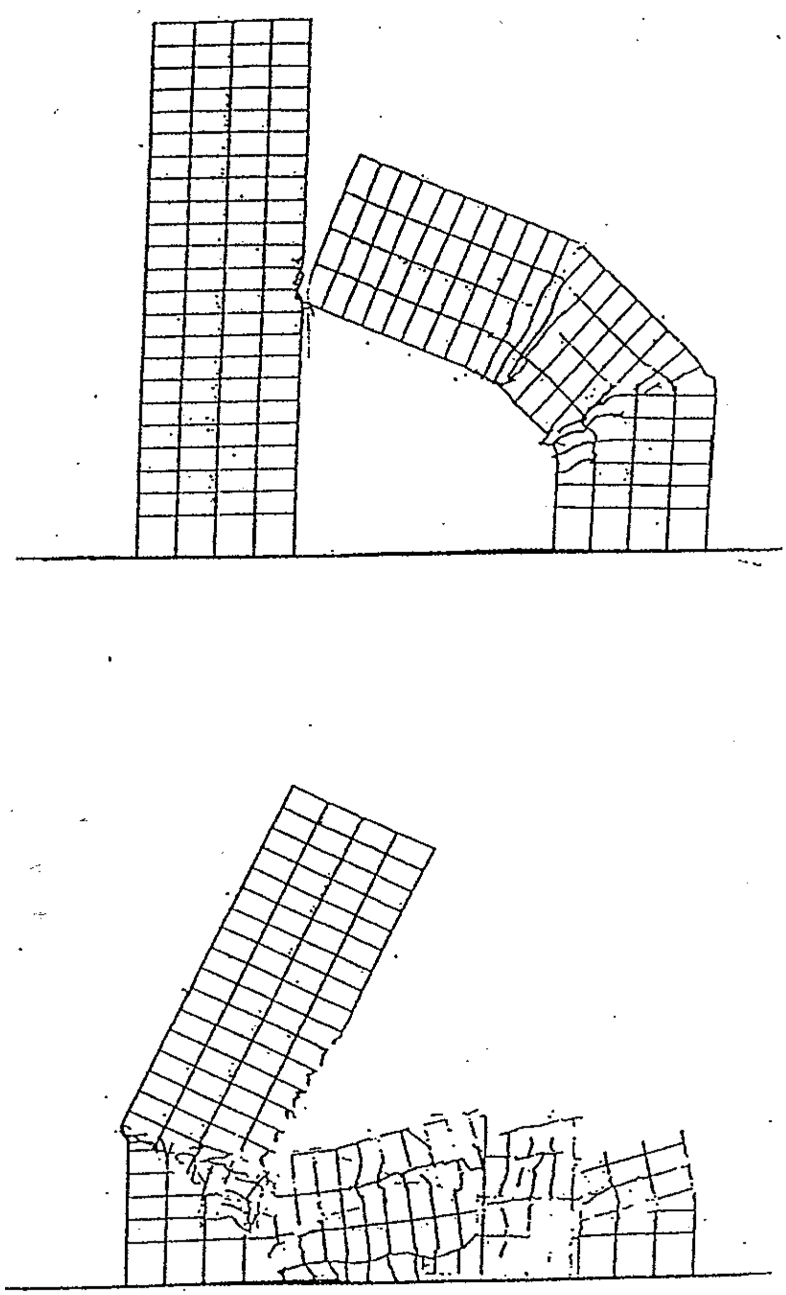


Figure 3 - Domino Model Type II, Unpinning Collapse. A second type of sequential collapse damages the columns at the base of an adjacent building and it collapses back on the first. This scenario is more likely to involve a building several hundred feet away.



2. LITERATURE REVIEW

The study of decision-making in preventing a high-rise building collapse scenario has no literature of record. Relevant research is logically divided into two contributing branches. The first is literature of hundreds of historical terrorist actions, which points to relevant terrorist criteria for future actions. This historical evolution will test (or question) any assumptions as to whether a given scenario is compatible with the historical context of terrorist actions. Second, with the resulting theory of a future attack scenario, the research literature of decision-making relevant to that scenario can be identified and discussed.

2.1 The History of Terrorist Attacks on Buildings

There is a master source of terrorist incidents research that grew from a Yale University dissertation by Edward F. Mickolus and published in 1980 as "Transnational Terrorism."(7) This work has been expanded by the original researcher and several collaborators to five volumes and includes reports on over ten thousand terrorist incidents, , Mickolus, Sandler, and Murdock (1989(8) and 1997(9)) Mickolus1993(10) , and Mickolus and Simmons(11) (1997). Examination of these files reveals about three hundred significant attacks on government, institutional, commercial and industrial buildings. These reports, together with additional reports involving building failures, yield seven conclusions.

First, historical patterns of attacks on buildings indicate that terrorists learn from failures, experimenting until a successful result is obtained, and then repeatedly using that technology. If some aspect is blocked by defensive strategy or material availability, they alter their methods, materials and even objectives as necessary. But the combined worldwide effort of terrorists to destroy architecture never ceases.

Second, in the past century, attacks on buildings have targeted increasingly larger structures. The destruction technology of buildings, however, has lagged several decades behind the construction technology of tall buildings. While the vast majority of these attacks have employed the use of explosive devices, terrorists have not developed explosive technology for high rises. The major attacks appear to occur on roughly an eight to twelve year cycle.

Third, the attack on the King David Hotel, in 1946, introduced to terrorists the military engineering concept of destroying individual structural members as an effective means of destroying large buildings.(12)

Fourth, the barricade and hostage scenario developed by Armenian terrorists in 1896, and repeated worldwide, provides a simple method to control one or more floors of any building while demolition personnel prepare to cut structural members.(13)(14)

Fifth, no damaged mid-rise or high-rise building has ever been left in a precarious position requiring emergency structural intervention to protect other high-rises. This absence precludes a literature of factual experience in the stated problem.

Sixth, in 1993, Ramzi Yousef developed the concept of toppling WTC I into other buildings. Theoretically, a toppling failure of WTC I and II could have reached for a fifth of a mile, destroying everything in its path and possibly initiating secondary toppling failures. Although he had knowledge of explosives, Yousef lacked education in the technical application of explosives to tall buildings and his attack failed.(15)

Seventh, there may be an, as of yet, unidentified rule that is directing the long-term advancement of effectiveness in terrorist actions. Stated broadly, anti-architectural terrorism is ultimately seeking the *maximum cultural impact* for the *minimum technical effort.* When this "holy grail" is reached, it could be repeated indefinitely until either the cultural icon (high-rise architecture) is discredited as functional (desirable) architecture, or the technical effort required of the attackers is no longer a minimum value compared to other effort/results ratios. Historically, the evidence for the holy grail of terrorism goes beyond any one terrorist cause. The termination of one cause only prepares the way for the next group to assume the quest.

In addition to the Mickolus research, review of other technical sources lends credence to the idea that emergencies eventually will arise that require immediate structural repair. To wit, technical instructions in U.S. Military engineering texts (U.S. Army Field Manual 5-25(16) and U.S. Army Handbook SH21-76)(17) and U.S. Army Engineering Center classes at Ft. Leonard Wood, Missouri, teach that steel and concrete structures can be collapsed with directed efforts against one or more individual structural members. Military veterans with a demolition Military Occupation Specialty know this information. In such an attack, failure to achieve immediate collapse may result in a crippled building that is vulnerable to progressive collapse from wind action over a period of time.

Although large aircraft have been substantially secured from terrorist use as weapons of mass destruction, smaller private aircraft, including multi-engine business jets remain easily accessed, due to fewer security provisions and the availability of legal lease and rental aircraft. Damage from the 2001 WTC plane attack indicates that high-speed jets are uniquely suited to cutting structural columns. It also appears likely that a high-speed impact by a business jet will be capable of severing some columns depending on the point of impact, although the reduced fuel load of smaller jets decreases the possibility of immediate building collapse. Nevertheless, it is possible that the building will be left crippled and vulnerable to collapse unless prompt action is taken to repair or demolish the building in a controlled manner.

Other simple weapons exist that have not yet been deployed against high rises at this time. Heavy weight vehicles, including loaded concrete trucks, armored military vehicles, and railway locomotives have the mass to sever or crumple a single high-rise column. There are multiple locations where roads and railroads run under or adjacent to high rises. According to the U.S. Army Field Manual 5-25, trucks containing high-temperature fuels (over 2000 degrees F.) have the potential of inducing temperature failure in exposed steel columns and beams that require only ten minutes at 1000 degrees F and somewhat longer if protected by common sprayed-on fire insulation such as used at the WTC. In these events, prompt repair and demolition decisions will be needed.

In addition, military engineering knowledge is widely available due to the unfortunate long-term availability of U.S. military engineering manuals in the army surplus and gun show market in the United States. The availability of highly qualified foreign military engineers from nations that support terrorism compounds this problem.[(18)]

In summary, the historical record, common demolition practices, and military engineering texts give evidence of the effectiveness and feasibility of cutting individual structural members on high-rise buildings as a means of destruction**.** Vehicle bombings are not as effective on high-rise structural systems as they are on mid-rises and large aircraft are increasingly secured against terrorist hijacking. Combine this information with the long-term terrorist efforts towards attacking increasingly large buildings and a covert action or a barricade-hostage situation involving the severing of individual columns becomes increasingly logical as a likely terrorist action.

Furthermore, it should be understood that engineers normally cannot exactly predict the reaction of a high-rise building to the removal of a column. In particular, engineers will have difficulty in predicting a building's impending failure without extensive time (days) to minutely analyze, quantify and calculate the effect of the damage.

These observations suggest that the column failure scenario could arise as a result of one of the following:

1) A poorly planned or interrupted terrorist effort in which the building does not collapse as planned and is left crippled requiring immediate repair, or
2) A deliberately limited attack designed to create a long-term impending collapse situation in a downtown high-rise district, or
3) A deliberately limited attack on key structural members, which allows a high wind to provide the additional overturning moment, thereby completing the collapse of the building.

The rationale underlying these attacks would be to induce column failure in a high-rise wind frame in such a manner that adjacent columns are overloaded and/or critical structural joints are subjected to greatly increased stresses to the point of failure. The failure of each column or joint, in turn, could increase the allowed movement of the building in normal wind forces over a period of hours or days. A severe wind load could cause the building to go from a slow progressive failure into an immediate toppling failure. If there is no significant wind, the continued building movement in a mild wind could eventually flex the most highly stressed frame connections to the point of failure. If this failure occurs in a contiguous area of high-rises, a toppled forty-story building could trigger successive domino collapses of adjacent high-rises. Consequently, in any contiguous area of high rises in which a single column in one building is severely damaged to the point of risk building failure, the entire contiguous area of tall buildings will require evacuation until the damaged building is at least stabilized for the plausible wind loads.(19) Such a consequence from a minor event could hold momentous implications for the American system of tall compacted city centers and future real estate values of these core value areas.

This low effort (cut one column), high impact (the threat to multiple high-rises) terrorist strategy is easily replicated once the concept has been established by action. It is an action that is difficult to prevent, but if implemented, may require a unique engineering reaction in a short response time to avert catastrophe. Moreover, there is no record in the engineering literature of high-rise short-term emergency repair studies or the record of an actual event with a tall building in actual practice.

There have been several buildings judged weak in wind framing, and programs carried out to correct the problem. Colaco, Ford, and Robertson[19] described a massive restructuring of a high-rise wind frame, but the planning and construction required years. Effective retrofitting of high-rises to thwart terrorists is largely theoretical and would certainly be expensive. To date, there has been only one known major structural retrofitting of a high-rise to thwart terrorism. The lower eight floors of a 51-story building (from foundation) received a massive reinforcement against large exterior vehicle bombs and very high-strength composite concrete column encasement was carried up 50 floors in conjunction with a wind retrofit. Such efforts require about one-half million dollars per floor to protect key external members and the wind frame from deliberate damage scenarios. While this addition provides damage protection for individual steel columns and increases resistance to progressive wind frame collapse, it cannot eliminate vulnerability altogether.[20] Measures developed on this project have been used on several new high rises since that project. A similar reinforcement of a Manhattan high-rise by Harvard Professor William Lemeasure[21] was also a critical project but, again, the response time was years rather than days. Neither building was reported to have actually suffered any damage from wind loading. Earthquake bracing adds to the likelihood of incomplete failure. Successful attacks would be more difficult in earthquake zones.

The most similar engineering situation may well be the Tacoma Narrows Bridge collapse in the state of Washington prior to World War II. Levy and Salvatori[22] have noted that America's third longest bridge had shown itself to be remarkably unstable in moderate winds even during construction. Given the nickname "Galloping Gertie," studies were launched and consultants brought in to attempt to stabilize the structure. The engineers, led by Professor F. B. Farquharson, were unable to move quickly enough to resolve the problem and the bridge destroyed itself in a moderate wind on November 7, 1940, as the professor watched and a movie camera recorded the now famous scene. It is particularly significant that the engineering response required months and events moved faster than the response.

2.2 Decision Making Literature

The available research literature on decision-making does not directly relate to the problem of immediate emergency engineering decisions concerning building structures, which constitute the key element of this study. Such crisis decision-making situations fall outside the normal engineering decision-making procedures as studied in college and practiced in professional offices. Situations demanding rapid judgment rather than painstaking analysis could be considered the very antithesis of normal engineering practice, which stresses a full evaluation of the problem with the best available means. Time available is not normally dictated to the engineer; rather the engineer dictates the time required.

The most relevant available information on high stress, time constrained decision-making by experts is in the following categories of research:

1. Decision-making in dynamic task environments. Dynamic task environments are ones in which various aspects of the problem or its environment change during the exercise. The column failure scenario is a dynamic task environment changing during the exercise and the resulting decision-making has certain unique characteristics that Korsthell and Raaijmanors [(23)] identify as follows:
   a) Change over time requires that the time element be taken into account explicitly. Indeed, the changing environmental itself defines time pressure in dynamic environments. Brehmer[(24)] had noted that decision-making in studies should be made in real time, the concept being that distorting the available time to make a decision in real time can alter the decision-making process.
   b) Availability of feedback is a critical feature of a dynamic decision task and divides into action-oriented strategies (reacting to observed change) or judgment-oriented strategies (which researches underlying performance deterioration).
   c) Complex dynamic situations require multiple interdependent decisions that affect the system under control or attempted control, as well as decisional reaction to autonomous developments within that same system.
2. Time pressured decision-making. A major factor in many decision-making situations is a lack of time to thoroughly analyze the situation, evaluate alternative courses of action, and implement a strategy. The column failure scenario is driven

by a severe lack of time in all three areas - situation analysis, alternative evaluation, and strategy implementation.

a) Hogarth and Karelaia[25] note that linear decision-making assumes that people can integrate all available information and act rationally upon it. This linear cognitive ability (skill) depends on having the time available to gather and process information. An implication of their analysis is that people do not need much computational ability (skill) to make accurate judgments in many cases, but they do need knowledge of when to use particular rules or heuristics. This leads to the concept for a particular situation of replacing engineering calculations with predetermined rules of thumb as an organized form of heuristics in emergency situations.

b) Zakay and Wollner[26] demonstrated that time pressure negatively impacted the subjects' ability to use a learned strategy for optimum results and the quality of decision-making suffered. This result may correlate to normal engineering problem-solving as a learned strategy for seeking unconstrained optimum values rather than seeking an adequate strategy within a limited time frame, i.e., Simon's[27] concept of "satisficing".

c) Also of interest are studies that show an increase in time pressure results in subjects reducing their risk-taking in decision-making.[28, 29]

3. The effects of expertise on dynamic decision-making.

a) The definition of expertise has been studied and discussed in scientific literature for decades with a failure to reach consensus. Cellier[30], citing Shanteau[31], and Fischer[32], stated that "it is not possible to provide a consensual and operational definition of expertise." There was agreement on one issue, that expertise was domain specific.

b) There are ten characteristics of expert performance: (1) Expertise is domain specific because the foundation of expertise is an extensive knowledge of a specific domain, (2) experts perceive patterns or chunks of information rather than individual pieces of information, (3) experts are faster and make fewer errors, (4) experts have superior memory in their domain, (5) experts see and represent a problem at a deeper level, (6) experts have strong self-monitoring skills, (7) experts have fine perceptual abilities, (8) experts have the ability to see typicality, (9) experts have the ability to see fine distinctions, (10) experts have the ability to see antecedents and consequences. [30]

Cellier et al also concluded that experts' decision-making is based on perceptual recognition skills representing an accumulation of experiences with the task. Expert decision-makers can distinguish between typical and atypical events and make fine discriminations between similar situational factors. They will also be able to generate expectations about how the situation arose and how it will evolve. Violations of these expectancies will cause the decision-maker to re-evaluate the situation.

c) In a fast-paced, dynamic decision-making situation, experts make decisions on a perceptual/heuristic basis rather than the usual conceptual basis that assumes extensive study and analysis. But, this process, in turn, may allow greater opportunity for bias on the part of the decision-maker.[31] If there is evidence of continued conceptual thinking under severe time stress, it may raise issues regarding the adequacy of the expert's background experience relative to the particular problem. Such findings could indicate a need for special training in emergency response to reduce the anticipated bias.

d) Consistent with the concept of a perceptual basis for expert decision-making, experts are found to have a more functional view of the process, and to be superior at anticipation and producing inference[33]. Appropriate expertise should exhibit these characteristics.

e) Fox and Clement[34] describe practical procedures for eliciting subjective probabilities from experts. In particular, the risk partition dependence and pruning bias are discussed as elements that can alter professional judgment.

4. Emergency response. Perry and Lindell[35], have identified the four principal emergency response functions as:

    1. Emergency assessment
    2. Hazard operations
    3. Population protection
    4. Incident management

In the context of a potential building collapse, emergency assessment involves collecting and evaluating data about the condition of the building and its environment (especially weather conditions), as well as forecasting the likely mode of building collapse.

Hazard operations involves an assessment of expedient methods of preventing building collapse or limiting the consequences of a collapse if it should occur. It also involves developing an action plan and implementing it, similar to determining stability of buildings and tagging them after earthquakes.

Population protection is primarily the issue of determining if a "safe" evacuation radius is needed and, if so, what is the required distance. It also involves taking appropriate action to protect emergency workers.

Incident management involves coordination among all the affected stakeholders, including local government acting through the Fire Department. The primary direction of the emergency response will come immediately from the Fire Department's Incident Commander and eventually the building owner acting through his/her engineering consultants.

5. Decision Studies for Anti-terrorism. Dillon et al.[(36)] detailed the ARDA risk-based decision-making approach for prioritizing anti-terrorism measures for the U.S. Navy. The study discusses 15 attack modes against 160 facility types and 22 mitigation alternatives. There is a limited discussion of cost-effective response and the general agreement that an expected value approach is not appropriate for low probability, high consequence events. This would be relevant for a study such as the one in which we are engaged.
6. Decision-Making in Projecting Future Events. Ezell et al.[(37)], note that a U.S. National Research Council committee has criticized the use of probability to assess the likelihood of terrorist events and suggests the use of decision trees in combination with probability studies. The NRC committee recognizes terrorist events as actions that can be predicted from their objectives, but studies using this approach have not been published to date.
7. The Fluency and Effort Heuristics. Traditional decision-making algorithms require considerable mental effort and concentration. Decision-makers have cognitive

processing limitations, as well as the constraints of the task environments such as time. This concept is known as bounded rationality.[38]

Fluency in cue weighting proposes that participants often weigh information according to the ease with which it can be processed. This is related to the availability heuristic which states events that come easily to mind will be judged as more likely to occur again in the future. Thus, fluency can serve as a basis for deciding which cues will be weighed most heavily in decision-making. The authors argue that fluency affects cue weighting when validity information is not present and that fluency may itself be a proxy for cue validity.[39][40]

The effort heuristic reflects that people judge the value of work by the amount of effort that they believe is put into it. Thus an "easy" solution such as removing the windows in the upper stories of a building to reduce wind load, may be seen as "too easy" a solution that has less value than welding and restructuring the damaged portion of the building.[41]

Shah and Openheimer[30] reviewed past studies for summaries of the strategies (heuristics) that people use for reducing the effort of decision-making. They concluded that the cues for decision-making have two separate components, a type and a value. An example is the heuristic for purchasing a car. Fuel efficiency is an example of one heuristic for decision-making while the actual mileage that the car gets is the value of that heuristic.

3. AN EMERGENCY DECISION MAKING MODEL FOR HIGH RISES

The research literature reviewed in the preceding section suggests an outline of the expedient hazard mitigation decision process for a column failure scenario as shown in Figure 4.

D1, the first decision, concerns the preliminary assessment of whether to risk making an emergency assessment of the building. If not, the building will remain in its unstable condition until wind load increases to the point of failure of the entire structure. This option is represented by the line to the left of D1, resulting in uncontrolled failure. If action is taken, it will be to place structural engineers close enough to review the situation and make a more detailed emergency assessment. Action leads to the D2 decision for expedient hazard mitigation mechanics to attempt to limit the movement of the building in the high wind and/or to prepare the building for demolition (i.e., these two options are not mutually exclusive). The key to this decision is that the building could be prepared for demolition at the same time that plans are being made to save it. Preparation for demolition provides an alternative in case the building cannot be braced due to excessive movement at the severed members. The next decisions are (1) to determine whether the steel wind frame can be braced or "frozen" in place by emergency welding, cabling, or bolting systems (D3 Decision) or saved by reduction of wind forces on the structure (D5 Decision) and (2) to estimate whether the completed repairs will ensure the building can survive any approaching windstorm. In addition to the decision-making for emergency assessment and hazard mitigation (taking action on the building structure) in Figure 6 is a group of population protection (evacuation) decision.

The emergency assessment and hazard mitigation decisions, together with the ability of the chosen constructors, will largely determine the failure or success if an uncontrollable event occurs, storm impact. If the D5 decision is made for controlled failure, the event might be turned over to the military, which could have major liability advantages. Alternately, D5 could be made for partial demolition by tools in which window walls are demolished on the upper floors to reduce the wind cross-section and increase the building's chance of survival. The D5 and/or D6 decision is for permanent structural repairs or removal. The D4 decision is the ultimate repair, mitigation and decision for a building that has survived.

Figure 4 – Proposed Decision Flow Chart

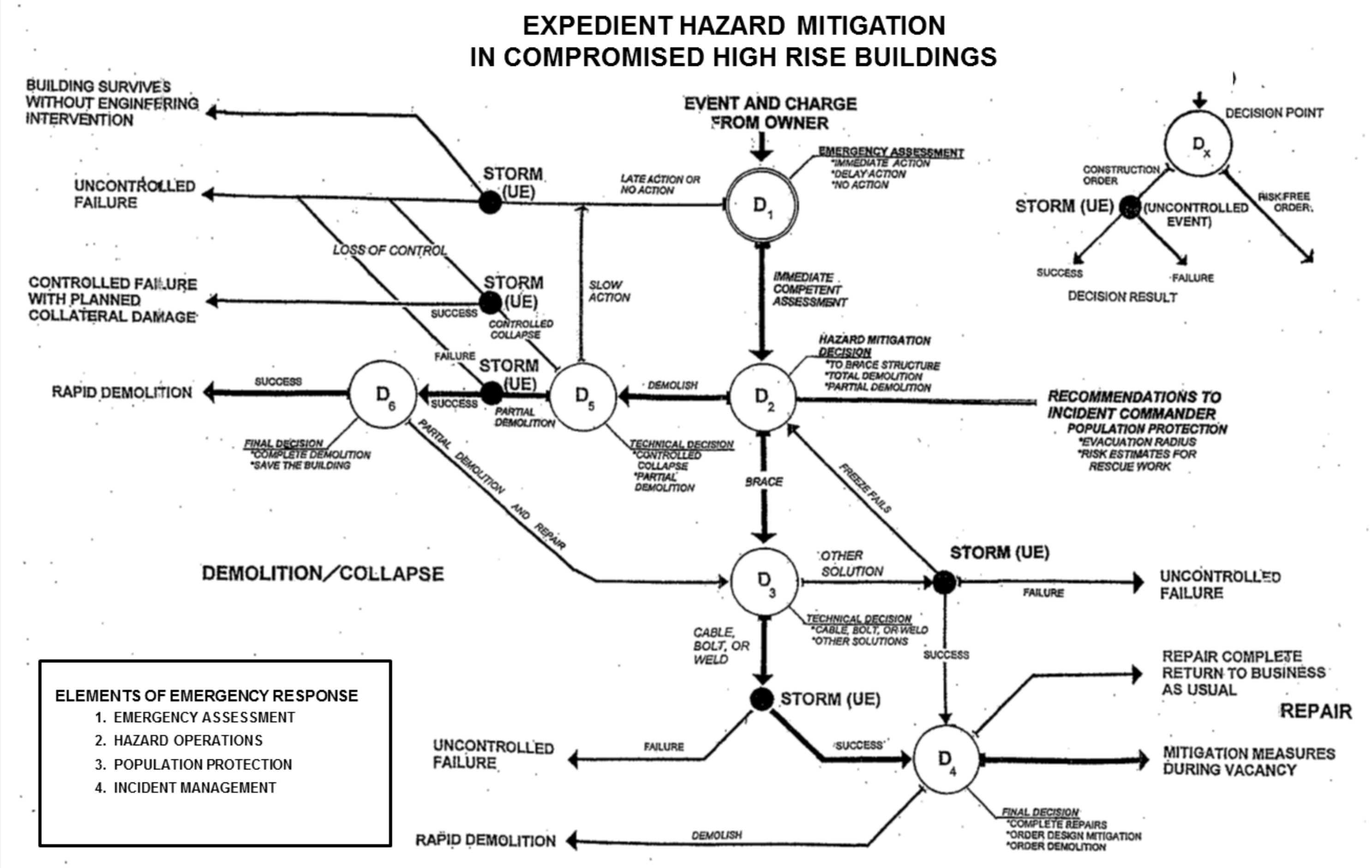


Figure 4: The anticipated Decision Flow Chart for the Study: Although the problem appears to be open ended, the technical procedures and tools available will constrain the engineering decision makers. It is anticipated that the primary decisions may evolve in a format similar to the above pattern. Storm (UE) identifies the points at which the critical decisions are tested and success or failure becomes manifest. Success at the Storm points would not only depend on the engineering decisions, but also the skill of contractors executing the instructions of the engineers.

Ultimately, all identified responses (or no response) in the face of an approaching storm lead to one of the following outcomes for the building: repair, demolition, controlled collapse, uncontrolled collapse, or survival without intervention. Clearly, the one result that should be identified by the decision-makers and avoided is uncontrolled collapse. Certainly in theory and likely in reality, an uncontrolled high-rise domino collapse could place a long line of buildings at risk. If the direction of the possible collapse is uncertain, an entire downtown could require evacuation. Yet, the stricken building and its contents may be worth in excess of a billion dollars. In current practice, the engineers would be in the employ of the damaged building's owner, who is unlikely to agree to a controlled collapse without considerable pressure from the other stakeholders in the situation. Figure 6 identifies stakeholders such as the building owner and his insurance company, the fire department, incident commander, city code officials and the mayor who are all sources of input for the major decisions. (See scenario in Appendix). The police and FBI would certainly be represented and working to preserve evidence at the crime scene. The insurers for the engineering (or constructor) firms, as well as the steel fabricator and construction team, might also impact the decision makers. Other parties, such as FEMA, are not included in this network because they are likely to take longer to mobilize.

A summary outline of Figure 4 based on elements of emergency response is as follows:

1. Emergency Assessment Decision (D_1) and Actions
    - Identify actions to quickly evaluate the condition of the building.
    - Identify actions to determine reasonable population protection.
    - Identify actions to determine working personnel protection.
    - Identify stakeholders' organizations and their senior decision makers.
    - Make D_1 Decision; Action/No Action.
    - Identify available engineering/construction assistance.
2. Hazard Operations Decision (D_2) and Actions
    - Identify expedient measures to stabilize the structure.
    - Estimate long term repair as impacting expedient measures.

Figure 5 – Communication Network for Expedient Hazard Mitigation

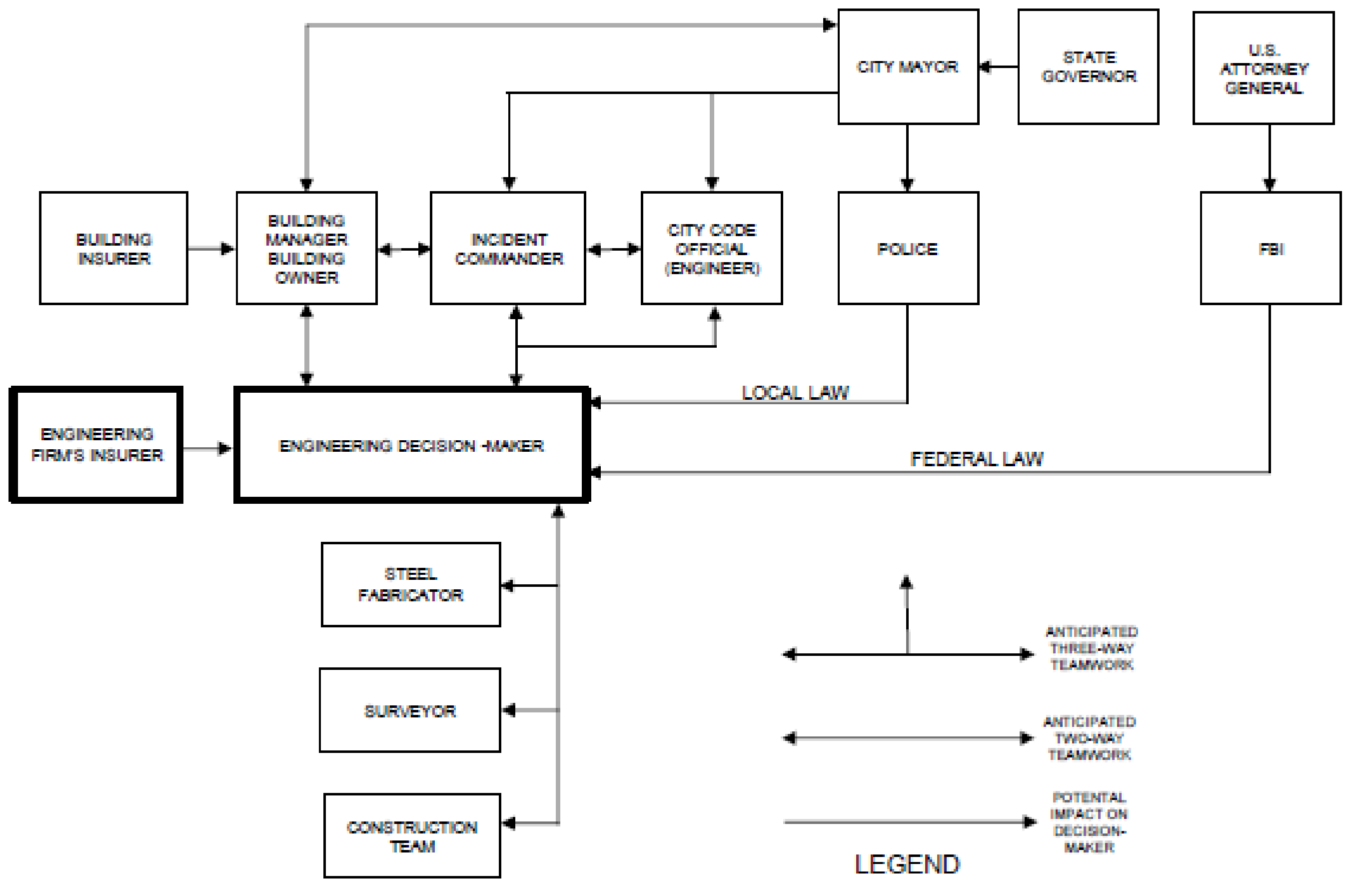


Figure 5: The anticipated communication network centered on the engineering decision maker. This model shows the business and government entities as they might be involved in decision-making in the first few hours based on financial, legal, and emergency planning responsibilities. FEMA is normally not involved in early issues discussed here.

- Identify relevant issues specific to the building.
- Identify engineering, construction skills and material resources.
- Make D_2 Decision for Temporary Mitigation with D_3 or D_5 follow up.

From this outline a normative model of a decision flow chart for expedient hazard mitigation follows.

3. Population Protection – D_2 Secondary Decision
    - Recommendations to incident commander.
        i. Evacuation radius.
        ii. Work rules in building (hazard exposure control).
4. Incident Management – Overview

The management of the incident may be driven in the early stages (3 hours) by certain individuals who are the first to grasp the nature of the risk. If no engineering or construction personnel initiate immediate expedient mitigation measures, then it is unlikely that the measures will be undertaken in a time critical manner. This failure to act could lead to loss of property and life again, as it did at 9/11 with the loss of WTC 7 and police and fire personnel in WTC 1 and 2.

4. RESEARCH OBJECTIVES

Although the study is discussed in terms of four immediate objectives, the ultimate goal of this study is to learn from a set of experts how participants in an actual crisis are likely to respond to situations outside the normal boundaries of engineering decision-making. Specifically, the knowledge gained from this study will support the design of effective repair response teams for specific risks. It will also provide a detailed and time efficient model of the decision-making process that an Incident Commander and engineer could use in an actual event. The study may also identify future engineering studies and/or computer programs needed to support such an action.

4.1 Identify Expedient Mitigation Actions

This objective involves identifying the number and type of expedient mitigation actions that participants generate. It is assumed the first group of actions is the emergency assessment to investigate the damage and acquire basic information about the building. The second group of actions is the set of repair operations options developed by the participants from the initial investigation.

4.2 Test the Proposed Model

The first element of this objective is to test the proposed decision flow chart described in Section 3.0 and Figure 4 by using subject matter experts in the field working a failed column scenario. Such a test will identify what actions the participants list as emergency assessment, hazard operations, population protection and incident management actions. It can also determine if the decision points are approached in the order hypothesized, if experts in a dynamic situation work several decisions at the same time, or even if they reverse the order of their decisions. More importantly, do they really identify all the options open to them? Would a more effective model actually begin with certain construction/demolition preparations paralleling or even preceding the first engineering decisions?

4.3 Research the Effects of Different Professional Expertise

The objective here is to explore whether there are areas in which the inclusion of experienced construction personnel on engineering teams may improve the overall decision-making in time-constrained emergencies. Evidence of such value could be constructors accelerating preparations for steel repairs, identifying alternative strategies or recognizing the need for specialists that the engineers overlook. This evaluation does not ask the constructor to match the engineer's knowledge, but only to effectively complement it and provide detail to a time pressured problem. In practice, constructors who think like engineers bring no additional value to the analysis. It is their uniqueness that is of potential value. The proposed reference model described earlier in Figure 4 is a traditional approach that assumes engineering analysis and planning precede construction mobilization. If construction personnel see different aspects of the problem from the beginning, it could change the proposed model and the optimum makeup of the first responder engineering teams. For instance, constructors might be more likely to identify "downstream" implementation actions that require a significant amount of preparation time and, thus, are on the critical path for project completion. Even this might not be obvious to engineers in the first hours.

4.4 Research the Effects of Varying Levels of Expertise

The first element of this objective requires examining any differences in answers an owner or Incident Commander receives from engineers or constructors with varying levels of expertise in high-rise construction. Level of expertise becomes a critical issue in an emergency occurring after normal business hours when the most well-trained people may not be immediately available. Should an owner or Incident Commander wait to locate and transport one of the small handful of top engineering experts (there are fewer than a dozen in Texas), or can the same answers be obtained from less educated or experienced personnel?

The second element of objective 4.4 is to understand the value of experience in time-constrained decision-making, both within the groups and across the entire participant population. Does education narrow or broaden the decision-making focus in a situation without precedent? Does training help avoid the trap of wasting time on non-essential issues? And, how do highly educated and executive individuals deal with liability risks to their firm? Are they more or less sensitive to liability issues and the work delays implied therein?

5. RESEARCH METHODS

This study identifies experienced high-rise engineers and constructors and provides them with a chronological scenario accompanied by realistic photographs of the damaged building. These study participants were presented a chronological series of open-ended questions to evoke responses without suggesting specific answers. To probe these questions, specific inquiries were made on certain subjects.

5.1 Participants

A total of 29 subjects participated in this research, fifteen engineers and fourteen construction management personnel. The participants were identified through meetings with their firms' managements. The engineers' maximum level of education included three Doctoral, ten Master and two Bachelor degrees. The constructors included one Master, seven Bachelor and two Associate degrees and four high school diplomas. This educational difference between the two groups, shown in Table 1, corresponds to differences between the two professions, as well as the fact that some senior construction executives are more oriented to business than construction and excused themselves from this exercise. Education was divided into four tiers, High School/Associate Degree, Bachelor, Master, and Doctoral degree. The actual work experience of the twenty-nine individuals is shown in Tables 1, 2 and 3. Each group is divided into four tiers of experience. The number of individuals in executive/management positions is indicated in parenthesis in the tables.

Table 1 - Maximum Level of Education

	HS	**AA**	**BS**	**MS**	**PhD**	**Total**
Engineers	0%	0%	13.3%	66.7%(4)	20%(1)	15(5)
Constructors	28.6%	14.3%	50%(3)	7.1%	0%	14(3)
Total	13.8%	6.9%	31%(3)	38.0%(4)	10.3%(1)	29(8)

HS – High School
AA – 2 Yr College
BS – Bachelors Degree
MS – Master's Degree
PhD – Doctorate
( ) Number of Executive/Managers
Related Figures and Tables: None

Table 2 shows the relation between the profession and the actual total years of experience of each individual. The constructors have a higher average level of experience than the engineering personnel. Some of this difference is attributable to the fewer years of education of the average constructor.

Table 2 - Years of Engineering/Construction Experience

	1-5	**6-10**	**11-20**	**21-30**	**31+**	**Total**
Engineers	13.3%	20%	26.7%(1)	13.3%(1)	26.7%(3)	15(5)
Constructors	0%	21.4%	28.6%(2)	42.9%(1)	7.1%	14(3)
Total	6.9%	20.7%	27.6%(3)	27.6%(2)	17.2%(3)	29(8)

( ) Number of Executive/Managers
Related Figures and Tables: Table 3

Table 3 shows the years of specific high rise experience of individuals by profession. Several individuals have fewer years of high rise experience than total engineering or construction experience showing in the previous tables. These individuals have been involved in construction of low and mid-rise buildings.

Table 3 - Years of High Rise Experience

	1-5	**6-10**	**11-20**	**21-30**	**31+**	**Total**
Engineers	20%	33.3%	13.3%(1)	6.7%(1)	26.7%(3)	15(5)
Constructors	35.8%(1)	28.6%(1)	21.4%(1)	7.1%	7.1%	14(3)
Total	27.7%(1)	31.0%(1)	17.2%(2)	6.9%(1)	17.2%(3)	29(8)

( ) Number of Executive/Managers
Related Figures and Tables: Table 2

5.2 Procedure

Table 4 describes the testing sequence, which was conducted between February and June, 2010. Individuals were drawn from three Houston engineering firms and two construction firms with extensive high-rise experience. All individuals had at least some experience with high rises and several were regionally or nationally known for their expertise. The negotiations with each firm and participant testing lasted approximately one month. During the negotiation and testing period, attention was paid to the media and professional publications to see if any events occurred that were relevant to any participant's decision making in the exercise. None was detected. These individuals constituted over 80% of high rise engineering expertise in the Houston area and over 50% of general contractor high rise experience. Therefore, although the number of participants is small, they are, in fact, a significant proportion of the actual population. For instance, of the top five high rise engineers in Houston by experience, four of them were in this sample.

Table 4 - Testing Sequence

Firm	# of Participants	Testing Period
Engineering Firm A	6	Feb 2010
Engineering Firm B	5	March 2010
Construction Firm A	9	April 2010
Construction Firm B	5	May 2010
Engineering Firm C	4	June 2010

The research exercise was conducted in conference rooms at the engineers' and constructors' offices on weekdays or Saturdays when participants were working. Clarification questions were encouraged but few were asked and none required adjustment of the questionnaire or instructions over the course of the exercise. In most cases, the exercise was run with two participants at a time, but there were five instances where individuals completed the exercise alone. Each participant sat separately and had a complete set of photos and documents. There was no talking between participants and the entire period was monitored. The same individual administered all of the exercises. Elapsed time was given to participants at the end of sections 1, 2, 3, 4 and on completion of the exercise. Participants were told that the exercise was not a test of knowledge, but a search for ideas. Participants were told the color of the writing pens would be changed at the ends of sections 1, 2 and 5. Although the subjects were free to revise any answers at any time, the color of the ink indicates when the concepts were recorded. The elapsed time of the exercise varied from about 45 minutes to well over two hours (see Appendix D.)

The research exercise involved a column failure scenario that is specifically based on the decision-making by engineering or construction personnel during a simulated structural emergency. The hypothetical building was a 40 story rigid steel frame structure that had suffered the severance of a single column on the 21st floor (Figures 6 and 7). If additional columns failed under wind or gravity loading, the entire structure would be at risk of toppling as previously illustrated (Figure 2). Time pressure was generated by a 48 weather forecast of a weather front with high winds.

Figure 6 - Rigid Frame Structure Prior to Incident. The hypothetical subject building for the study: The building is forty stories tall of rigid framed steel construction as is typical of hundreds of high rise buildings in the U.S. The exterior wind frame columns are thirty feet on center. The removal of a column on the 21st floor results in the exterior wind frame condition as shown in Figure 7.

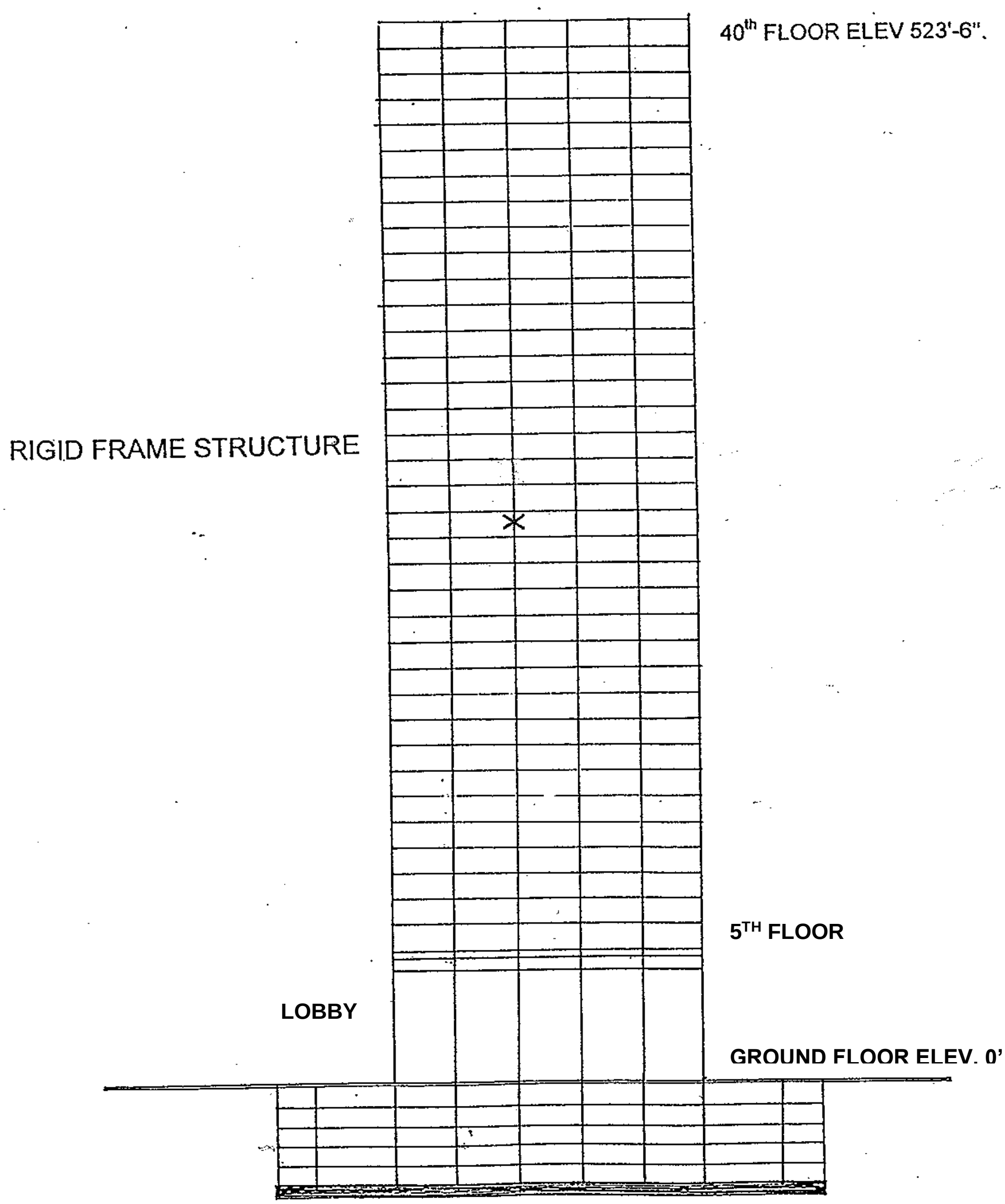
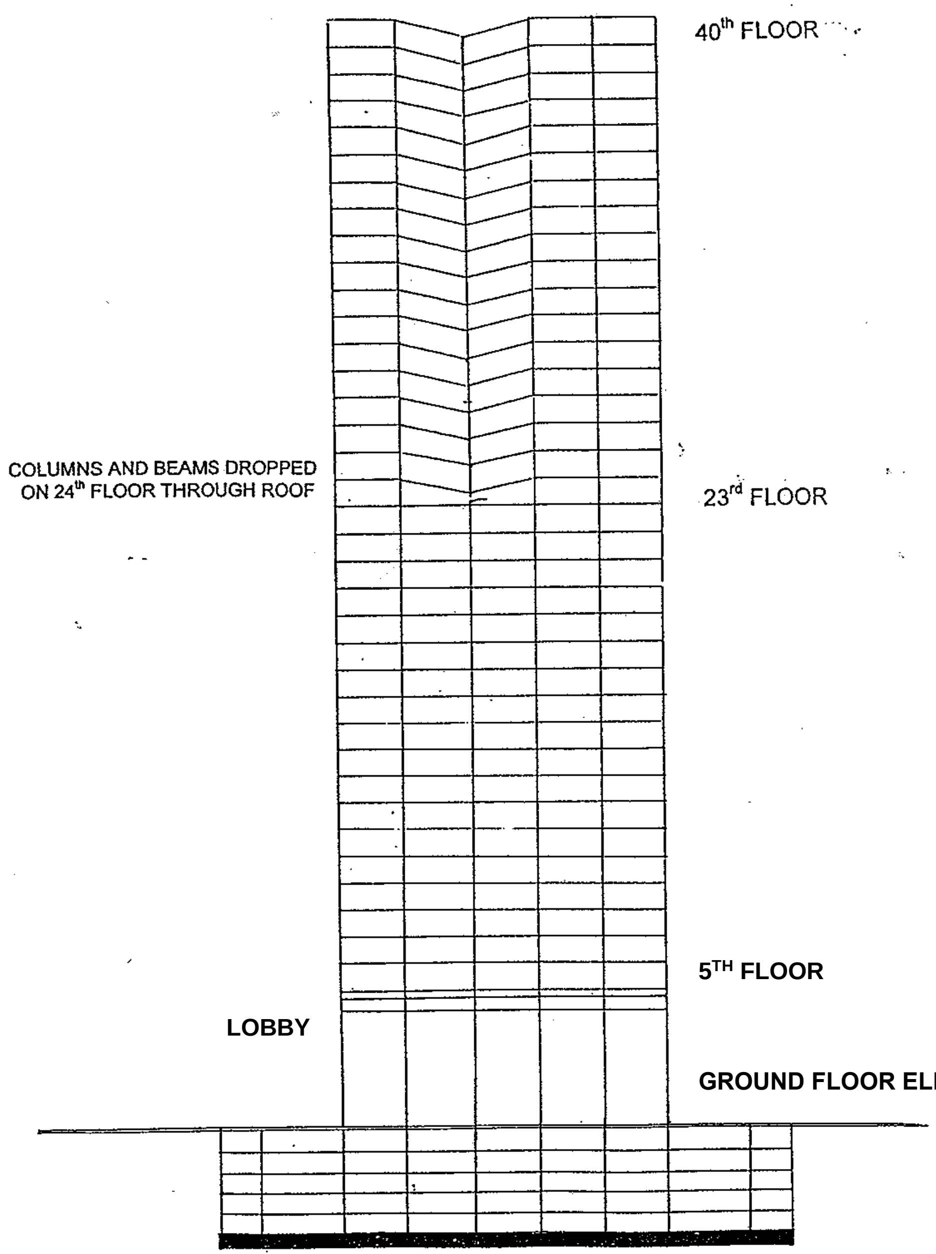


Figure 7 - Condition of Hypothetical Building at Beginning of Exercise. The removal of a column on the 21st floor results in the downward sagging of floors 22 through 40 as indicated. The exact condition of the typical beams will vary somewhat from what is shown here and will be covered by detailed photos.



Each subject read a four-page scenario that was interspersed with several pages of questions, and the exercise was run in real time except for contraction of travel and movement time. Photographs of a three dimensional model of the building were used to exactly illustrate the damage with enlarged photographs showing the damage in detail (See Appendix A for photographs). The buildings columns were 30 feet on center. These relatively long spans resulted in a large damaged area, as the 60 feet of unsupported beams sagged into the void left by the missing column. The beams formed a shallow V on the face of the building with the severed column at the point of the V. The distortion of the frame twisted and broke the windows up the building to the roof and would be visible for miles if not obscured by other tall buildings.

The load previously carried by the severed column was shifted to adjacent columns on either side and seriously increased their loading. The exterior girders, which also served as the horizontal members of the wind frame, were seriously distorted and their loading distribution to the columns would have been difficult to estimate, much less accurately calculate. Welded connections at the columns partially failed in tension and threatened further failure in the 15 to 25 mile per hour wind movement. Due to the partial failure of the wind frame, the movement of the building was exacerbated. There was no routine means of exactly calculating the building's remaining strength or even the capacity of individual floors.

The removal of a small section of column greatly reduced the building's ability to withstand wind loading. The destruction of twenty floors of rigid framing broke the continuity of the structural square tube and substantially lowered the building's ability to withstand high winds. The damage on the west side of the building would cause substantial torsion in any lateral movement of the building.

The exercise documents consisted of the photos of the model (Appendix A), the map of the immediate area where the building is located (Appendix B), the photos of surrounding buildings (Appendix C) and the Engineer's (or Constructor's) Questionnaire (Appendix D). A complete structural plan of the building was provided to the participants, but is not included here. The Constructor's Questionnaire is not included, but was identical to the engineers' except for a few necessary word changes so that the document would apply to construction personnel.

The specific questions asked of participants were in four main areas:

1. Concerns about liability risk to the participant or his/her firm (4 questions). This series of four questions began by asking an opinion about the risk of continuing to occupy the building. The willingness to provide engineering opinions in a life or death situation is used to judge liability concerns at the beginning of the exercise (Table 7). The second question was prefaced by a discussion with the firm's CEO, who is out of town but recommends that the participant discuss the matter with the firm's legal counsel. Then the participant was specifically asked what action he will take on the recommendation (Table 8). The influence of attorneys is commonly suspected to be detrimental to the free flow of professional advice necessary for hazard mitigation. So, a few questions later a third evaluation was made (using the same judgment criteria as Table 9) as to whether the participant was showing concern about the advice he was giving. This can be compared to the liability judgment (Table 10).

   Toward the end of the exercise, after a series of structural risk questions (see #3 below), the participant was informed that his firm's insurer had announced that they would no longer cover his/her professional judgment. The participant was then specifically asked what, if any actions are necessary to continue to give advice (Table 16). This was followed by a single question about the use of government authority to facilitate hazard mitigation. This question asked if the participants would request government transport or escort for an important individual a hundred miles away during traffic congestion. This question explored whether participants understood the additional power that the emergency grants to government authorities. This was an open-ended question and answers were not suggested in the question format.
2. Structural engineering judgments (5 questions). These questions revolved around key safety issues that emergency management personnel would ask. The questions asked for estimates of the wind speed needed to induce structural failure (Table 11), the risk of collapse in 24 hours (Table 12), a safe evacuation radius (Table 13), the possibility of domino failure (Table 14), and an estimate of time required to analyze damage and begin repairs (Table 15). These questions were multiple-choice except the last, which was open-ended.

3. Methods for initiating the event (2 questions). These two multiple choice questions were added for background information concerning the participant's knowledge of steel buildings' vulnerabilities. The first question asked for an estimate of the size of parcel containing the device that inflicted the damage (Table 17). The second question asked the participant to estimate the time it would take to prepare the device and install it in the building (Table 18).

The continental United States averages several windstorms a month with winds exceeding 60 mph and freak gusts occur often in Central Business Districts. Participants were told that a windstorm was expected 48 hours from the initial review of the damage. This information was expected to force decisions and reduce the opportunity for procrastination, as it would in an actual event.

5.3 Statistical Analysis

Because this study is using the majority of engineering and construction experts in the city of Houston, conventional statistical inference techniques are not appropriate. Consequently, differences in means or percentages will be discussed in terms of their theoretical and practical significance. For the geographical location where this study was made, we must recognize, of course, that these differences may change as this small population evolves over time due to retirement and or relocation. If our sample were assumed to be representing a larger population then 30% variation would be a meaningful difference. Due to the majority of the small population being included in the study, the small differences shown in the tables here may be more significant than they would be if this sample were representing a much larger population.

6. RESULTS

The participants first generated a list of emergency assessment actions. This was followed by a list of immediate repair options to mitigate the danger of collapse from a windstorm. In addition, participants were asked to indicate whether the building could be returned to service ("yes" or "no"). From these three self-generated lists, the participants made decisions for implementation of a single strategy for expedient hazard migration.

The participants thus generated four lists with the following totals:

1. A list of 12 immediate emergency assessment and incident management actions.
2. A list of 12 options for hazard operations (expedient hazard mitigation) actions.
3. A list of opinions as to the long-term use of the building "yes-no".
4. A list of eight final strategies defined by the participants' combination of expedient mitigation and long-term disposition of the building after the storm (e.g. brace before the storm and demolition of structure afterward.)

In addition, a series of multiple choice and open-ended questions furnished some insight into the participant's professional opinions on legal, management and structural issues that probably influence the selection of an expedient mitigation strategy.

6.1 Outline of Participants Strategies 1-8 and Order Presented

The participants collectively generated eight expedient hazard mitigation strategies, all of which followed the decision patterns D_1 through D_6 proposed in Figure 4. Those eight strategies are graphically detailed and discussed in Section 6.6.

The decision strategies had two phases. First, there were decisions related to mitigating the *immediate* danger (within 48 hours) of the building collapsing; second, there were decisions as to whether the building could later be repaired and eventually returned to use.

Decisions D_1, D_2 and D_3 related to immediate (48 hour) repair options, D_4 and D_5 related to immediate demolition (48 hour) options, and D_6 related to permanent repair or long-term demolition (dismantling). Some options in D_4 and D_5, such as implosion, would also, of course, be permanent in nature. Otherwise, immediate options were temporary in nature, designed to stabilize the structure until a permanent resolution for the future of the building could be determined at D_6.

The eight ultimate strategies contained only five major variations for immediate mitigation. Those five initial strategies were:

1. Weld or bolt the two segments of the severed column together to carry some of the load and prevent further deterioration. (Options 1 and 2).
2. Reduce the overload on adjacent columns by shoring the floors or bracing the adjacent columns or otherwise transferring loading around the damaged column. (Options 3 and 4).
3. Partial demolition of upper floors to reduce wind resistance at the point of maximum overturning moment by removing exterior glass and interior walls (Option 5).
4. Take no immediate action to protect the building. Participants either believe the building is too dangerous to work on or conversely, that it can survive without action. (Options 5, 6 and 7)
5. Immediate demolition by military or civilian explosive experts (Option 8).

The eight ultimate strategies contained the long-term mitigation options of either systematic demolition or repair and return to service. These long-term decisions would, in turn, impact the immediate mitigation decision.

The remaining variation in the strategies concerned whether or not the building could be permanently repaired. The immediate options 1, 2 and 4 above have multiple proponents who disagreed on the validity of the long-term repairs to save the building. This disagreement resulted in those three options having double results raising the total number of strategies to eight.

The decision flow charts for each of the eight strategies are included in Section 6.5. As discussed above, each strategy consisted of an immediate mitigation option (48 hours) and a permanent strategy. In the case of implosion, the immediate and permanent options were the same.

6.2 Strategies by Profession, Education and Experience

6.2.1 Researching the Effects of Different Expertise: Strategy Results by Profession

The strategies generated in the exercise were remarkably similar across profession. Table 5A below shows initial emergency operation strategies by profession. The long-term options that complete the strategy will be addressed later.

Table 5A – Percentage of Participants by Profession Using Each Expedient Hazard Mitigation Strategy

	Engineers	**Constructors**	**Total**
Initial Strategies 1 & 2 Repair	53%	36%	13
Initial Strategies 3 & 4 Repair	20%	21%	6
Initial Strategies 5 Repair	7%	0%	1
Initial Strategies 6 & 7 No Action	20%	29%	7
Initial Strategy 8 Demolition	0%	14%	2
Total	15	14	29

Strategies 1 through 5 are temporary repair strategies while 6 through 8 are non-repair strategies. The most popular strategy was 1 and 2, which was twice as popular as either 3 and 4 or 6 and 7. Strategies 5 and 8 had very few proponents.

Strategies 1 and 2 included the repair (rejoining) of the severed column. Engineers were generally optimistic about repair and their confidence resulted in a gap between professions in Strategies 1 and 2. The primary differences between professions were on strategies 1, 2, 8 and to a lesser extent, 5.

Strategy 8 was implosion of the building. Only constructors proposed it, possibly because they have a closer working relation to the demolition business. Also, engineers might have been more optimistic about the success of interventions in increasing the building's chances of survival.

Strategy 5 is the removal of glass and walls to allow wind to pass through the building. The only participant to choose this solution was also the most highly educated and most senior executive participant in the exercise. This is a near foolproof way to reduce the overturning moment on the building. Three constructors considered the idea, but did not ultimately use it.

In Strategies 1 through 4, the answers from engineers reflected greater understanding of the overall role played by the wind frame. Whereas constructors were very concerned about the column repair or substitute support, the engineers addressed the overall exterior frame that resists the wind loading. An example of this difference in focus was constructors shoring up the floor while engineers shored the wind beam (which resisted wind loading) at the critical location. The engineer's strategy hopefully not only worked to assist the gravity loading issues, but also the wind loading in the rigid frame. Nonetheless, the constructors often showed an acute concern for the time element and the practicality of construction.

The primary difference between professions was that engineers preferred repairs (80% of answers) more often than constructors (57%). This difference can be attributed to engineering education providing a more complete vision of the remaining strength of the structure and an understanding of the specific repairs necessary to recover strength in the wind frame.

The overall results indicate that constructors and engineers were generally similar in their strategies in that both groups emphasized Strategies 1 – 4 and 6/7 rather than 5 or 8. Nonetheless, they did differ somewhat in their focus on the strategies, with the engineers perhaps underemphasizing practicality of construction and related time issues, while the constructors tended to overlook wind frame issues. Possible implications will be discussed in Section 7.

6.2.2 Strategies by Level of Expertise (Education)

The aggressive approach to repairs held true within the engineering participants as shown in Table 5B where 77% of graduate-level participants favored temporary repair action (Strategies 6/7) and none favored immediate demolition (Strategy 8).

Table 5B – Percentage of Engineers Identifying Each Strategy by Education

	BS	MS/PhD	Total
Repair Initial Strategy 1-5	100%	77%	12
Non-Repair Initial Strategy 6-8	0%	23%	3
Total	2	13	15

Table 5C – Percentage of Constructors Identifying Each Strategy by Education

	HS/AA	BS/MS/PhD	Total
Repair Initial Strategy 1-5	50%	62%	8
Non-Repair Initial Strategy 6-8	50%	38%	6
Total	6	8	14

Among constructor participants, there was a greater uncertainty about the building surviving the storm. That resulted in 43% (29% + 14% Table 5A) of constructors choosing to take no action or to implode the building. Table 5C shows that the less educated were more likely to choose this route. While the percentage is small, it is consistent with the previously discussed concept of education contributing to optimism for repairs.

6.3 Initial Action Options by Participants

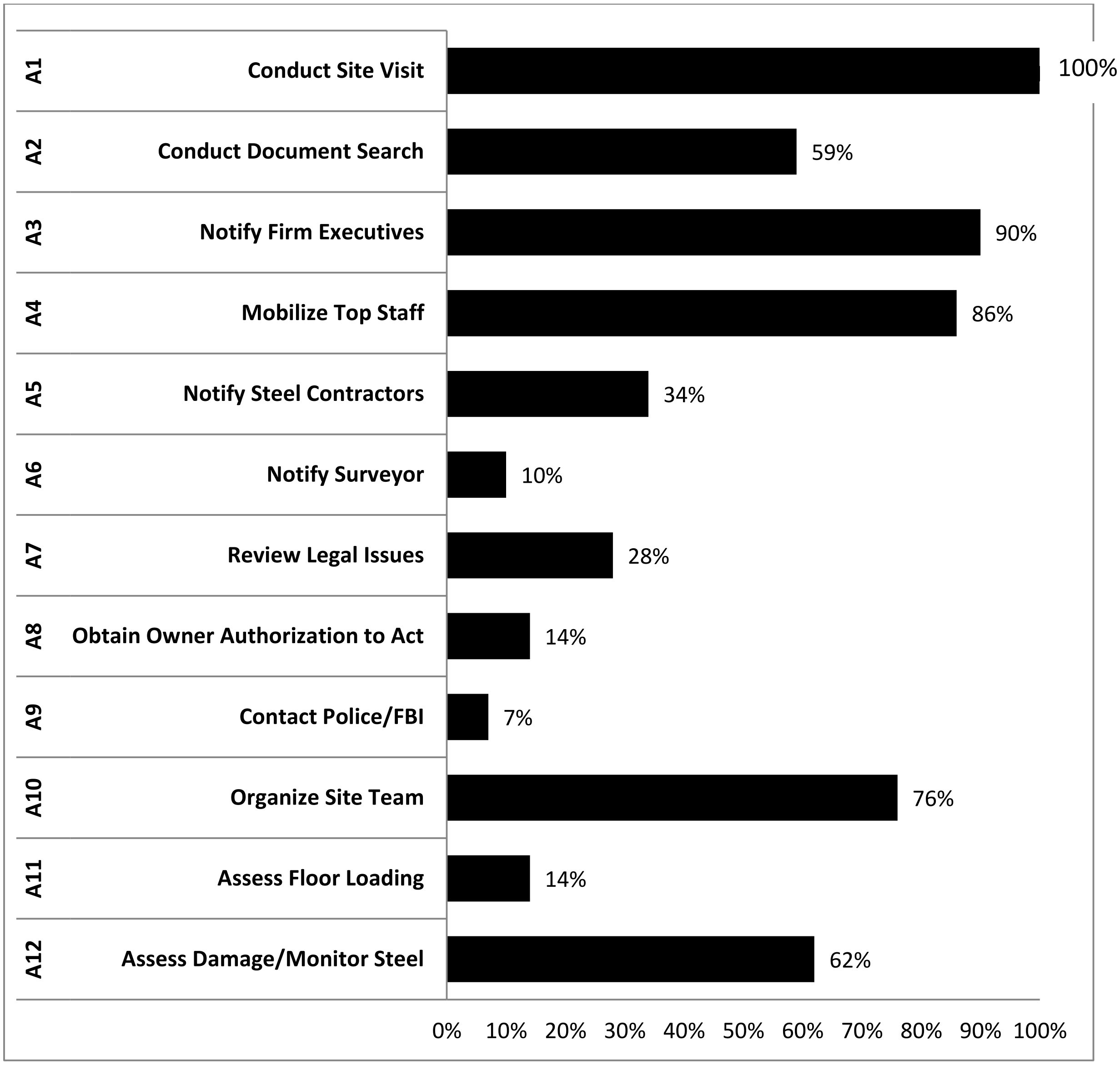
Following the initial event of a building manager calling the participant's office for assistance on a Sunday afternoon, participants responded to three questions. First, how would the participant respond to the manager on the phone; second, what actions would he take after hanging up; and third, what instructions would he give to other members of his firm that could be contacted by phone. The questions were open-ended with no hints for action except the building manager's request to come to the site. This part of the scenario reflects the normal manner for a building manager to request engineering assistance. Answers such as obtaining personal safety gear and calling spouses were deleted.

The remaining answers that were relevant to mitigation were compiled in the following list, which is presented in the general chronological order that the participants listed them. This order was to some extent determined by the sequence of questions, but it is a logical chronology for an actual event. The constructors had a slightly higher mean number of actions (6.28) than did the engineers (5.33).

Figure 8 following the list shows the frequency with which each of the assessments was mentioned. The initial actions for expedient hazard mitigation are as follows:

A1. As indicated in Figure 8, all participants listed a site visit. This action is necessary as soon as possible for several reasons. First, the client has requested support on site. In a crisis there is psychological value to the physical presence of a knowledgeable engineer or constructor. Second, the emergency managers and the building manager are going to have a series of questions, some of which are listed in the next section (Section 6.4). In particular, the critical question is whether the building could collapse suddenly. An expert's presence on site is necessary to evaluate that urgent question. Third, initiating several lines of investigation into the condition of the building can only be done on site. The director of the operation must evaluate where it is safe to send technicians, surveyors, welders, and laborers. Fourth, legal and law enforcement issues are going to develop very quickly as law enforcement and the intelligence community exert investigative control over the site. It must be recognized that that the FBI will try to isolate the area of the most intense damage for crime scene

Figure 8 - Histogram of Emergency Assessment and Incident Management Actions for Expedient Hazard Management: Percentage of Participants Who Identified Each Action
Related Figures and Tables: Table 6



investigation even though this is also the area where the majority of engineers and constructors say they would concentrate their repair efforts.

A2. Most participants (59%) listed a document search for the building's structural plans, specifications, and if possible, the original structural calculations; all of these would help to assess the building's stability. In the exercise, the building manager had a structural set but no calculations were available. This unavailability would be typical in a real event.

A3. An overwhelming majority (90%) of participants listed notification of their company's executives, which is a key step in smoothly taking control of the project. Support personnel should be charged with locating and informing the executives related to this type of project as soon as possible. Executives not only bring broad expertise beyond engineering to the problem, but also can cause disruption to a plan of action if they suddenly inject themselves at a later time.

A4. Most participants (86%) also mentioned assembling top staff, which is necessary to handle the myriad facets of the problem that will arise in a matter of hours. Figure 6 (p. 31) identified the stakeholders in the problem and their interrelationships. Failure to anticipate these relationships from the outset can seriously interrupt a mitigation plan. A separate office team to handle calculations and structural planning and drawings would also be advisable.

A5. Only a minority (34%) mentioned early notification of steel constructors, which was a move to reduce the time required to implement mitigation actions. The constructors could move welders and their bulky equipment into place during the many hours that the engineers and constructors were making decisions D1, D2, and D3. If a radical situation finally rules out repair mitigation, the cost of a few hours of unutilized mobilization is minor. If the planner negotiated the mobilization request correctly, there might be no cost at all if the work was not performed.

A6. Very few participants (10%) listed the immediate notification of a surveyor, but it would have been critical in order to understand the condition of the building. If the building was out of vertical alignment, it could bring the P-Delta lever discussed earlier into being. This effect could result in heavier loading on the critical columns adjacent to the severed column. A surveyor would also be essential in determining the amount of wind movement due to the damage.

A7. A minority (28%) of respondents identified a review of legal issues, which primarily revolved around liability concerns in case of damage, injury or death while the consultant was in charge. Of particular concern was the possibility of further collapse involving workers.

A8. A minority (14%) of participants listed owner authorization, which involved a clear understanding of what is being requested by the owner's representative and insuring he really had the authority to make commitments on the owner's behalf. The initial consulting would almost certainly take place on verbal authority. This was something to be passed to an executive or attorney while the consulting continued.

A9. A small minority (7%) of respondents identified police and FBI contact. This was a concern because of the history of law enforcement agencies demanding and getting control of crime scenes to the detriment of other stakeholders. In this case, the urgency of the emergency repair mitigation would have to be impressed on law enforcement. An excellent argument is that the existing crime scene would vanish if the building collapses.

A10. A substantial majority (76%) of participants listed team organization, which refers to the overall mitigation team consisting of engineers, constructors, owner's representatives, and various specialists such as surveyors. In a time critical incident, this organization would take place in a site meeting in which "roles and goals" are explained to the teams before entering the building to commence work. At this time, the engineers would need to have basic sketches prepared or personally direct the work. Such a meeting might be possible in 12 to 24 hours with efficient organization and even less with preplanning.

A11. A minority (14%) of respondents mentioned determining floor loading. This would evaluate whether falling wreckage has overloaded floors below, thereby risking localized collapses that could endanger workers below or even the stability of the building. If this were determined to be a risk, the debris would have to be reduced or the areas below evacuated. A slightly different version of this action also appears in the list of mitigation options in Section 6.5, mitigation option 9.

A12. A slight majority (62%) listed damage assessment and monitoring steel which refers to an engineering evaluation of the individual points of damage and any creeping expansion of that damage. Expansion of damage by wind movement of the building was of particular concern to participants. Monitoring the steel referred to personally watching or remotely monitoring any cracked beams, the severed column and to detect any further expansion of cracks or deterioration of the situation. A surveyor's findings of building verticality and alignment would also be essential to this report. This report would be the foundation for the selection of hazard mitigation options to form the ultimate strategy such as those shown in Section 6.6.

The initial response action shown in Table 6 was listed by each participant. These 12 actions are believed to be important and unique to the engineering decision maker, thus not duplicated by other stakeholders identified in Figure 6. None of the engineers or constructors identified all of the initial actions that were identified by the group as a whole. Instead, the largest number of initial response actions was nine, which was listed by one of the constructors. The smallest number of initial actions, three, was listed by one engineer and one constructor. On average, the constructors listed slightly more initial actions (6.28) than did the engineers (5.33). Moreover, of the 180 opportunities for mentioning initial actions (12 initial actions x 15 engineers) for the engineering participants, only 80 (44%) were identified. Similarly, of the 168 opportunities (12 x 14) for the 14 construction participants, only 88 (52%) were identified.

The differences between engineers and constructors with respect to the number of initial actions mentioned can also be seen, to a limited extent, in differences between these two groups with respect to three of the initial actions. Using 30 percentage points as an indication of a meaningful difference, Table 6 shows that there were differences between professions for conducting a document search, notifying a steel contractor, and reviewing floor loadings. The engineers showed significantly more concern with locating documents (30% difference), which is reasonable as their work is normally focused on this activity. The constructors, meanwhile, focused on notifying their key subcontractors, the steel contractors (30% difference). The constructors also focused on a key safety issue that they are normally responsible for, the permissible floor loading of their work area (29% difference).

There were a few activities that were associated with education. Document search shows a significant correlation with increased education (which also correlates with the engineers being more highly educated). However, higher education is weakly related to a decreased tendency to notify executives. Finally, with respect to experience, there are no meaningful correlations other than an association of increased experience with a greater likelihood of requesting an immediate damage assessment.

Table 6 - Percentage of Participants Taking Initial Emergency Assessment and Incident Management Actions

		Site Visit	Document Search	Call Executives	Assemble Staff	Call Steel Contractors	Call Surveyor	Review Legal Issues	Owner Authorization	Police/FBI Contact	Site Team	Review Floor Loading	Damage Assessment	Participants
		A1	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**A9**	**A10**	**A11**	**A12**	**N**
PROFESSION	**Engineer**	100%	73%	87%	80%	20%	7%	27%	7%	7%	73%	0%	53%	15
	Contractor	100%	43%	93%	93%	50%	14%	29%	21%	7%	79%	29%	71%	14
	Total													**29**
EDUCATION	**PhD**	100%	100%	67%	100%	67%	0%	33%	33%	0%	100%	0%	67%	3
	MA	100%	73%	91%	82%	18%	9%	18%	0%	0%	73%	9%	55%	11
	BS	100%	44%	89%	78%	33%	11%	44%	22%	11%	67%	22%	67%	9
	HS/AA	100%	33%	100%	100%	50%	17%	17%	17%	17%	83%	17%	67%	6
	Total													**29**
EXPERIENCE	**1-10**	100%	63%	88%	75%	13%	0%	25%	13%	0%	75%	13%	38%	8
	11-20	100%	63%	100%	100%	38%	25%	25%	0%	13%	88%	13%	50%	8
	21-30	100%	50%	75%	100%	50%	0%	25%	38%	13%	75%	13%	50%	8
	31+	100%	60%	100%	60%	40%	20%	40%	0%	0%	60%	20%	100%	5
	Total													**29**

Related Figures and Tables: Figure 8

6.4 Responses to Specific Questions

Tables 7-18 are numbered in the chronological order in which questions occurred in the exercise. By observing the numbers of the tables, the reader can sense each question's context. For instance, the liability question asked in Table 16 was preceded by a series of high-risk structural questions (Tables 11–15) that could clearly lead to loss of life if the participant made an error in his/her judgment.

Table 7 shows how participants say they would respond to concerns about personal and firm liability when advising the owner or authorities on risk issues. All of the engineers and all but one of the constructors show no concern about liability. The difference between engineers and constructors is not meaningful.

Table 7 - Participants Initial Liability Concern

	No Concern or Delay	Delay in High-Risk Decisions	Delays Until Release Promised	Delays Until Released Signed	All Decisions Deferred to Others	Total
Engineers	100% (5)	0%	0%	0%	0%	15(5)
Constructors	92.9%(3)	7.1%	0%	0%	0%	14(3)
Total	96.5%(8)	3.5%	0%	0%	0%	20(8)

( ) Number of Executives/Managers
Related Figures and Tables: Tables 8 and 10

Table 8 reflects the participant's reaction to a suggestion to seek legal advice concerning both their firm's and their own liability risk in trying to assist the building owner. This question was designed to provide a follow-up probe to the question about liability concerns described in Table 7. As Table 8 indicates, only a minority of either group refused to call a lawyer, but only one respondent would follow a lawyer's direction or defer to a lawyer or the CEO. Instead, a majority of constructors and a substantial majority of engineers would give direction to a lawyer. Differences between engineers and constructors are minor.

Table 8 - Participants Reaction to Suggestion to Talk to Lawyer

	Does Not Call Lawyer	Delays Calling Lawyer	Gives Lawyer Direction	Follows Lawyer's Direction	Defers to CEO or Lawyer	Total
Engineers	20%(2)	6.7%(1)	73%(2)	0%	0%	15(5)
Constructors	28.6%(1)	7.1%(1)	57.1%	7.1%(1)	0%	14(3)
Total	24.1%(3)	6.9%(2)	65.5%(2)	3.4%(1)	0%	29(8)

( ) Number of Executives/Managers
Related Figures & Tables: Tables 7, 8 and 10

Table 9 explores the awareness and willingness of the participants to request assistance from government authority to resolve specific problems. In general, the participants expressed little need for government assistance of any kind. Although the constructors were about 30 percentage points more likely to request some kind of assistance, there was no consistently significant pattern for a single type of action.

Table 9 - Participants Willingness to Invoke Government Authority

	No Requests	Police Escort	Air Transport	Military Assistance	Mixed Requests(1)	Total
Engineers	86.7%(5)	13.3%	0%	0%	0%	15(5)
Constructors	57.1%(3)	7.1%	21.4%	7.1%	7.1%	14(3)
Total	72.4%(8)	10.3%	10.3%	3.4%	3.4%	29(8)

( ) Number of Executives/Managers
(1) "Mixed requests" refer to at least two of the previous categories.

Related Figures & Tables: None

Table 10 categorizes participants' responses to the executive's recommendation that they seek a lawyer's advice. None of the engineers expressed any concern about how this recommendation would affect their actions. Three of the constructors would limit their advice to some extent, but the rest were as unconcerned as the engineers.

Table 10 - Participants Legal Concern after Executive Recommends Lawyer

	No Concern or Delay	Delay in High-Risk Decisions	Delays Until Release Promised	Delays Until Released Signed	All Decisions Deferred to Others	Total
Engineers	100%$^{(5)}$	0%	0%	0%	0%	15$^{(5)}$
Constructors	78.6%$^{(3)}$	21.4%	0%	0%	0%	14$^{(3)}$
Total	89.7%$^{(8)}$	10.3%	0%	0%	0%	29$^{(8)}$

$^{( )}$ Number of Executives/Managers
Related Figures & Tables: Tables 7 and 8 are the antecedent of this question

Table 11 shows participants' responses to a question asking them to estimate the wind speed at which the building would experience total failure in its weakened condition. The answers covered the full range of the alternatives from 40 to 80 mph. Some of this range of answers is attributable to participants' varying opinions about the progressive nature of cracking of welds in the wind girder connected to the damaged column as the building moved in the wind. Several engineers indicated that there was no precedent for rapidly analyzing the problem, but proposed procedures to estimate the building's strength and, thus provided higher estimates of the wind speed required to induce structural failure. The exercise postulated a 60 mph windstorm predicted in 48 hours.

The engineers' mean estimate of the wind speed needed to induce failure was 51.3 mph and their median judgment was < 40 mph. The constructors' mean judgment was 46.4 mph and their median judgment was <40 mph. These averages are both well below the predicted wind storm speed (60 mph). The majority of participants (80% of engineers and 93% of constructors) estimated structural failure at < 60 mph. There were no meaningful differences between the engineers and constructors. The slightly greater confidence by engineers in the structures is consistent with Table 5A where constructors were quicker to give up on repairs.

Table 11 - Participants' Estimates of the Wind Speed Required to Induce Structural Failure

	<40	50	60	70	>80	Total
Engineers	53.3%(2)	13.3%	13.3%(1)	6.7%(1)	13.3%(1)	15(5)
Constructors	64.3%(2)	21.4%	7.1%	0%	7.1%(1)	14(3)
Total	58.6%(4)	17.2%	10.3%(1)	3.4%(1)	10.3%(2)	29(8)

( ) Number of Executives/Managers
Related Figures and Tables: Table 12

Table 12 shows that participants' estimates of the risk of collapse within 24 hours provided a wide range of answers. In both groups, the most common estimate was 25%, but, on average, engineers made somewhat lower estimates of the chance of collapse with a mean of 22% compared to the 30.4% for constructors. These data are consistent with Table 11 indicating engineers have greater faith in the integrity of the structure. Only 65% of constructors place 24-hour structural failure at 25% or less, while 87% of engineers do. In the same vein, twice as many engineers as constructors (4 vs. 2) believe the chance of collapse to be 0%.

An interesting aside is that no participants believed the chance of collapse to exceed 50% even though the site was experiencing low winds at the time of the analysis. This would suggest that no participant believes the building will collapse without major additional stress being induced.

Table 12 - Participants' Estimates of the Risk of Collapse within 24 Hours

	0%	25%	50%	75%	100%	Total
Engineers	26.7%(3)	60%(2)	13.3%	0%	0%	15(5)
Constructors	14.3%(1)	50%(2)	35.7%	0%	0%	14(3)
Total	20.7%(4)	55.2%(4)	24.1%	0%	0%	29(8)

( ) Number of Executives/Managers
Related Figures & Tables: Tables 13 and 14

Table 13 lists responses from a question asking for a recommended protective action distance. Engineers recommended evacuating an average radius of 2.3 blocks (21.6 square blocks) with a standard deviation of 1.2, whereas constructors recommended an average of 3.4 blocks (46.2 square blocks) with a higher standard deviation of 1.7. Thus, constructors would evacuate more than twice the area, implying a doubling of the cost of the evacuation. Again, these results are consistent with a greater optimism on the part of engineers as to the building's stability and somewhat less concern about a domino failure.

Table 13 - Participants' Estimates of Safe Evacuation Radius

	1 Block	2 Blocks	3 Blocks	4 Blocks	5 + Blocks	Total
Engineers	33.3%(3)	26.7%	26.7%(1)	6.7%	6.7%(1)	15(5)
Constructors	14.3%(1)	21.4%(1)	14.3%	7.1%	42.9%(1)	14(3)
Total	24.1%(4)	24.1%(1)	20.7%(1)	6.9%	24.1%(2)	29(8)

( ) Number of Executives/Managers
Related Figures & Tables: Tables 12 and 14

Table 14 lists participants' estimates for the risk of the building toppling and impacting adjacent buildings in such a manner that they also collapse (domino failure). Only a small minority (17.2%) of participants rejected the possibility of a domino failure, but the estimates covered the entire range of probabilities all the way up to 100%. Nonetheless, the most common response for both groups was 25%, indicating that domino failure was believed possible, but not likely. Although engineers were again more optimistic as a group, the differences between groups were consistent, but not significant.

Table 14 - Participants' Estimates of the Possibility of Domino Failure

	0%	25%	50%	75%	100%	Total
Engineers	20%$^{(3)}$	53.3%$^{(2)}$	20%	6.7%	0%	15$^{(5)}$
Constructors	14.3%$^{(1)}$	50%$^{(2)}$	7.1%	14.3%	14.3%	14$^{(3)}$
Total	17.2%$^{(4)}$	51.7%$^{(4)}$	13.8%	10.3%	6.9%	29$^{(8)}$

$^{(\ )}$ Number of Executives/Managers
Related Figures & Tables: Tables 12 and 13

Table 15 shows participant's responses to a question as to the number of days required for a "proper" analysis before temporary repairs. While there is no significant variation between professions, the answers cover the entire range of the options provided. For both groups, the most common response is one day (the low end of the scale), but the next most common response is five or more days (the high end of the scale).

This extreme variation in the estimate of time analysis within the groups partly resulted from different concepts of an emergency work day (8 or 24 hours?), the extent of shortcuts that can be taken in an emergency (verbal instructions as opposed to fully designed drawings), the rapidity of cost approvals in an emergency (minutes as opposed to days), and the time savings that multiple teams can accomplish. Some participants seemed to grasp these accelerated procedures more quickly than others.

Table 15 - Participant's Estimate of Time Required to Analyze Damage and Begin Repairs

	1 Day	2 Days	3 Days	4 Days	5 + Days	Total
Engineers	40%(2)	13.3%(2)	13.3%	0%	33.3%(1)	15(5)
Constructors	50%(3)	7.1%	14.3%(1)	0%	28.6%	14(3)
Total	44.8%(5)	10.3%(2)	13.8%(1)	0%	31%(1)	29(8)

( ) Number of Executives/Managers
Related Figures & Tables: None

Table 16 lists participant's opinions as to the degree of interruption that would be caused if the participant's employer was notified that their liability policy did not cover emergency consulting. This table implies a greatly increased level of concern for liability as compared to Tables 7, 8 and 10.

The key issue that this table introduces is the possibility that the repair effort will be shut down for a lack of professional advice if professional liability insurance is withdrawn. Almost all (93%) of the engineers and 79% of constructors effectively stopped advising until a liability release was at least promised. Only one engineer indicated he would continue as a sense of public duty with some concern indicated. Three constructors took a similar stance.

Table 16 - Risk of Delay Caused by Liability Issues

	No Concern or Delay	Delay in High Risk Decisions	Delays Until Release Promised	Delays Until Release Signed	All Decisions Deferred to Others	Total
Engineers	0%	6.7%(1)	6.7%	46.7%(3)	40%(1)	15(5)
Constructors	21.4%	0%	14.3%(1)	28.6%(2)	35.7%	14(3)
Total	10.3%	3.4% (1)	10.3%(1)	37.9%(5)	37.9%(1)	29(8)

( ) Number of Executives/Managers
Related Figures & Tables: Tables 7, 8 and 10

Table 17 explored the participant's understanding of the size of the device that could have produced this magnitude of impact on a steel framed building. The responses ranged from the size of a purse to the size of a small suitcase with the engineers consistently providing larger estimates of the device's size. The most common engineer's was a small briefcase while constructors' was a purse.

Table 17 - Size of Device for Action

	Purse	Small Briefcase	Large Briefcase	Small Suitcase	Large Suitcase	Total
Engineers	20%(2)	46.7%(1)	20%	13.3%(2)	0%	15(5)
Constructors	64.3%(3)	28.6%	7.1%	0%	0%	14(3)
Total	41.4%(5)	37.9%(1)	13.8%	6.9%(2)	0%	29(8)

( ) Number of Executives/Managers
Related Figures & Tables: Table 18

Table 18 related to the participant's understanding of the time necessary for a trained technician to prepare a structural member for demolition. Most participants (76%) predicted the time to be an hour or less. As was the case in Table 17, the engineer's estimate of time required (the most common response was one hour), was significantly more than the constructors (the most common was one half-hour). However, there was significant dissension among the participants with estimates varying by a factor of four from ½ hour to 2 hours and one engineer estimating 8 hours of preparation time.

Table 18 - Time Required to Prepare for Action

	½ Hour	1 Hour	2 Hours	4 Hours	8 Hours	Total
Engineers	26.7%(1)	46.7%(2)	20%(1)	0%	6.7%(1)	15(5)
Constructors	57.1%(2)	21.4%(1)	21.4%	0%	0%	14(3)
Total	41.4%(3)	34.5%(3)	20.7%(1)	0%	3.4%(1)	29(8)

( ) Number of Executives/Managers
Related Figures & Tables: Table 17

6.5 Hazard Mitigation Options by Participants

The second category of information furnished by the participants is a list of mitigation options for emergency operations. These are the engineering strategies that the participants themselves developed while working the exercise. These solutions were developed independently by each subject. No repair options were either implicitly or explicitly suggested during the exercise. The results show that none of the solutions were outside the normative model diagram although several fell under "other solutions", "partial demolition", or "no action." If we look at the first five options, engineers only identified 51% and constructors only 40%. The remaining seven options had even lower percentages.

Options 1 through 5 were the primary solutions for saving the building that were generally identified. The other solutions may or may not be practical and effective. Option 11 was both practical and effective, but does not save the building.

The results not only include the options discussed in Section 6.1, but also other alternatives that participants chose not to use for various reasons. Participants discarded some strategies because they would take too much time to implement and discarded others because they were simply less effective solutions to the problem. There could also be cases where the discarded strategy was not fully thought out and thus, its suitability was underestimated.

6.5.1 An Engineering Description of the Participant List

Figure 9 shows the frequency with which each of the mitigation options was mentioned. The initial actions for expedient mitigation for hazard operations are as follows:

O1. Reconnect the two severed sections of the damaged column to reduce further movement in the wind and transfer any additional load from the upper floors back into the column line. Welding was the most popular approach, with 59% of the participants mentioning it.

O2. Brace the frame to regain the lost stiffness in the external wind frame. This is a separate problem from gravity loading and could be accomplished by cabling or welding or bolting braces. This is the third most popular response with 48% of the participants mentioning it. As Table 19 indicates, engineers were much more likely than constructors to mention this option.

Figure 9 - Histogram of Options for Expedient Hazard Mitigation. This graph shows the percentage of both engineers and constructors who suggested each option. The first five options are more conventional and relatively straight forward in execution. The last seven are more unusual and may be difficult to execute.
Related Graphs and Tables: Table 2

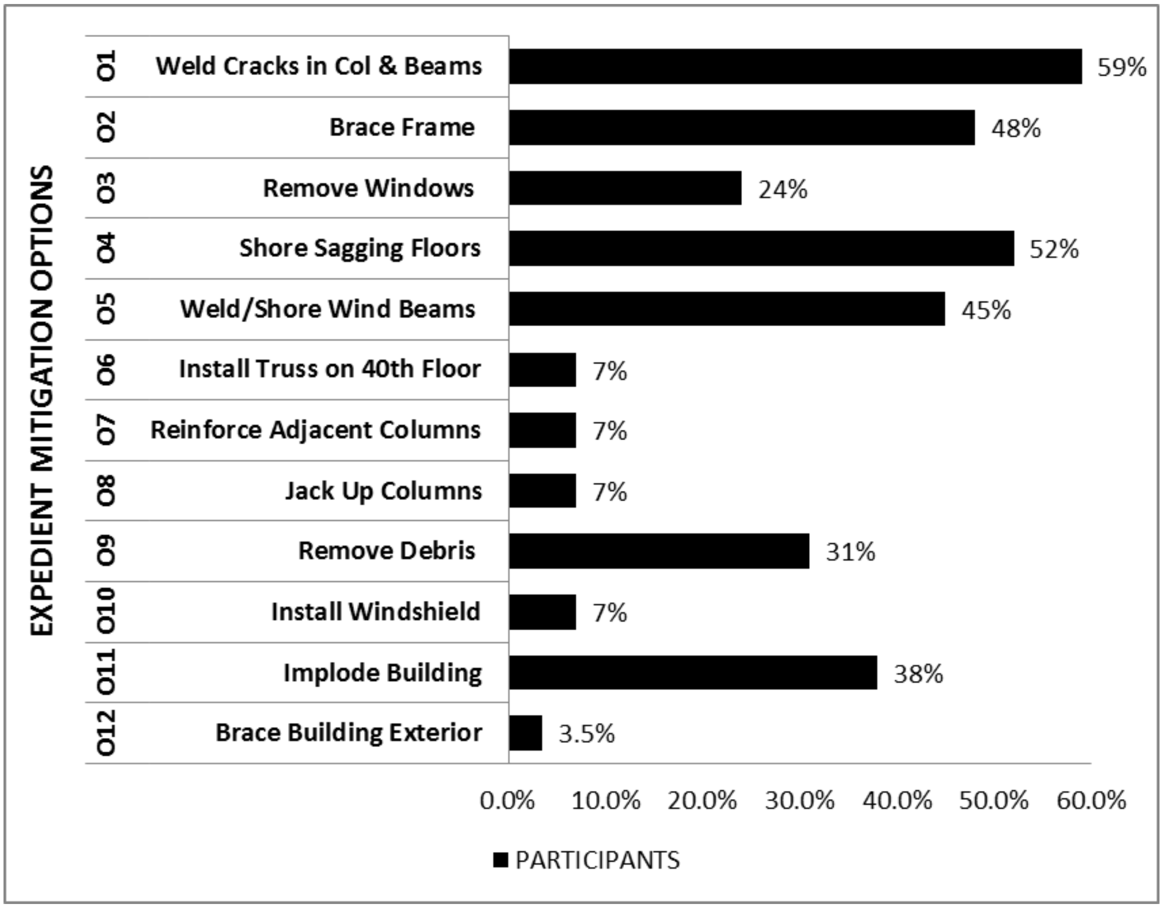


Table 19 - Percentage of Participants Identifying Options for Expedient Hazard Mitigation

		Col/Bm Crack Welding	Brace Frame	Remove Windows	Shoring	Weld/Shore Wind Beams	Truss on 40	Beef Adjacent Columns	Jack Up Columns	Remove Debris	Windshield	Implosion	Exterior Brace	Participants
		O1	**O2**	**O3**	**O4**	**O5**	**O6**	**O7**	**O8**	**O9**	**O10**	**O11**	**O12**	**N**
PROFESSION	**Engineer**	60%	66%	20%	53%	53%	13%	7%	13%	20%	13%	27%	7%	15
	Contractor	57%	29%	29%	50%	36%	0%	7%	0%	43%	0%	50%	0%	14
	Total	**59%**	**48%**	**24%**	**52%**	**45%**	**7%**	**7%**	**7%**	**31%**	**7%**	**38%**	**3.5%**	**29**
EDUCATION	**PhD**	66%	66%	33%	33%	33%	0%	0%	0%	66%	0%	33%	0%	3
	MA	55%	82%	18%	46%	55%	18%	9%	9%	9%	18%	27%	9%	11
	BS	67%	22%	33%	56%	67%	0%	11%	11%	44%	0%	44%	0%	9
	AA/HS	50%	17%	17%	50%	0%	0%	0%	0%	33%	0%	50%	0%	6
	Total	**59%**	**48%**	**24%**	**52%**	**45%**	**7%**	**7%**	**7%**	**31%**	**7%**	**38%**	**3.5%**	**29**
EXPERIENCE	**1-10**	50%	63%	13%	38%	38%	13%	25%	0%	13%	13%	50%	0%	8
	11-20	88%	63%	38%	63%	50%	13%	0%	13%	38%	0%	38%	13%	8
	21-30	50%	25%	25%	50%	50%	0%	0%	0%	38%	13%	50%	0%	8
	31+	40%	40%	20%	60%	40%	0%	0%	0%	25%	0%	0%	0%	5
	Total	**59%**	**48%**	**24%**	**52%**	**45%**	**7%**	**7%**	**7%**	**31%**	**7%**	**38%**	**3.5%**	**29**

This table shows the relationship of experts by education and experience to the identification of repair options open to them at D3 and D5. The percent of participants listing each option are shown. The first five options make up the majority that participants mention and form the core of eventual strategy solutions. There appears to be a tendency for the individuals with the greatest education and experience to less frequently identify Options 6 – 12. In addition, the table indicates that greater expertise in education and experience leads to the more frequent use of Options 1 – 5 and Option 9. These options represent more conventional approaches to the problem. It is also indicated that the radical solution of implosion is inversely related to education and experience. Also, of the six unusual or radical solutions (O6, O7, O8, O10, O11, and O12) only one individual of the most highly educated and experienced groups, subscribed to any of these solutions. This represents a subscription rate of less than 2% among the top experts. (O9 is not considered to be a radical alternative and was widely subscribed to.)

Related Figures and Tables: Table 4

O3. Remove windows as a partial demolition option which would also require removal of interior walls so that air could move through the building and reduce the wind resistance related to the overturning moment of the building. This option was suggested by 24% of participants, but only carried through as a final option by one engineer.

O4. Shore floors is primarily a strategy for transferring gravity loading around the damaged column. Temporary columns are installed down through the building surrounding the location of the damage. This option could either apply directly to shoring of floors or to the shoring of the beams carrying the floors. This option was the second most popular and was suggested by 52% of participants and was implemented by several as their primary option.

O5. Weld and shore wind beams to restore the integrity of the disrupted rigid wind frame on the exterior of the building. This was the fourth most frequently suggested option, with 45% of participants mentioning it. Several use it in combination with options 1 and 2.

O6. Truss the 40th floor to achieve two objectives; first, it could help restore some of the integrity to the rigid wind frame. Second, it could possibly transfer loading from the damaged column line beyond the adjacent columns to outside columns that are not overstressed. The truss would almost certainly have to be airlifted by a heavy lift helicopter and placement would require exquisite skill sets. This option was only mentioned by two participants (7%) and was not used in either of their final choices.

O7. Reinforce the adjacent columns to carry the load safely around the damaged column through the adjacent columns. This would require reinforcing columns many floors below the level of the damage, possibly all the way to the foundation. This option was mentioned by one engineer and one constructor (7%), but neither one listed it as a primary option.

O8. Jack up the dropped column to reestablish the status-quo. Even if the sunken floors could only be raised a few inches, jacking would perhaps put some of the gravity load back on the proper column line. It would appear to be a logical partnering strategy with #5 above, which attempts to re-establish the status quo of the wind frame. Implementation could be very hazardous, as applying force could cause a shift in the damaged frame. This option was mentioned by two engineers (7%), but neither advanced it as a strategy.

O9. Remove debris on damaged floors to reduce the weight on or below the overloaded adjacent columns and reduce the loading on the severed column being carried by the exterior beams. Working on the damaged floors could be extremely dangerous. Thirty one percent of participants suggested this option, 20% of engineers and 43% of constructors.

O10. Establish a windshield around the damaged building to reduce wind load. However, this appears to be very difficult. Wind tunnel tests on building models definitely show that adjacent wind blocks do reduce wind loading on structures and that the temporary shape of a structure can affect the actual wind loading. This, however, is a theory, not a proven design. How such principles could be implemented was not explained by the two engineers that discussed it and neither used this concept in his ultimate strategy. Seven percent of the participants discussed this idea.

O11. Implode or demolish with explosion in one of two ways. One is the civilian demolition business which is extremely precise, but normally requires weeks to design and install for a high-rise building. Second is military demolition which normally uses far fewer charges, but can be installed in hours, if not minutes. The military application would probably be accurate enough if there were adequate planning prior to the event. The key issue, of course, is to bring the building straight down and not imperil adjacent structures. Immediate implosion is the fifth (38%), most mentioned option.

O12. Brace the exterior with cables to prevent the structure from moving in the wind. This is routinely done with very tall aerial antennae in rural locations. Studies done for buildings in urban locations have been hampered by the lack of space and the unfortunate aesthetics that result. However, in an emergency with government authority, a temporary bracing assistance from heavy cables might have some value. The primary issues appear to be highly concentrated forces at the connection points on the building and the technical aspects of placing ground anchors. Prefabricated assemblies might be an answer. Only one engineer toyed with this idea and he did not address serious issues in the concept. It should be noted that the previous attempt to stabilize an oscillating structure with cables was the Tacoma Narrows Bridge in 1940. The 1½ inch diameter cables added to that structure "snapped like threads" in a relatively mild wind on two different occasions before final collapse.

6.5.2 A View of Engineering Options from the Perspective of Decision-Making

A key point of the study is that participants must move from traditional engineering procedure into the realm of dynamic decision-making. The basic premise of engineering, that all decisions rest on previously calculated conditions that are in turn supported by precise engineering laboratory studies, was largely abandoned for decision-making heuristics.

The Decision Flow-Chart for Expedient Hazard Mitigation (Figure 4, page 19) is essentially a sequential model based on normal engineering practice. This, however, is overlaid with the heuristics introduced by the lack of time in an emergency. This overlay reflects the action of the environment on the decision results in a manner that is normally not found in engineering design and decisions. It can be argued that a primary result of this study is to identify the heuristics introduced by the lack of time and eventually to provide a heuristic base for decisions concerning various types of damage to buildings so that weeks of computation (or discussion/augmentation) will not be necessary.

Yang and Hwang, in their reappraisal of engineering decisions, have pointed out that theories and models for explaining human decision behavior is focused mainly on cognition of reasoning not of the broader perspective of decision-making. This has resulted in previous models being deficient in accounting for the dynamic nature of decision-making. A decision-making task is usually accompanied by one or more decision processes, each of which may include many decision stages and the dominant mental activity carried out in each decision stage is reasoning. They note that decision processes fall into two main categories, static decision processes and dynamic decision processes. Static decision process means that no interaction exists between the decision-maker and their external environment. That is the decision outcome will not change the state of the external environment. They define dynamic decision-making as meaning that interaction does exist between the decision-maker and external environment. The decision outcome can change the state of the external environment and this can make a decision outcome deviate from the optimum condition. The decision-making involved with repair of a damaged high-rise building clearly falls into the area of dynamic decision-making. That is, the changes to the building made by the participant will affect the external environment of future decisions.

In this study, a lack of time (and non-existent formulas) resulted in the reduction of engineering theory into two key heuristic judgments, (1) evaluating a loss of lateral bracing and (2) evaluating the loss of columns supporting gravity loads. The difficulty of applying values to these cue types leads to the wide variation in answers that we observe. Many participants only identified one of the two cue types for decision-making and almost all of them indicated difficulty in assessing values to the cues for decision-making purposes. This study is of value in evaluating the processes that the participants go through when they clearly do not have time to develop engineering calculations. Indeed, it can be argued that the concepts of gravity support and lateral bracing, as well as demolition simply become rough approximations for the formulaic assessments that the engineering profession is supposedly based upon. The decision-making process in some cases hints at a process called attribute substitution in which difficult-to-evaluate cue types are replaced by cue types with more easily evaluated data. An example is a participant who declared the building beyond permanent repair for financial reasons and thus, circumvented the repair decisions with an immediate call for implosion. This is a questionable decision shortcut considering that less than 15% of the building is damaged and immediate implosion will certainly deal major economic damage to the building's occupant firms.

6.6 Review of Participants Strategies 1-8

During the exercise, the participants identified a total of 12 options for mitigation of the damaged structural building frame. From his/her list of mitigation options (or no action), each participant was asked to select a single option as an action decision. Coupled with this commitment was an assessment (yes/no) as to whether the building was permanently repairable. The long-term repair assessment was important to understand the short-term mitigation option that was recommended. This dual short-term/long-term decision is defined as the participant's strategy, where "no action" is also a strategy.

Eight strategies (plus the unstated option of no action) were reviewed and organized according to their effects on the building's structural system. These strategies were to:

1. Brace the structure – repair after storm.
2. Brace the structure – demolish after storm.
3. Shore the gravity loads – repair after storm.
4. Shore the gravity loads – demolish after storm.
5. Reduce lateral wind force – repair after storm.
6. Implode the building immediately (demolish).
7. Take no action – repair after storm.
8. Take no action – demolish after storm.

These eight solutions represent the final strategies of the 29 participants. The participant's belief as to the ultimate repair of the building may logically impact the decision for temporary repairs or even dictate implosion or a lack of action.

Table 20 - Properties of Various Strategies

Strategy	Immediate Response	Permanent Repair	Lateral Bracing	Gravity Support
1. Cable, Bolt, Weld – Brace Building then Repair	Yes	Yes	Yes	Limited
2. Cable, Bolt, Weld – Brace Building then Demolish	Yes	No	Yes	Limited
3. Gravity Shoring then Repair	Yes	Yes	Limited	Yes
4. Gravity Shoring then Demolish	Yes	No	Limited	Yes
5. Remove Window Walls then Repair	Yes	Yes	Reduces Lateral Load	No
6. Implosion	Yes	No	N/A	N/A
7. No Action then Repair	No	Yes	No	No
8. No Action then Demolish	No	No	No	No

The relations of the (short-term) mitigation options to ultimate strategies are shown in Table 21. There is one additional strategy that is represented by mitigation option 9, the removal of debris. This option is a special case of the strategy of reducing gravity loading. However, no participant selected this as his action decision. The following pages show two tables (21 and 22) discussing the eight strategies and track them on the Proposed Decision Flow Chart.

Table 21 - Relation of Expedient Mitigation Options to Final Strategies

Expedient Mitigation Options Developed by Participants	**Number Identity of Final Strategy Incorporating Option**	
	Strategies for Permanent Repair	**Strategies for Demolition**
O1. Weld cracks/gaps in columns and beams	S1	S2
O2. Brace frame	S1	S2
O3. Remove windows	S5	Not used (S9*)
O4. Shore sagging floors	S3	S4
O5. Weld/shore wind beams	S1	S2
O6. Install truss on floor 40	Not used (S1)	Not used (S2)
O7. Reinforce adjacent column	S1	Not used (S2)
O8. Jack up columns	Not used (S1)	Not used (S2)
O9. Remove debris	Not used (S10*)	Not used (S11*)
O10. Install windshield	Not used (S5)	Not used (S9*)
O11. Implode building	N/A	S8
O12. Brace building exterior	Not used (S1)	Not used (S2)
(No repair action)	S6	S7

*S9-S11 are labels for strategies that are theoretically possible, but were not used by any participants.

Related Figures and Tables: Figure 9 and Tables 19 and 20

Table 22 - Strategies by Profession, Education, and Experience

	Cable-Bolt-Weld -- Perm Repairs	Cable-Bolt-Weld -- Will Demolish	Misc Temp Repairs & Perm Repairs	Shoring-Column Bracing -- Will Demolish	Remove Windows & Walls -- Will Demolish	No Action -- Can Be Repaired	No Action -- With Demolition	Immediate Implosion	Participants
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**Subtotal**
Engineer	6 (2)	2	3	0	1 (1)	3 (2)	0	0	15 (5)
Contractor	5 (1)	0	2	1 (1)	0	3 (1)	1	2	14 (3)
Subtotal	**11 (3)**	**2**	**5**	**1 (1)**	**1 (1)**	**6 (3)**	**1**	**2**	**29 (8)**
PhD	1	1	0	0	1 (1)	0	0	0	3 (1)
MA	5 (2)	1	2	0	0	3 (2)	0	0	11 (4)
BS	4 (1)	0	1	1 (1)	0	2 (1)	0	1	9 (3)
AA	1	0	2	0	0	1	1	1	6
Subtotal	**11 (3)**	**2**	**5**	**1 (1)**	**1 (1)**	**6 (3)**	**1**	**2**	**29 (8)**
1-10	2	2	1	0	0	2	0	1	8
11-20	3 (1)	0	2	0	0	2 (1)	0	0	7 (2)
21-30	3 (1)	0	1	1 (1)	0	1 (1)	1	0	7 (3)
31+	3 (1)	0	1	0	1 (1)	1 (1)	0	1	7 (3)
Subtotal	**11 (3)**	**2**	**5**	**1 (1)**	**1 (1)**	**6 (3)**	**1**	**2**	**29 (8)**

Related Tables: Tables 20 and 21

This table lists the eight strategies and the frequency they were chosen by participants based on profession, education, and experience. The superscripts represent the subset of managers or executives in each entry. For instance, there are 2 managers/executives among the 6 individuals listed under S1 - Engineer.

The first four S1 through S4 are immediate repair options requiring highly skilled workers. The last four, S5 through S8 are no action or demolition options, generally requiring less skill except for S8 which would require military skills.

There are no significant differences by profession, education or experience.

Strategy 1: *Brace the Frame – Permanent Repair* Engineers: 6/15, Constructors: 5/14

As indicated in Figure 10, these participants answered, "yes" to Decision #1 in Section 5, "Would you initiate work to increase the building's ability to survive anticipate storm winds of 60 mph expected in 48 hours?" The participants also answered "yes" to Decision #4 in Section 5, "Assuming that the building survives the coming storm, do you believe the building can be permanently repaired?" Participants proposing this strategy advocated taking key actions to analyze the situation in D1 and D2 and would direct constructors to implement various expedient mitigation options in D3 using cabling, bolting or welding connections to (1) brace the building or (2) reinforce or reconnect damaged structural members or both.

Discussion of Strategy: This strategy incorporates expedient hazard mitigation options that are solutions to two separate issues. First, maintaining the overall stability of the undamaged portion of the building involves increasing the wind bracing to replace the rigidity lost in the damaged area. Second, repairs to severed and failing structural members in the damaged area can assist in preventing progressive column failure that would further compromise the overall structure. The participants who chose this approach were equally likely to be an engineer or a constructor and represented a cross section of experience and education (see Table 22). In all 11 specific questions (See Section 6.4), there do not appear to be any distinctive characteristics common to this group of participants that separates them from their peers. In identification of Key Actions for Emergency Response, the engineers in this group, again appeared to fall close to the values of their peers. However, the constructors in this group consistently identified a higher percentage of Key Actions than their peers. In identifying Options for Expedient Hazard Mitigation, both engineers and constructors again performed similarly to their peers without the radical departures that will occasionally be seen later in participants using Strategies 5, 6 and 7.

The question concerning the time required for engineers to analyze the problem prior to beginning repairs brought substantial variance in time estimates ranging from a few hours to a week or more. The distribution did not seem to be associated with profession, education or experience (see Table 22). For instance, the Strategy 1

1. *Strategies: E1, E4, E8, E10, E13, E15, C4, C7, C9, C10, C13*

Figure 10 – Strategy 1 of Decision Flow Chart

DECISION FLOW CHART FOR EXPEDIENT HAZARD MITIGATION

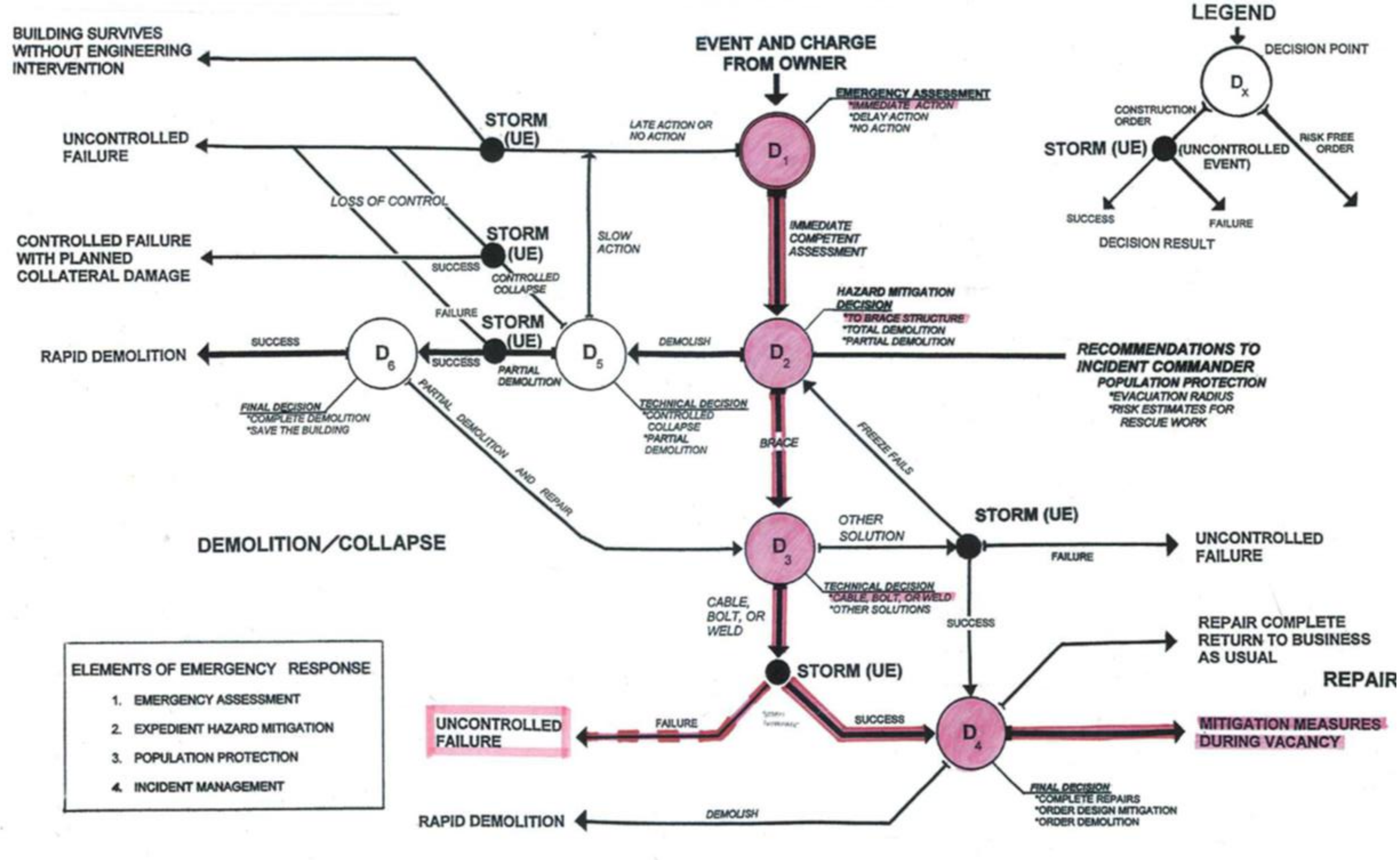


Figure 10

engineers had a mean of 2.7 days with six estimates of one day and five estimates of five days. The Strategy 1 constructors had a mean of 2.5 with seven estimates of one day and four estimates of five days. The remaining answers fell between the extremes. This extreme variation in the answers can probably be attributed to conflicting concepts of how to approach the problem. Some participants are focused on the expedient aspect of shortcutting the problem while others are concerned with a thorough understanding of the issues prior to any decision-making. This leads to extremes of answers from a few hours to several days.

The opportunity for participants to use government authority to solve a transportation problem led to one of the widest response gaps of the exercise. The problem was a key engineer stranded by traffic hours from the site. All six engineers eschewed any use of government transportation, while failing to find an alternative solution. Meanwhile, four of the five constructors turned to government authority for emergency transportation. The overall difference between professions (as shown in Table 9) was 42.9% of constructors use government authority while only 13.3% of engineers did so. This may reflect a certain street savvy of constructor's real-world experiences.

The question of critical wind velocity to initiate collapse of the crippled building resulted in a remarkably even division between professions. Engineers and constructors in this strategy believe the critical wind speed to be below 40 mph. One of each thought the speed was 40 to 50 and one engineer thought the critical speed to be 50 to 60 mph. Thus, two groups which split significantly on some areas had a high level of agreement on structural strength of the building, even though the engineering group is highly trained in evaluation of structural strength and the constructors have minimal formal education in this area. This, again, suggests a participant's formal education is of little use in producing this answer or that education contributes little beyond what expertise is conferred by having some experience in the subject matter. As suggested previously, the disarray of the damaged structure negates the value of conventional structural calculations. At the same time, Strategy 1 naturally appeals to participants who believe that the building is vulnerable to wind and therefore needs lateral bracing. This reinforces the concept of bracing the building as a key component of the division of strategies. This specific question of the likelihood of collapse prior to the arrival of the predicted storm gave a relatively tight distribution of estimates with a median response of a 25% chance of collapse and only 0% and 50% receiving endorsements from the remaining participants. One constructor chose 0% and one engineer and a constructor chose 50%. Again, among the participants endorsing Strategy 1, there is close agreement about the immediate risk.

The question of evacuation radius gave a nearly uniform distribution from one to five blocks. The question was open-ended and a few respondents gave answers above five blocks. For evaluation, the highest answer was restricted to “five or more” blocks. It should be noted that a five block evacuation radius would totally clear 121 blocks assuming the subject building is block zero. This impact will be further discussed in Section 8.1. Seven of the Strategy 1 participants estimated a 25% chance of domino collapse. One engineer estimated 0% chance, one constructor estimated 50% and the remaining engineers and constructors chose 75%. No one felt that domino collapse was 100% certain.

The impact of potential legal liability on participants’ decisions is revealed in the four related questions of (1) willingness to immediately give advice, (2) reaction to executive suggestion to seek legal advice, (3) restriction of advice over a period of time after the executive suggestion, and (4) restriction of advice after professional liability insurance is canceled.

Briefly, ten of the 11 Strategy 1 participants volunteered initial advice without condition. The other had minor qualms, but still gave advice. Interestingly enough, this was the only participant of the 29 who had initial reservations. This group also consistently took stronger than average action to seek legal advice in Table 8. All 11 of these participants contacted lawyers as suggested by their CEO, while at least seven of the total group made no call at all. However, only one of the 11 Strategy 1 participants restricted advice and he had consistently done so earlier. Therefore, the group appears to be very stable and cohesive prior to the final question in which they are notified that their professional liability insurance has been canceled. At this point, the group destabilizes. Eight individuals stop advice pending indemnification or defer to a higher authority. One places minor restriction on advice. Only two participants maintain the advisor capacity that they had earlier. Thus, the resolve of the group was severely disrupted by the loss of professional liability coverage and the critical flow of consulting advice ceased from almost all participants.

Summary of Strategy 1**:** A group of 11 participants, spread evenly over the testing population in profession, experience, and education approached the problem with a systematic method. Their repair strategies involved welding, cabling, or bolting as discussed in Section

6.5. These participants showed agreement in the areas of critical wind speed to collapse the building (lower than other participants), and estimated chance of collapse prior to the windstorm (about 25%). There was agreement in rejecting possible legal threats to the decision-making process although the loss of professional liability insurance finally led to the collapse of this resistance and most assistance was withdrawn. There was lack of agreement on evacuation radius although the answers appeared to be related to the participant's personal belief in the risk of sequential building failure (domino failure). On the use of government authority or assistance, the constructors were quicker to agree to government assets for transportation or demolition than engineers, probably due to daily experience.

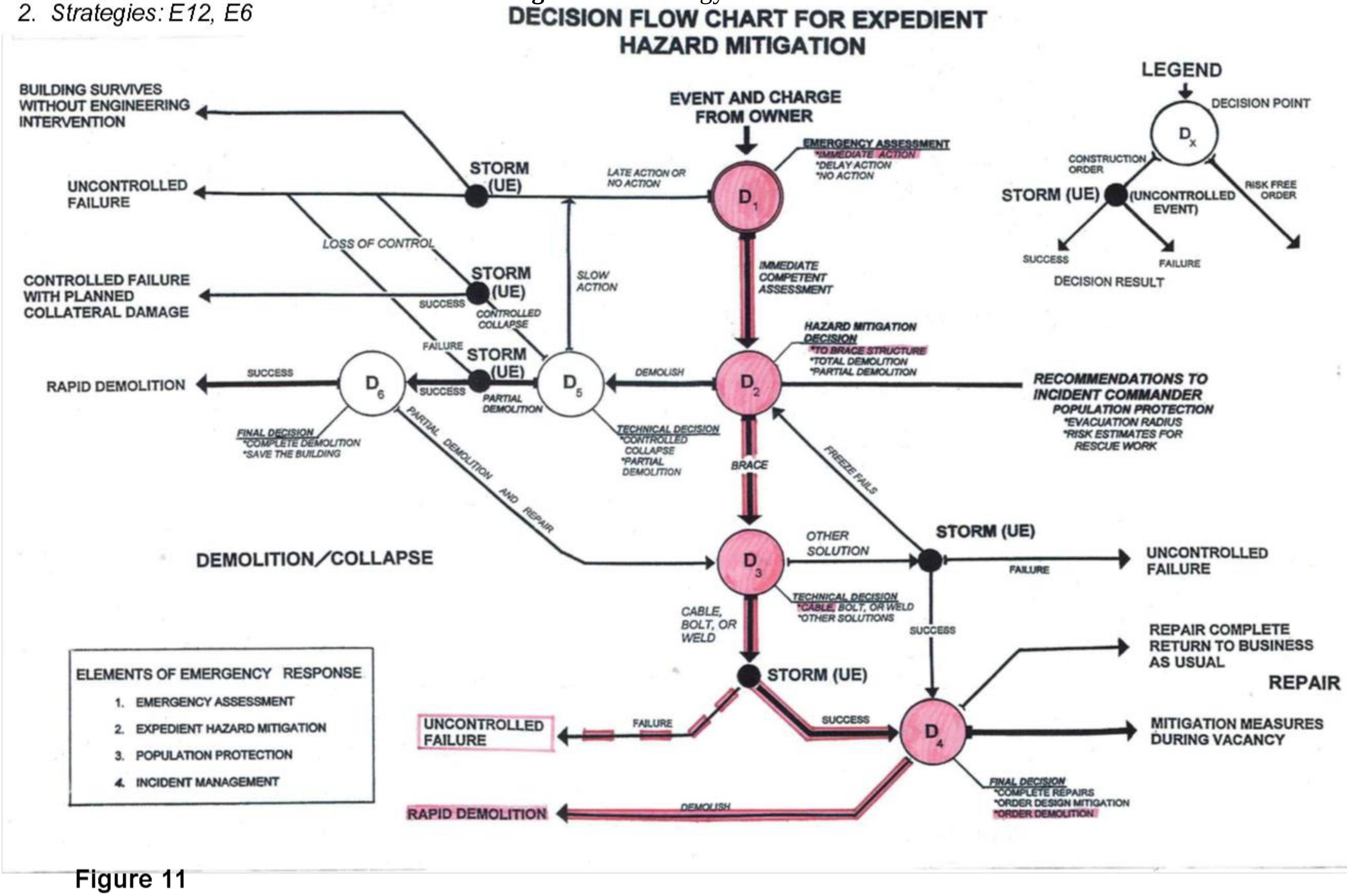
Strategy 2: *Brace The Frame – Demolish* - Participants E2, E6.

These participants made the same expedient hazard mitigation decisions as those in Strategy 1, but Strategy 2 participants do not believe building is going to be repairable. These participants answered "yes" to Decision #1 in Section 5, "Would you initiate work to increase the building's ability to survive anticipated storm winds of 60 mph expected in 48 hours?" They then answered "no" to Decision #4 in Section 5, "Assuming that the building survives the storm, do you believe the building can be permanently repaired?"

Discussion of Strategy: These participants were very concerned about the condition of the "undamaged" portion of the building frame either for reasons of overstressing from the explosion or from extreme stresses induced by the dropping of the severed column and the simultaneous mass failure of the thirty-eight girders on floors 23 through 40. E2 noted specifically that he believed the building must be skewed and that the cost of repairs would exceed the value of the repaired building. He did, however, mention the concept of only demolishing the top 20 floors and rebuilding from that point up. E6 also estimated that the ultimate cost of permanent repairs may exceed the value of the building and that the market would dictate demolition after the storm. This participant's belief that the building could survive for the short term, but will be unusable due to distortion recalls a unique experience in 1970 in Lubbock, Texas. A 20 story high rise building survived a tornado but sat vacant for 5 years with a twisted frame. Engineers were divided about strategies, but it was eventually repaired. At the same time that participants E2 and E6 listed these concerns in Section 5, they expressed average or above average confidence that the building could survive with reasonable repair efforts.

E2 and E6 had typical responses in key actions and listing of options for repair. Both participants listed column repair, bracing the frame, and shoring as possible options. E2 added reinforcing the damaged wind beam as well. For engineering analysis however, E2 saw only one day for analysis while E6 saw five days. The participants did not indicate whether these differences in time perception are related to the magnitude of the problem, the availability of resources, variation in the degree of documentation for repair to begin, or perhaps, extensive checking of the frame for less visible damage.

Figure 11 – Strategy 2 of Decision Flow Chart



E2 did not plan to use government assistance at all. E6 did so to a minimal degree for a police escort. As noted in Table 9, 87% of all engineers did not invoke government authority.

E2 believed that the building could withstand 80 mph winds and E6 believed the building was good for 50 mph winds. The mean for engineers was 51.3 mph, so E2 was much more optimistic than average. Both of these engineers believed the collapse risk in the first 24 hours before expedient hazard mitigation can be implemented is 25%. The mean for engineers was 22% and constructors was 30%, so E2 and E6 were typical of all participants in this respect. Also, both engineers only estimated the chance of domino failures at 25%, but one called for an evacuation radius of two blocks and the other recommended three blocks.

Both of these individuals showed some concern in one of the four questions that reflect participants' responses to the mention of legal liability and the suggestion of withdrawal of professional liability insurance. E2 was concerned about giving advice after his CEO suggested he talk to a lawyer and both E2 and E6 said they would withdraw assistance if liability insurance were cancelled. Both were willing to consider continuing if fully protected from liability.

Summary of Strategy 2: Two highly educated engineers with low and medium experience are concerned that the extreme stress of the event has damaged the frame beyond reasonable or cost-effective repair. They recommend measures to survive the storm, but anticipate orderly demolition later.

Strategy 3: *Gravity Shoring – Permanent Repair* - Participants E3, E7, E9, C8 and C14. P

Participants recommended various actions to increase the building's ability to survive at D3 other than the previously discussed actions of bolting, welding, and cabling. If the building survived the storm, the participants believed it is feasible to repair it. All of these participants answered "Yes" to Decision #1 in Section 5 "Would you initiate work to increase the building's ability to survive anticipated storm winds of 60 mph expected in 48 hours?" All of these participants answered "Yes" to Decision #4 in Section 5 "Assuming that the building survives the storm, do you believe the building can be permanently repaired?"

Discussion of Strategy: These participants had ideas for other strategies to D3 to survive the storm, but like the participants in Strategy #1, believed that the building could be put back into service. All three of the engineers identified similar concerns about repairing the severed column or the resulting crack propagation and shoring the column or floors to address the gravity load in the damaged area. In addition to compression shoring (columns), they also proposed tension schemes utilizing cables along the outside of the building. The constructors saw similar problems and responded with shoring schemes to help support the collapsed floors. As before, the constructors showed great awareness of the time necessary to implement their schemes. C8 also considered an alternate idea of removing window glass to reduce wind loading as an option for immediate repair, but did not act on it in his final strategy.

As a point of reference, the two most experienced engineers also believed that a "proper" engineering analysis would require five days or more before temporary repairs would start. This supports the earlier conjecture that the requirements for expedient hazard mitigation and traditional engineering practice are incompatible in an emergency.

Of the three engineers and the two constructors using Strategy 3, only one engineer suggested using government authority and that was only for escort purposes.

Responses to another question show that all five participants in Strategy 3 believed the building could collapse at very low wind speed, 40 mph or less. Indeed E3, C8 and C14 believed the building to be a 50% risk of collapsing in the first 24 hours. These opinions would logically lead to efforts to shore the building, assuming the participant did not believe the structure to be too dangerous to work on.

Figure 12 – Strategy 3 of Decision Flow Chart

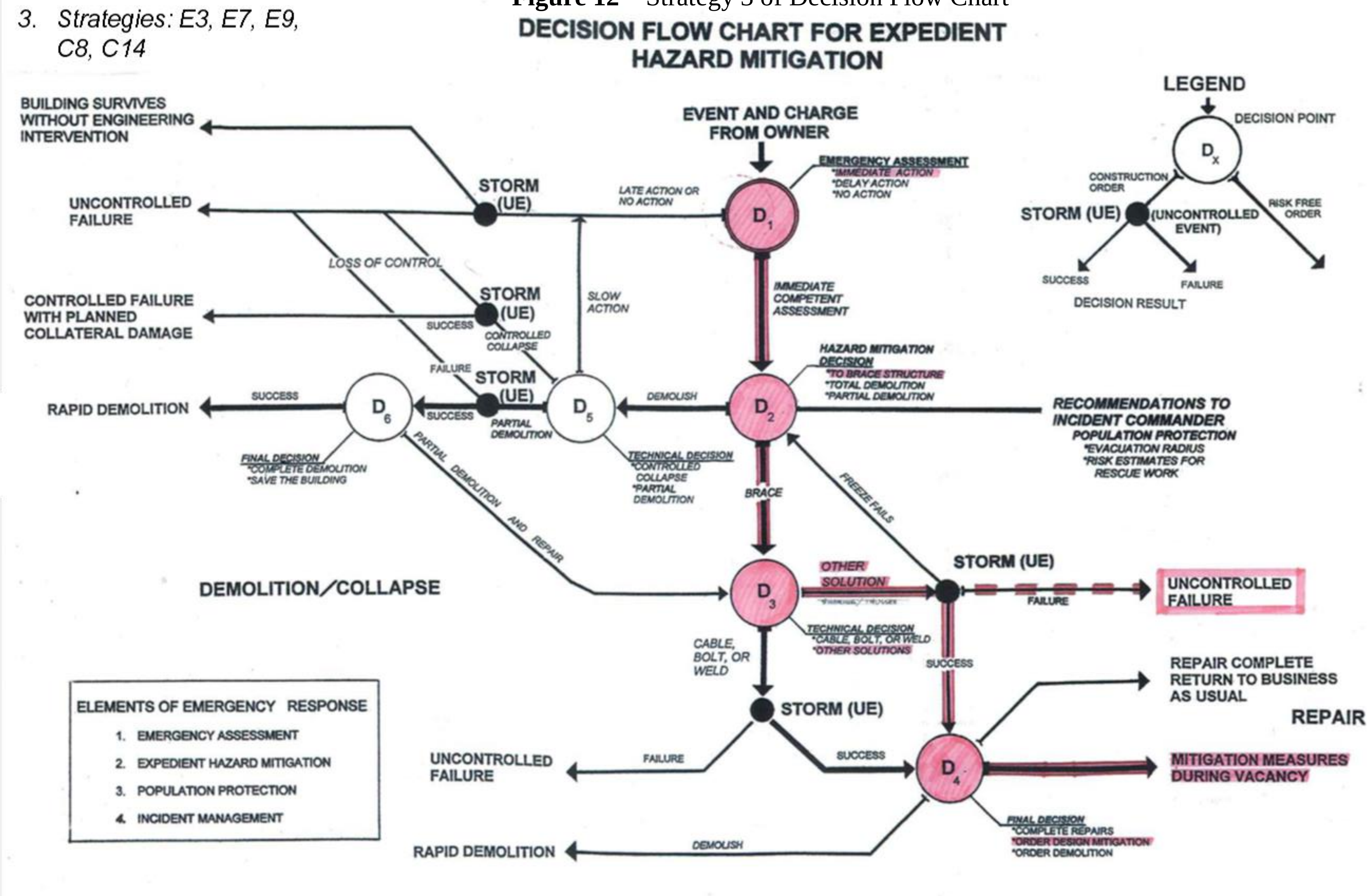


Figure 12

Four of the participants believe two or three blocks to be an adequate evacuation radius, but C8 is concerned enough to request five or more blocks. Participants E3, E7 and C8 also believe the possibility of domino failures to be 50%, which is higher than the average for all participants. Questions about legal and liability issues related to consulting in a high-risk situation did not elicit concern from any members of this group except for E9, who indicated he would withdraw all assistance upon notice that his firm's liability insurance would not cover this consulting situation. C8 required an immediate release of liability to continue. E3 showed much concern early in this series of questions, but relaxed as the exercise proceeded. The remaining participants indicated some hesitation, but not to the point of disrupting the process.

Of special interest is the evaluation process noted by participant E3 who identified three issues inherent in D3. First, there is a need to stabilize the beam crack propagation and by inference the severed column that caused the cracking. Second, there is also a need to stabilize the gravity system globally, and third, there is a need to address the issue of the compromised moment connections relative to the lateral resistance of the wind frame. This participant's response was one of the most coherent attempts to organize the different structural issues inherent in the problem and perhaps is a future guideline.

Summary of Strategy 3: Five individuals explored repair options other than welding, bolting and internal cabling. Their strategies revolved around shoring with some attention to damage details. Legal and liability issues appear to have minimum influence on their decision-making. All participants believed the building to be at higher risk than previous groups have thought and they focused their attention on the gravity loading issues in the damaged bays. One participant appeared to identify various components of the problem more clearly than other participants at Decision 3.

Strategy 4: *Gravity Shoring – Demolition* – Participant C6:

This participant believed the building can survive the storm, but that it is too badly damaged to be economically repaired and returned to service. This participant answered "yes" to Decision #1 in Section 5, "Would you initiate work to increase the building's ability to survive anticipated storm winds of 60 mph in 48 hours?" C6's strategy was to support the dropped floors with shoring. This participant answered "no" to Decision #4, "Assuming that the building survives the coming storm, do you believe the building can be permanently repaired?"

Discussion of Strategy: This executive constructor believed shoring to be the practical short-term strategy for expedient hazard mitigation. After listing five typical key emergency assessment and incident management actions to start with, Participant C6 listed six options for expedient hazard mitigation and systematically eliminated them for reasons of excessive risk or lack of time. By default, he was left with a shoring and column-bracing scheme to help distribute the gravity loading in the collapsed area.

C6 believed that the design time for temporary mitigation is only a few hours. This estimate is consistent with the shoring concepts that he proposed, but is significantly less repair time than the rest of the participants estimated would be needed.

On the question of initiative in using government authority, C6 made no use of the power, which is the same response as 57% of the constructors.

In questions dealing with the risk of wind induced structural collapse, C6 responded that the building could collapse at 40 mph or less. Consistent with this belief, C6 estimated the risk of collapse in 24 hours, to be 25%. Both responses were similar to those of the majority of participants.

Regarding the risk to surrounding buildings from domino failure, he estimated 0%, with substantially less concern about collapse than the other participants; 83% of them said 25% or more. In response to the question about safe radius for evacuation, C6 called for an extreme distance of five plus blocks (actually six on his questionnaire) specifically because of the asbestos identified in the photographs, rather than for the risk to adjacent buildings. C6 referred to the liability issue of the asbestos, presumably from the asbestos cloud during 9/11.

In response to the question about legal liability, C6 showed major concern after being told to talk with the company attorney. After the threat of a loss of liability insurance, C6 added that he would need a full liability release.

4. *Strategy: C6*

Figure 13 – Strategy 4 of Decision Flow Chart

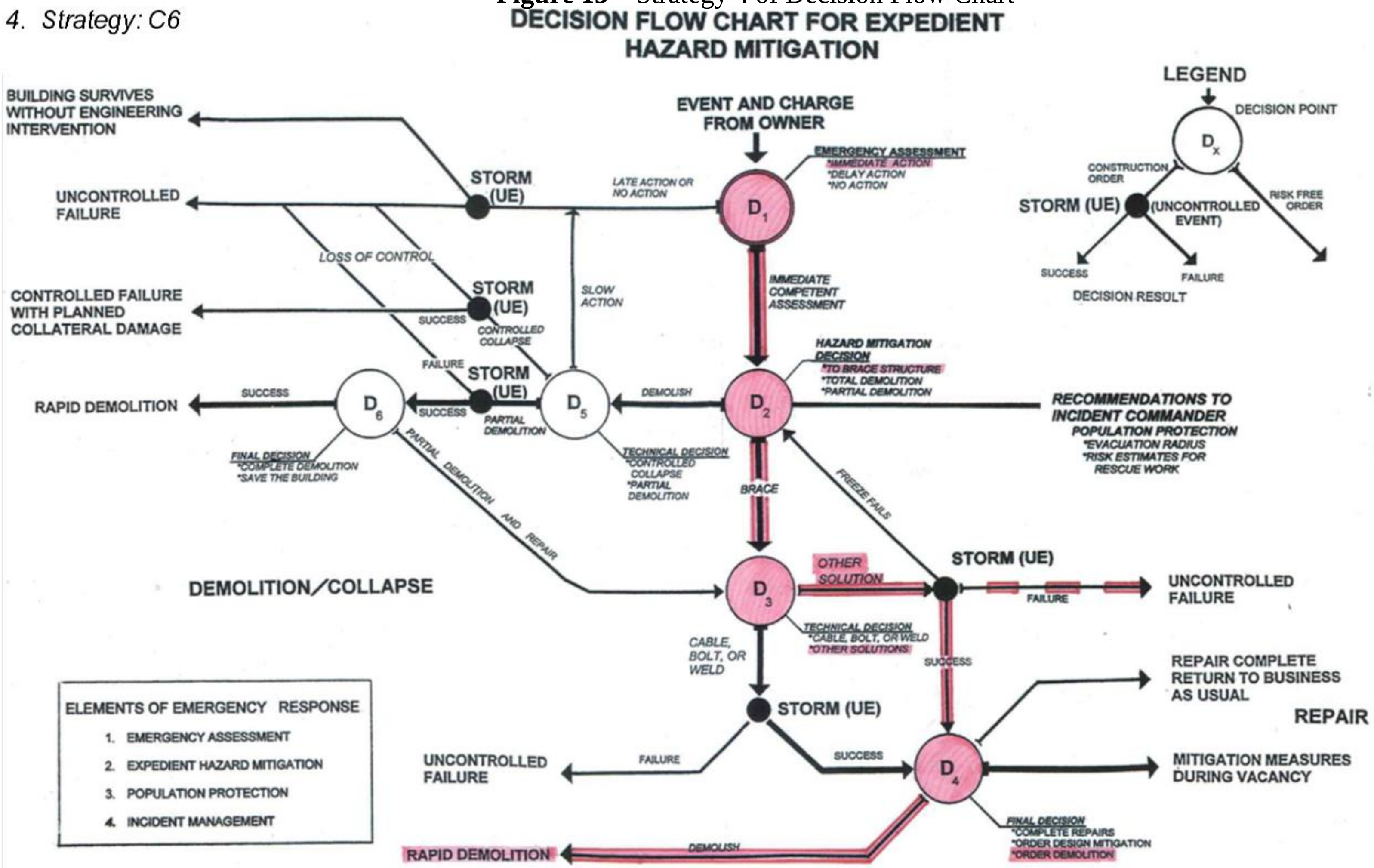


Figure 13

In comments in Section 5, Decision #4, C6 commented that the structural engineer will have major long-term concerns about the effects of the explosion on concealed connections at a distance from the blast location on Floor 21. He also noted that a partial demolition to accomplish permanent repairs would put unknown stresses on the remaining building frame. His ideas for Key Actions were typical of those provided by the other participants.

Summary of Strategy 4: An executive constructor with a civil engineering degree believes he can save the building from the storm. However, he believes the explosion and partial collapse may have induced such stress in the frame of the building that there may be long-term structural issues that make the building unsuitable for repair. He also has considerable concern about asbestos and requests an unusually large evacuation radius for that reason. He is not particularly concerned about sequential (domino) failure and he intends to demolish the building after the storm.

Strategy 5: *Remove Walls* – Participant E14:

This participant recommended partial demolition by removing windows and interior walls in upper floors to reduce the building's wind resistance. After the storm, the building would be repaired and returned to service. The engineer answered "yes" to Decision #1 in Section 5, "Would you initiate work to increase the building's ability to survive anticipated storm winds of 60 mph in 48 hours?" His strategy to reduce wind resistance separated this strategy from all others. He also answered "yes" to Decision #4, "Assuming that the building survives the coming storm, do you believe the building can be permanently repaired?"

Review of Strategy: This highly educated and experienced engineer only focused on two expedient hazard mitigation options. The first option was to reduce the building's wind resistance by removing both windows and interior partitions to allow wind to blow through the building. The second was to cable brace the steel frame of the building to restore some of the wind bracing lost in the damaged bays. However, he did express concern that the cracked beam could fail completely, resulting in "fracturing of welds between beam and columns-unzipping," but did not carry this scenario to any conclusion. After reviewing the situation, he decided that reducing the wind resistance would be adequate and settled on removing the windows and interior partitions. The reduction of wind stress was his main strategy.

He believed that the time to analyze the building to do repairs would only take a few hours which is in the lower half of the distribution. Moreover, this highly educated executive engineer stated that he did not see any issue that required extraordinary measures for recovery, so he did not bother with government assistance for transporting engineers.

This participant did not show major concern about the legal issues and liability. His summation of legalities and liabilities was that, although he would discuss the cancellation of insurance with legal counsel, "I believe that the engineer's fundamental duty to protect life would predominate all considerations." He indicated that the remaining building frame could withstand 80 mph winds, which were in the top 10% of participants' estimates, and that the chance of failure in 24 hours was 0% which is in the bottom 20% of the participants' responses. That is, he had much higher confidence in the damaged building than the other participants.

5. *Strategy: E14*
2A Alternative C1, C8, C9

Figure 14 – Strategy 5 of Decision Flow Chart

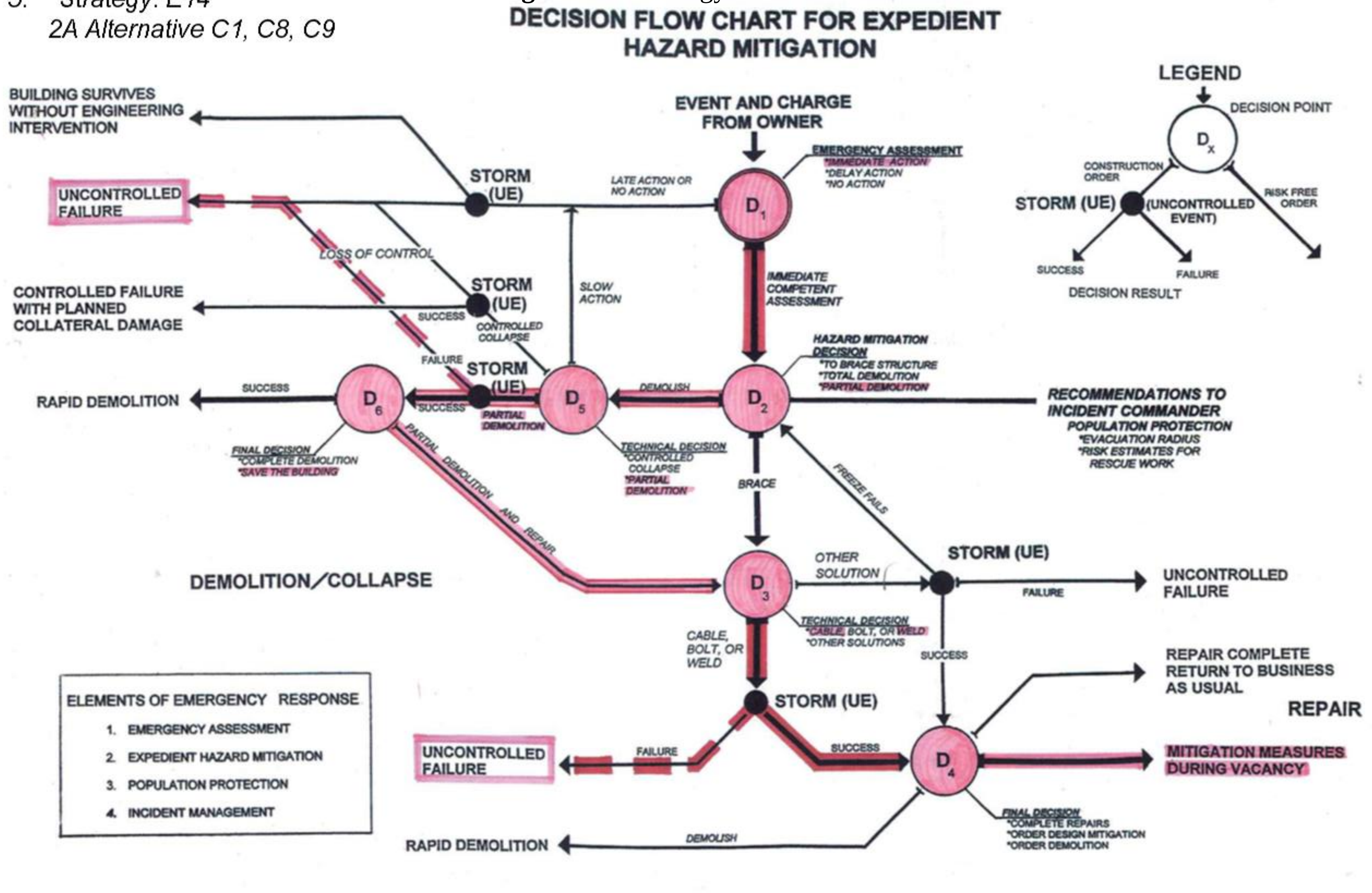


Figure 14

E14 doubted that a collapse would lead to more than one additional building collapsing, although he called a domino failure a 25% chance. He noted that he would expect a basically vertical collapse with "some leaning" during the fall. From this concern, he advised an evacuation radius of three blocks which is right in the middle of the distribution of responses.

E14 laid out a detailed procedure for analysis of the total damage after the building survived the storm and outlined a detailed review to confirm the financial viability of returning the building to service.

Summary of Strategy 5: The exercise's most educated and experienced participant proposed an unusual strategy of partial demolition of the upper floors to reduce wind resistance. He recommended the removal of windows and interior partitions to allow wind to blow through. He believed the building could survive the storm, but raised issues of possible beam to column connection (weld) failures without specifically stating a repair strategy. This strategy assumes building survival without repair. E14 outlined a structural and detailed financial review following the storm to confirm his belief that the building can be saved. This individual showed a high level of confidence throughout the exercise. He showed very little concern about legal liability and indeed, wrote a statement about an engineer's responsibility to society in such a situation, overriding his own liability concerns.

Strategy 6: *No Action – Permanent Repair* – Participants E5, E11, E12, C1, C3 AND C5:

These participants' final decision was to forgo action and withdraw from site. They answered "no" to Decision #1 in Section 5, "Would you initiate work to increase the building's ability to survive storm winds of 60 MPH expected in 48 hours?" They answered "yes" to Decision #4 in Section 5 "Assuming the building survives the storm, do you believe the building can be permanently repaired?"

Discussion of Strategy: These six participants had ideas similar to those of other participants for bracing and shoring, but apparently had reservations as to how quickly the ideas could be implemented. Only E12 stated he had no ideas (a notation of 0 in Table 19), but this was with the stated proviso that time is extremely short and he proceeded to list shoring as an intermediate response to long-term repairs if the building survived.

Participants E5, C1, and C3 showed higher than average levels of concern about legal liability and also showed extreme reactions to possible loss of professional liability insurance to the extent of stopping all advice. Hence, they decided to make no effort to save the building. Also, logically contributing to this position for E11, E12, C1, C3 and C5 is a belief that the building can withstand higher winds without repair than most participants believed possible. Consistent with this position, E11, E12 and C5 expressed a belief that the building was in no danger of failure (0%) in 24 hours from the existing winds that were described as being from fifteen to twenty-five miles per hour. It must be noted that this confidence stemmed from the strength of the remaining undamaged frame. However, at the same time, C1 and C3 did show great concern about the short-term failure (24 hours) of the damaged portion of the frame from progressive tearing of steel. As a result, they expressed concern about the risk of putting workers in the building to brace against the storm. Thus, opposite beliefs contributed to lack of action. E5, E11, E12, C1, C3 and C5 responses are typical for their experience tiers for the key actions. The same is true for expedient hazard mitigation, except for E12, who gave a score of 0, (as discussed above), perhaps indicating a preconceived course of action. The other five individuals had various ideas for expedient hazard mitigation, but, as discussed above, chose not to implement them.

Figure 15 – Strategy 6 of Decision Flow Chart

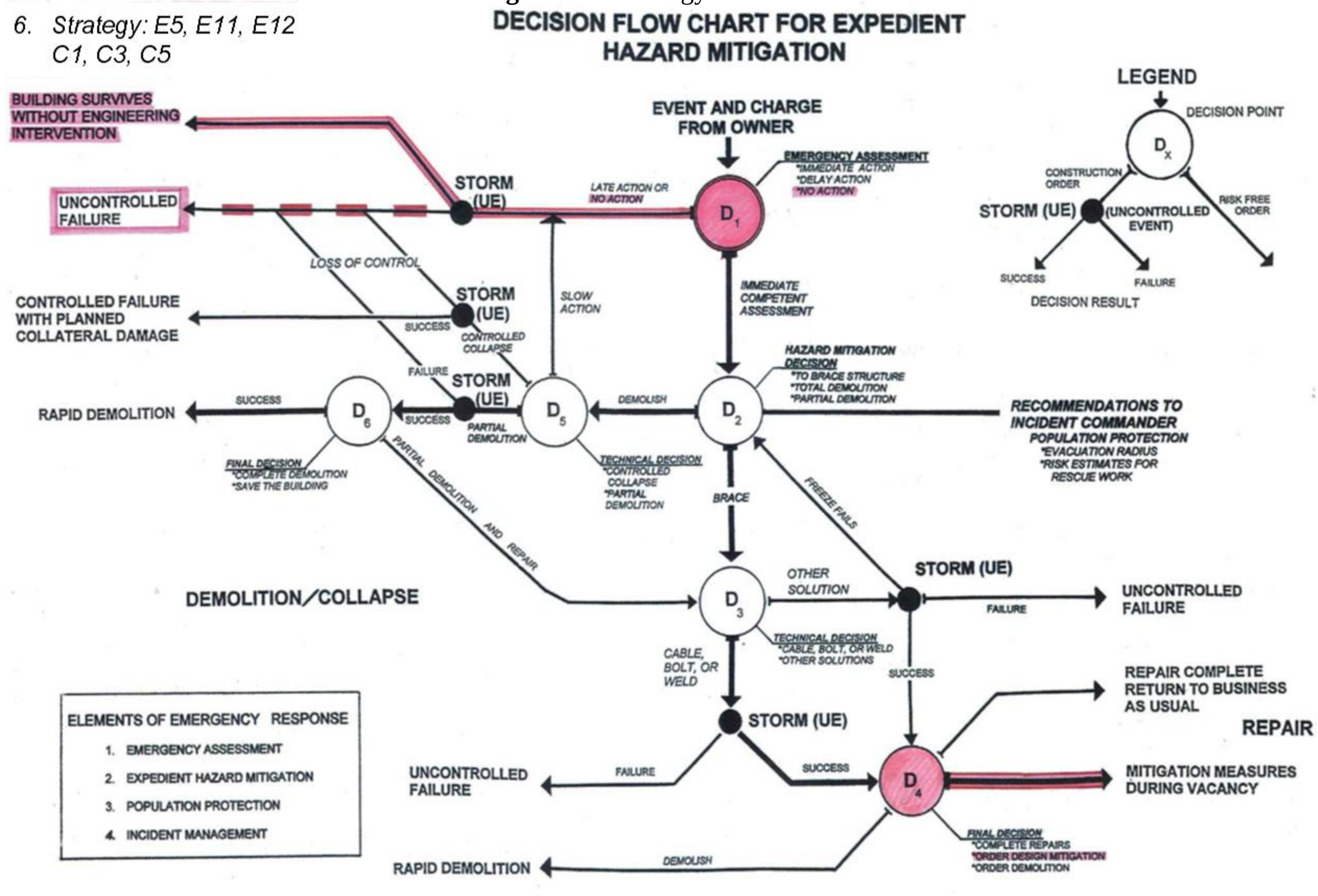


Figure 15

This group of participants estimated response time for repair to be one or two days with the exception of one constructor who thought the drawings might require a week.

Only one participant called for government assistance, a constructor with moderate experience. He, however, had multiple ideas of how the government might assist including police escorts and government helicopters.

The two engineers of this group had no concern about domino failure, although the constructors had a much higher level of concern that a collapse could compromise surrounding buildings.

The evacuation radius recommended by these participants varied considerably with both engineers calling for one block and constructors requesting an average of almost four blocks. As we noted previously, this correlates with some participant's greater concern about domino failure.

Summary of Strategy 6: Six participants rejected expedient hazard mitigation for various reasons including concern about professional liability, fear of workers being caught in a rapid collapse from fatigued steel, and a belief that the undamaged portion of the frame could survive a short duration storm without additional work. In the written answers, there was evidence that participants had conflicts over two different models of failure. First was the issue of the steel girder (beam), which was visibly torn and might be progressing in its failure. If it did completely sever and allow the severed column to slide from its position on the lower stub, there was concern it could trigger a progressive failure of the adjacent beams above the same column line. The second issue was the overall strength of the remaining undamaged rigid building frame. These participants tended to address these issues separately and seemed to be making decisions on the basis of either one or the other. There is no evidence that anyone choosing Strategy 6 had effectively integrated the two separate issues, which appears to be a major confounding factor for participants for both analysis of the risk and the expedient hazard mitigation strategies. It would seem reasonable that two or more separate strategies are required, perhaps of completely different engineering design, materials and skills.

Strategy 7: *No Action – Demolition* – Participant C11:

This participant recommended no action. If the building survived, he believed it would be demolished. (See the flow chart on the following page). As in Strategy 6, this participant answered “no” to Decision 1 in Section 5, (“Would you initiate work to increase the building’s ability to survive anticipated winds of 60 mph expected in 48 hours?”) In addition, this participant also answered “no” to Decision 4 in Section 5, that is, “Assuming that the building survives the coming storm, do you believe the building can be permanently repaired?”

Discussion of Strategy: This participant was very concerned about an early failure of the building, believing that it was too dangerous to initiate work on (50% chance of collapse), that domino failure was a severe danger (100%), and advising a rapid, widespread evacuation of many blocks of downtown area. This participant had the highest concern of any participants on the questions about the critical wind speed to induce structural failure, the risk of collapse in 24 hours, the safe radius for evacuation, the chance of domino failure, and the time necessary to analyze damage and begin repairs. C11 believed that domino failure was very likely if the damaged building toppled. At the same time, he expressed no concern about legal liability and volunteered that he would consult even if his firm’s insurance were cancelled. This willingness to assist strongly suggests he is not avoiding expedient hazard mitigation for fear of liability. In Key Actions for Emergency Response, his number of responses is reasonably typical for his experience although on the low end. This participant did not list any expedient hazard mitigation options. Of special interest is that the subject had no formal construction management or engineering education above the high school level and therefore, may not be aware of the potential of a disrupted rigid frame to support itself. Again, the lack of structural education may lead to a conservative overreaction.

C11 makes no use of government authority for the mitigation of the building’s problems. He is totally focused on evacuation of the area.

Summary of Strategy 7: An experienced constructor believed the building is more dangerous than most other participants believe and recommended withdrawal from the area and extensive evacuation. His concerns are consistent with his recommendations. He also believed the building to be too badly damaged for repair even if it survived the storm. There is reason to believe his lack of formal training in engineering is contributing to the difference of his response from the other participants. His technical background is

7. Strategy: C11

Figure 16 – Strategy 7 of Decision Flow Chart

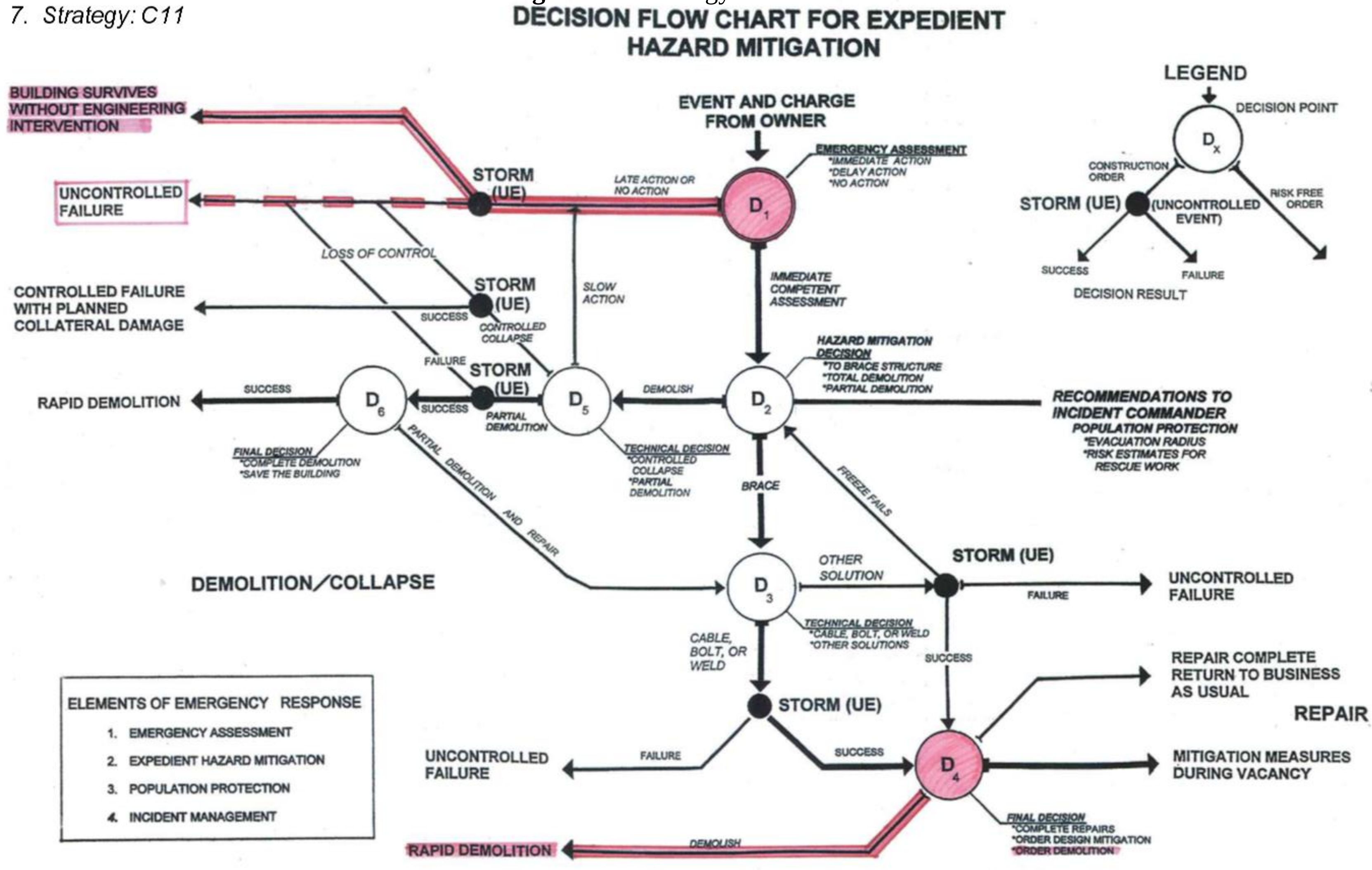


Figure 16

similar to that of fire department emergency personnel and it should be not be unreasonable to expect similar extremely conservative reactions.

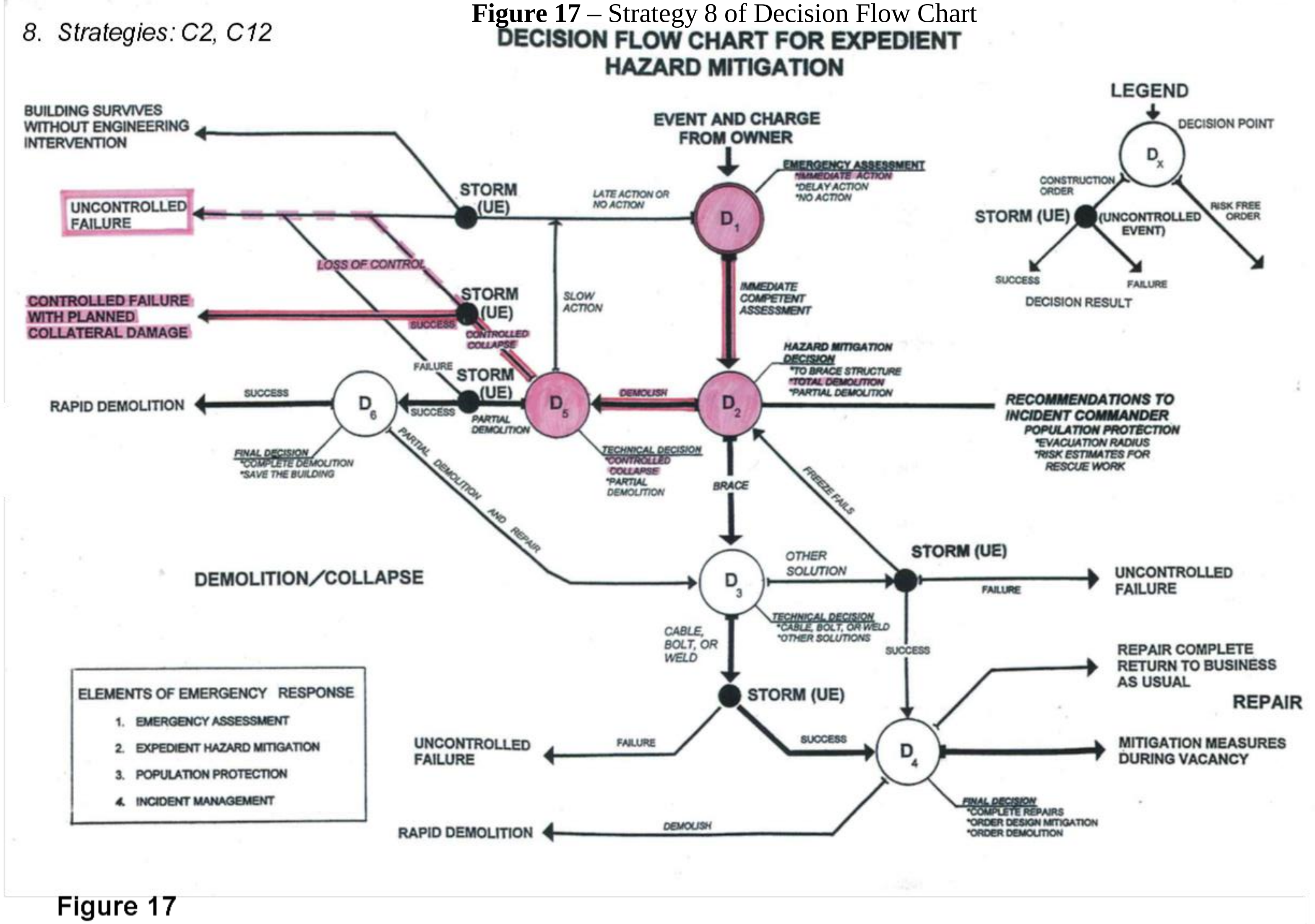
Strategy 8: *Immediate Implosion* – Participants C2 and C12 proposed that controlled demolition (implosion) be used to demolish the building prior to storm. Even if the building did survive the storm, these participants did not believe it to be repairable at reasonable cost. Both participants answered "no" to Decision #1 in Section 5, ("Would you initiate work to increase the building's ability to survive anticipated winds of 60 mph expected in 48 hours.") Both participants confirmed their decision for implosion by answering "no" to Decision #4 in Section 5, "Assuming that the building survives the coming storm, do you believe the building can be permanently repaired?" This, in turn, reinforces the decision not to attempt immediate repair.

Discussion of Strategy: Participants C2 and C12 outlined their analysis of the problem and the search for a qualified engineer. C2 attempted to fly the stranded engineer to the site by government helicopter. However, both also proposed simultaneously mobilizing a demolition constructor (and C12 referred to possible assistance from the government.) C2 suggested shoring as an expedient hazard mitigation measure, with concern for tying the damaged wind beams back to the building's center columns to avoid additional failure of secondary beams, but rejected the long-term repair of the building (Decision 4 above) and opted for demolition. C12 looked only to a consulting engineer for ideas and did not recommend any specific mitigation action himself. Implosion became his final strategy by default.

Regarding their estimates of time required to analyze damage and begin temporary repairs, C2 believed the time to be only a few hours, consistent with his concept of shoring the floors. C12 gave a time estimate of over five days for analysis of the building's condition and engineering, which is well beyond the two days available for analysis, engineering and repair.

As indicated above, C2 and C12, they both showed a willingness to call on government resources. C2 recommended exploring the use of government helicopters for transportation. C12 recommended military or police assistance in the form of dogs to sniff out additional explosives in the building.

Figure 17 – Strategy 8 of Decision Flow Chart



In response to the question about critical wind speed to induce structural failure, C2 believed the building could collapse in a 40 mph wind and C12 indicated a collapse point at 50 mph, which are close to average for construction personnel (about 46 mph). Regarding the risk of collapse in 24 hours, both construction managers showed slightly less concern than other construction personnel (50% compared to a mean of 55%). Regarding their estimates of safe radius for evacuation, C2 called for a two-block radius (near the mean) while C12 called for 4 blocks (top 30%). For their estimates of chance of domino failure, C2 believed the risk to be 25% (the most common response) while C12 estimated 50% (in the top third). Regarding their reaction to the suggestion to talk to a lawyer and their legal concern on giving advice, these individuals did not show undue concern over contacting a lawyer and did not severely restrict advice. Also of interest are their responses to the risk of delay to engineering and construction caused by liability issues. In this question, both participants reacted strongly to a suggestion of withdrawal of their firm's liability coverage. C2 required an immediate liability release and C12 indicated he would severely limit advice.

Summary of Strategy 8: Two constructors with varying experience believed the building to be at risk without adequate means of expedient hazard mitigation and proposed controlled demolition to destroy the building prior to the arrival of the storm winds. They shared concern about liability issues and a belief that the building could collapse in relatively low winds with a fifty percent risk of collapsing in twenty-four hours. C12 also believed that an engineered expedient hazard mitigation strategy could take five days to implement with only two days available. A major issue appears to be that the participants have few ideas to reduce risk to the building other than rapid demolition. As with participant C11 in Strategy 2, C12 was highly experienced, but without formal training in engineering or construction science.

7. DISCUSSION

This section summarizes the results of the exercise and uses these results to address the research objectives described in Section 4.0.

7.1 Discussion of Proposed Model – Decision Points

Question 1: Are Decision Points Approached in the Order Hypothesized?

The eight decision flow chart strategies are all within the pattern presented in Section 3.0. The flow chart anticipated normal engineering practice without concern for time constraints. The participants' decision-making processes appeared to closely follow normal engineering practice not only in form, but also in pace. There is little evidence of decisions being accelerated by anticipation or overlapping of procedures. Although all participants expected to go to the building and the majority of participants would search for plans to the building, few would mobilize steel workers prior to discussing analysis of the problem even though the need of steel workers' skills was evident. Other key actions were seldom anticipated, such as need for surveying instruments to check the verticality of the building. This was lacking even though P-Delta lever loading issues (see Section 1 and Figure 1) should be intuitive, at least for the engineers. Acceleration of these key actions that would be necessary for a different pattern of decision-making was rare, even in the problems in Section 2, where the participants saw clear photographs of the nature and extent of the damage.

With a few notable exceptions, the formality and pace of routine procedure was followed. The variation in initial key actions included differences between participants in their approaches to the assessment of the problem. The rule of thumb in this unprecedented situation was to go to the site, get a *visual* assessment of the damage and then run through possible strategies based on the individual's previous experience and education. The participants identified 12 options for expedient hazard mitigation at decision points D2 (between implosion, partial demolition, and repair directions), D3 (specific repair alternatives) and D5 (specific demolition alternatives). These 12 options are listed in Section 6.5. Thus, on critical expedient mitigation options at Decision D3, engineers and constructors reviewed similar ideas to consider gravity shoring of the building's visibly damaged floors, (53% vs. 50% in Table 19) and to consider correcting the visible column and beam cracking (60% vs. 57% in Table 19). However, the practicing engineers were twice as likely to identify the *theory* of the compromised wind frame and review the need to brace the wind frame (66% to 29% in Table 19). One constructor and one engineer did not review bracing, but would achieve an equivalent effect by reducing wind loading (the removal of glass and partitions). Thus, the ratio of engineers to constructors who addressed the wind-loading problem is still two to one.

Similarly, several constructors' training and experience led them to reject their own judgment and repeatedly seek licensed engineers depending on how far the decision was from their normal responsibility. Ironically, many ideas from constructors were similar to engineers, but they would not take responsibility to implement them notably because of the traditional rigid separation of professional responsibilities. Thus, the answer to the question, "Are decision points approached in the order hypothesized" is "yes."

7.2 Discussion of the Proposed Model – Experts and Options

Question 2: Do experts really identify all the options open to them?

This question has two components, the first of which is the set of key emergency assessment and incident management actions that began early in the exercise to access the situation and prepare a response to the risk. The second component is the expedient mitigation actions that involved actual construction work on the building.

Table 6, Key Actions for Emergency Response, showed that, on average, each engineer only identified 36.4% and each constructor only identified 41.8% of the 12 key actions that were generated by the group as a whole. Again, we note that these actions are ones that participants themselves identified, not ones that were produced by other sources.

In Table 19, Options for Expedient Hazard Mitigation, the first five expedient mitigation options were the most frequently identified by the participants. The most frequently listed option for expedient mitigation by constructors and engineers was repair or bracing of the damaged column and the cracked wind girder (beam), with 60% of engineers and 57% of constructors listing this strategy. The option most frequently listed by engineers was temporary bracing of the wind frame, with 66% of engineers listing this option. By contrast, only 29% of constructors did so.

On average, Table 19 indicates the engineers mentioned only 50.4% of the five primary expedient mitigation options and the constructors mentioned only 40.2% of them. The secondary options had even lower frequency of mention. Thus, the answer to Question 2, “Do experts identify all options open to them?” is “no”.

7.2.1 Discussion of Propose Model- Subordinate Questions

Subordinate questions. Do experts consider multiple options at the same time or even reverse the order of decisions? The answer appears to vary with the participants. The specific path followed depends on multiple perceptions of the participants. The D1 Decision (“Should I conduct a detailed assessment?”) is an “Action” or “No Action” decision related to concern about personal accountability, i.e. fear of highly publicized professional error, lack of ideas for mitigation, or confidence that the building is stable enough to survive the approaching storm front.

It appears that these questions are being considered at the same time and some time to reinforce each other, such as: (1) “the building is probably stable,” (2), “I have no confidence in my technical strategies,” and (3) “I don’t want to make a public blunder”, all of which reinforce a “No Action” decision.

An alternative perception is, (1) “the building is <u>not</u> stable, (2) “I have no confidence in my technical strategies,” and (3) “I don’t want to make a public blunder”. These perceptions tend to offset each other and may account for drastic alternative strategies that avoid making engineering decisions. An example is the multiple suggestions for explosive demolition at D2 (“Should I begin expedient hazard mitigation?”) and D4 (“How do I make long-term repairs?”) decision points. Such strategies eliminate the detailed engineering problem and turn the technical execution over to someone else as Participants C2 and C12 recommended.

Also of interest is that the implosion experts would be the only people on the site whose normal training and expertise is exactly appropriate for the strategy. This “escape option” may be a powerful temptation to future decision makers as it was to participants C2 and C12. A technology that can be precisely implemented during a chaotic situation could hold understandable appeal to a highly stressed decision maker.

The answer to the subordinate question, “Do experts consider several options at one time” is suggested by the fact that several participants listed their thoughts on decisions as stream of consciousness statements that were consistent with the sequential statements discussed above. Also, it can be logically argued that engineers and constructors routinely plan ahead and are not going to make decision D2 without a least a theoretical concept of technical strategies at either D3 or D4. Thus, the answer to question “Do experts consider several options at one time?” is “yes.”

If D3 and D4 are considered before decision D1 is made, then it can be argued that some participants do reverse the apparent order of the decisions. This idea that individuals back into the decision is further supported by the observation that, of 29 participants, not a single one answered yes to D1 and then failed to present either expedient mitigation options or the implosion strategy at D3 and D4. All three participants, E12, C11, and C12, who did not list ideas for mitigation opted for “no action” at D1 or implosion at D2. It appears that participants search for ideas first, and then make the D1 decision, or perhaps return to it and reverse the decision. It should be recognized, however, that the inverse does not hold true. The availability of a large number of mitigation ideas does not automatically mean that the participant will employ any of them, and answer “yes” at D3. Several participants identified multiple strategies, but took no action. They either believed the building to be capable of surviving the storm, believed time was insufficient, or showed fear of personal or firm accountability and answered no to initiating action at D1 as discussed in Strategy 1. It cannot be argued that they thought of the mitigation ideas too late because the exercise was specifically constructed to allow them to backtrack and correct a decision if they wished. Such backtracking was clearly identified by the changing of participants’ pen colors at specified intervals.

In summary, the answer to the subordinate question, “Do some individuals reverse the order of the decision?” is “yes.”

7.3 Discussion of the Effects of Different Expertise

Question 1: How can experienced construction personnel contribute to the strategy?

Discussion: Table 6 compares issues that engineers and constructors identified as Initial Key Actions. Constructors responded more strongly than engineers, (a difference of 18%+) on four of the thirteen critical key actions. These are (1) early mobilization of steel constructors (2) reviewing floor loading in damaged areas (3) immediately organizing a damage assessment and (4) monitoring the evolving condition of the severed column and the adjacent cracked girder. The strongest difference was in the constructor’s approach to damage assessment, where 71% of constructors identified a need for an organized damage assessment while only 53% of engineers did so. This is critical because the engineers generally preferred a personal observation of the damage. Yet touring an entire building searching out damage may not be practical or wise. An organized team search to find specific damage and access routes for engineering visits would appear to be an efficient alternative. Incidentally, constructors also took greater immediate responsibility for evacuating and controlling the work area, which is consistent with their normal responsibilities at a work site. Such action would have to coordinate with fire department responsibilities.

A comparison of engineers' and constructors' responses to identify expedient mitigation options showed engineers with a greater awareness of structural strategies for the five basic options except for constructors exhibiting a marginally (9%) greater awareness of reducing wind load on the building by removing windows. Overall, the engineers identified 38 options to the constructors 28.

In secondary options, the constructors did express greater concern about the weight of debris in the damaged portion of the building and the removal of it. This concern is consistent with their estimating floor loading as a key action. Again, these responses are logically tied to a constructor's responsibility for floor loadings during construction and renovation of buildings.

The constructors also showed a greater awareness of the availability of implosion in case immediate removal of the building was desired. However, it should be noted that a greater percentage of them (86% of constructors vs. 66% of engineers) felt that the building could not survive the storm. This could result in more thought by this group on alternative strategies (implosion).

In the category of structural estimates, the constructors showed significantly lower estimates of fatal wind speeds, believed the risk of collapse in 24 hours to be greater than did the engineers, called for greater evacuation radii and believed domino failure posed a greater risk. More constructors (86%) than engineers (66%) believed the building will collapse in a 50 mile an hour wind.

In the use of government resources, six constructors suggested using government assistance in transporting personnel and providing emergency services compared to only two engineers.

In the areas of concern for legal liability (Tables 7 and 10) constructors showed slightly higher levels of concern than engineers did (Table 8 differences were minor). However, this concern reversed when the issue was presented as one of cancellation of liability insurance. In that situation, 86% of engineers would withdraw their services as compared to 64% of constructors. The overall message appears to be that constructors are not going to be any more constrained by liability issues than engineers would be. That is, we can infer that whatever liability protection the engineers require is probably going to satisfy the constructors.

The time needed for engineering calculations and document preparation is not very relevant to the constructor's role because they would not be performing this service. It can be noted, however, that the average constructor estimated the time to properly prepare documents for repair to be 2.5 days, which is quite similar to the engineers' estimate of 2.7 days. From this we could infer that the constructors have a similar understanding of what is required to assess the damage and prepare the documents.

Summary: As noted in Question 1 of the normative model, constructors appear to have stronger responses in areas that are visually evident and reinforced by their own experiences. Thus, they are more responsive to visibly cracked columns, debris loading of floors, and damage assessment. Constructors also seemed to see the issue as part of a *team response* to the problem, whereas almost every engineer saw the assessment of the damage to be a matter of *personal observation*. In short, constructors advocated organizing the site quickly. Also, constructors were more resistant to legal stress than engineers. In a very high stakes game, maintaining focus throughout distractions will be important.

7.4 Discussion of Various Levels of Experience and Expertise

There is a tendency to subgroup individuals within a given group by experience. It is a basic, intuitive and tested assumption that a given individual who has performed a complex task repeatedly will significantly improve his performance of that task. Therefore, repeated practice on identical threshold tasks (testing) to gain admittance to a professional group assures that, for certain predetermined problems, the group will respond consistently within certain parameters or boundaries. In this case, civil engineering degrees and licensing provide these identical group tasks and the traditional boundary of civil engineering is understood to be structural failure. Crossing that boundary is a serious professional issue.

Moving beyond this textbook threshold shared by the group, the practice of engineering divides into various specialties. The elite civil engineers that become high-rise designers join one of a handful of specialized offices in the U.S. or abroad. Designers often become narrowly focused and highly specialized. Although the field is constantly experimenting with new concepts and materials, professional communication through professional publications, peer reviewed journals and continuing education assure a reasonable homogeneity in outlook and approach to problems. At some point in this process, the term "experienced engineer" may begin to be equated with "high-rise expert." If these experts with decades of experience are given a traditional engineering problem, there may be some range to the answers based on personal engineering philosophy, but ultimately most answers will be tightly grouped and show consistency in approach and results.

However, when the design problem *begins* with multiple failures of members, unknown overstressing of the remaining frame, and eccentric redistribution of loading, their problem has, from the outset, moved beyond the defined boundaries of structural engineering. The entire pre-determined mathematical topography that engineering depends upon is thrown into confusion. A partially collapsed building is a mathematical tornado beyond the comfortably gridded topographical Kansas of new building mechanics. As one participant remarked, "It's like finding yourself in another world. You not only don't know how to get out, you don't even know where you are." This confusion outside the conventional boundaries of engineering was clearly shown in the extreme variations of the routine questions concerning wind speed for collapse (Table 11), the risk of collapse in 24 hours (Table 12) and the time required to provide analysis for temporary repairs (Table 15). The basic tenet of engineering that these questions should have produced a tightly grouped set of answers from engineers is nowhere to be found. It is apparent that the damage to the structural frame has produced a disorienting confusion about expedient hazard mitigation.

This confusion suggests a quandary. The traditional definition of a structural engineering expert is a thorough knowledge of the mapped and explored mathematical topography. However, once the tasks move beyond the pre-determined answers of textbooks and the routine of an engineering office, the definition of expert becomes more vague. Is an expert of unexplored terrain the individual who simply knows the most about the adjoining mathematical landscape and in his experience has perhaps caught an intuitive glimpse of the adjoining unknown? Or should he be some sort of explorer who is pre-equipped to launch into this suddenly created unknown on a moment's notice, with a planned agenda to roughly but quickly map the new territory? Can broad generalizations and assumptions for computer generated programming serve where there is a lack of time for the painstaking scientific research that is the foundation of traditional engineering? Or, perhaps, a combination of approaches is required in this strange new land if the twenty-first century means we are no longer in Kansas.

Further confounding our rigorously trained participants finding themselves in an unknown mathematical land is a strange rabbit hole that suddenly plummets to a legal landscape completely beyond the familiar comfort of mathematical logic. Their careers, their firms, and possibly their lives suddenly become subject to rules, laws and precedents for which they have had little training or experience.

The engineers' level of concern about legal liability had dropped radically to the point that 100% expressed no concern. Most importantly, they were still giving advice and no one had walked away. This calmness changed radically in Table 16 when they were informed that their firm's liability insurance had been cancelled. The percentage of engineers expressing "no concern" dropped from 100% to 0% and no less than 87% of the fifteen engineers required immediate releases or completely deferred decision making to others who were not on site. The experienced engineers were also heavily impacted. The actual loss of liability coverage produced major differences among the engineering participants with each of the four alternatives to "no concern" having at least one endorsement and suggested some lack of confidence in their engineering positions. Constructors responded with 79% requiring releases or deferring although 21% (3) continued to express no concern. Although the results from initial questions (Tables 7, 8 and 10) concerning legal risks to the engineers and constructors show that these professionals consistently put service to the architectural and construction community ahead of risk to themselves, the results from Table 16, delay for cancelled liability insurance, provide strong evidence that specific government intervention might be needed to provide an umbrella coverage for experts acting in good faith in emergencies. This need is further emphasized by the divergence of opinion for immediate actions and mitigation strategies.

Summary**:** Overall, experience bodes well for reducing extreme concern and focusing on the issues at hand. The more experienced participants showed less radical judgment to both structural risks and legal concerns. These two areas are important for avoiding expensive and time-consuming overreaction to the dangers and keeping professionals on the job for timely repairs. However, in the matter of laying out courses of action in emergency assessment of the problem and in expedient mitigation strategies, there may be evidence of a tendency for experts to bring previous experience to the problem without a broad survey of the possibilities. This evidence shows up in fewer alternatives listed by the more experienced and educated individuals. In Table 19, participants with 11 to 20 years' experience outperformed more experienced individuals in 10 of 11 repair categories. The counter argument that the latter have just intuitively eliminated impractical alternatives is questionable because these experts themselves list different alternatives, i.e., each lists favorites without identifying strategies that others are listing, even though alternatives are specifically requested. Disagreement among these experts as to the best strategy is prima facie evidence that a broader review could be hugely beneficial. While it can be argued that because this exercise is very time pressured, an early instinctive strategy may be justified in the face of a complete lack of planning. However, a *few* hours to widen the options may also be wise. As discussed earlier, the participants in the exercise identified two separate engineering problems, the overall wind loading and the further deterioration of the local damage with building movement. If improvised strategies are required, all portions of the problem should be identified and addressed - which was not accomplished by the participants. There is a clear need for a pre-planned agenda and concepts similar to medical triage may result.

Assuming the engineers are correct that they need to personally observe areas of severe damage, it would seem logical to use a team, as suggested by the constructors, to identify areas of damage and guide the evaluating engineer to the various sites in the building. The logical personnel for such a team would be construction personnel who would know from experience the appropriate appearance of various structural members and connections. This concept would free the engineers for specific and critical tasks that only they can perform. Meanwhile, the constructors are gaining firsthand knowledge of the problems and the opportunity for understanding the engineers' perceptions of the problems. Other issues such as the floor loading, debris removal, and mobilization of steel constructors would naturally integrate into this process. As far as a possible disruption to the process, constructors showed even less concern about liability than engineers (Table 16).

7.4.1 Effects of Expertise

These questions explore the difference in answers that would be obtained by emergency personnel depending on the quantity of education and/or experience of the individuals whom they enlist for help.

Question 1: How do answers from more experienced engineers and constructors differ from the less experienced?

For this question, we will review Table 6, the number of Participants Taking Initial Emergency Assessment and Incident Management Actions, as well as responses to the questions in Section 3 of the questionnaire.

The results in Table 6 show education to be related to an awareness for the need of documents (A2). However, other issues do not show differences across education levels (A1, A3, A4, A5, A7, A8, A10, A11 and A12). For experience, there were small differences, except for more experienced participants seeing a greater need to conduct a damage assessment. The apparent education correlation for A2 might be due to the fact that the engineers are much more highly educated and the constructors are more field-oriented. However, the differences on A11 between professions do not have corresponding differences between education levels, which suggests profession is the determining variable.

Table 15 shows the time that participants believe would be required to prepare documents or sketches to begin expedient hazard mitigation actions. This table indicates broad disagreement about the requirements to begin repair. The exact question in the exercise is "How much time would it take to properly analyze the structural condition of the building for temporary repairs?" The full range of answers exceeded the table scale on both ends, ranging from a few hours to weeks. The scale on the table was from one to five days or more. The experienced engineers estimated the fastest time for analysis, a mean response of 1.8 days. Their actual estimates are somewhat shorter since two estimated a few hours that translated to a minimum of one day. If we adjust these "off scale" estimates, the mean rating drops slightly to 1.55 days. Of further interest is the fact that four of these five experienced participants are executives. The mean of the executive estimates is only .68 day or about 16.5 hours to run calculation and prepare sketches to begin repairs. This answer begs the question of the definition of expertise and would imply that the issue is as much about one of management position as one of experience.

7.5 Ultimate Goals

7.5.1 Task 1: Mobilize the Resources for Emergency Assessment

The exercise revealed that the respondents varied in their approaches to the problem. No one participant provided a complete analysis or identified all of the actions presented in Figure 7. This suggests the actions considered and implemented in an actual emergency would vary substantially depending upon who received the call to report to the site. It also implies that valuable time could be wasted in discussing alternative options and selecting the best one. However, when answers from all of the participants are reviewed, a "best combination" of action emerges. The options comprising this composite strategy were listed in Figure 7 and Table 6 and are discussed in more detail below:

Initial Response for Emergency Assessment

1. Visit the site as soon as possible with necessary safety equipment, available building construction drawings, a camera, binoculars, cell phones, quality photo transmission equipment and appropriate computers. Staff the site in two steps. The first step is to put the decision maker on site with the basic observation and communication tools. The second step is for a staff member to follow with documents and equipment including structural drawings, architectural drawings, fax machines, etc. and any other relevant support.
2. Locate and obtain a full set of construction drawings with revisions and have them delivered to the site. Many high rises are currently in business contracts with engineering firms other than the original designers. In some cases, the original designers are long since retired and the firm sold or shuttered. This may require the assignment of an individual to specifically locate complete structural sets and transport them to the site, a process that could take several hours complete. The problem is exacerbated because many owners primarily use architectural and mechanical sets for the routine renovations, build-outs, and other "churn" in the building. The only time a

structural drawing is required is for unusually heavy floor loadings, stairs between floors, or clearance studies for air conditioning ducts. On the rare occasion when the use of a structural drawing is required, the collateral result is the loss of the drawing when it is loaned out for the immediate project and not returned. Thus, neither the original engineers nor the owner may have a complete set of structural drawings in an emergency. After all, as one participant noted in this exercise, "Who ever heard of a structural emergency in a high-rise that required drawings?"

3. Determine the firm's Incident Commander (IC). Notifying the firm's senior executives of the situation will trigger an internal discussion as to who will control the firm's decision making at the building site. "Who is in charge" is a perennial problem. Select a "duty officer" and designated back-ups of succession to the position. Define the duty officer's scope of authority. Failure to address this issue is a potential source of delay and is an area in which prior emergency response planning would be valuable. If an emergency response plan is not available, then much of the organization and action described in this list will have to be improvised by the executives during the crisis or at least have their tacit approval. Unfortunately, this study has shown that at least four individuals were required to identify the majority of these recommended key initial actions. Also, an incident that occurred on a Sunday afternoon, as in the exercise scenario, would complicate matters and extend the time necessary to locate the individuals that might normally take charge. There are two probable outcomes to this situation. First, the firm takes no action until most responsibilities are finally decided upon, in which case there is little or no action in the first several hours. This could include the failure to rapidly mobilize the firm and supporting constructors. Second, the firm empowers the first professionals contacted to take charge of initial assessment and preliminary mobilization. The firm may choose to replace this initial IC with more qualified individuals as they are located. The advantage of this second option is that a significant amount of time could be saved. Mobilizing a team and activating facilities/equipment can take place in parallel with the identification of the company IC. Thus, all assets are available when the company IC arrives at the incident scene. The disadvantage could be a greater initial risk incurred by the firm, likely by an individual who may not be a specialist or is not a partner and does not share the

economic cost resulting from large mistakes or legal action. Expedient hazard mitigation of a crippled building requires efficient mobilization of all decision makers and critical skillsets to the building. In this case, an engineering firm would likely be incurring risk to itself in a manner that is difficult for the partners to justify except as a noble public service. When it is taken into consideration that engineering is normally a risk-averse profession, and that even a single failure is avoided at all costs, a rapid, possibly instinctive response to a massive problem is inconsistent to all engineering education, training, and experience. The remarkable result of this exercise is the large percentage of individuals, including executives, who were willing to rush into the breach, and when challenged with legal issues by the scenario, maintained a steadfast determination to assist until professional liability insurance itself was cancelled. There were even unsolicited references to public responsibility and placing the needs of society ahead of personal risk. The great question raised and unanswered in this exercise is the effect of group decision-making. Would an engineering or construction firm as a group show the same risk taking proclivity as was seen in this exercise? If group decision-making is more risk averse, then the notification of firm executives could result in a smaller group of expedient mitigation strategies than recorded here. Again, pre-planning an emergency response organization not only appears to be effective, but is consistent with the engineering predilection for methodical approaches to problems.

4. Identify the engineering team and initiate their notification. This organization may be two-fold, one team at the disaster site (Incident Command Post) and a subordinate team at the engineering firm's office (Emergency Operations Center). The exact composition of the organization may vary with the nature of the damage, the danger at the site, the practicality of running engineering analysis programs at the site on laptops, the location of the structural drawings and the availability of needed communication links and peripheral devices such as scanners and large printers. Another factor is the distance between the site and the engineering offices. It is not inconceivable that one could be in the central business district of a city and the other in a suburb or even that the two of them are in different cities. The initial organizational issues related to locating individuals were discussed in Item 3 above. It also must be remembered that

the engineers as well as the constructors are probably already fully engaged with other projects. In the exercise, all participants seem to assume that their existing work would be subordinated to an emergency such as a critically damaged high rise. If this is true then the organization may simply follow the lead of decision makers rushing to the site If the key managers appear on site, there may be a greater tendency to set up most operations at or near the impacted building. Again, prior emergency response planning could lead to more efficient and well thought out approaches to staffing the emergency response organization.

5. Identify general and steel constructors and mobilize their managers to the site because both general and structural steel constructors will be required. Steel fabricating shops will also require notification but would normally be contracted by the steel subcontractor. Mechanical, electrical, and plumbing (MEP) subcontractors will normally have blanket maintenance contracts with the owner or the owner's management company. The emergency response plan should indicate that these MEP subcontractors will be notified by the building manager. Both the electricians and plumbers should be mobilized to the site immediately to deal with electrical and water damage as well as fire sprinklers. In addition, they may require reassurance from the structural team. All constructors would be contracted on a time and material basis. Assuming normal professional and working relationships, the initial mobilization would be done on verbal orders to be followed up by the various purchasing and accounting groups on the next workday. If there was a complication to these business relationships, in particular if the building owner was known to be in financial straits or bankruptcy, it might not be possible to mobilize for expedient hazard mitigation as there is no legal means to force constructors or for that matter, engineering firms to assist. In that case, it could be days before an effective response is launched.
6. Identify surveyors and mobilize them to site immediately. One of the first pieces of information that will be required to determine the status of the building is its verticality. Severe damage such as shown in this exercise can induce a building to a lean in the direction of the damaged side. The increased gravity loading on the columns on that side is the P-Delta lever effect discussed earlier. In addition to increasing gravity loading on the damaged side, the building will almost certainly increase its wind

movement. This also increases the P-Delta lever as well as actual wind stress in the frame. Highly competent surveyors will be required to determine both the lean of the building and its movement. A close working relation between the engineers and the surveyors will probably be required to assure accurate interpretation of the measurements. It is very likely that some improvisation may be necessary due to the damaged condition of the building. This information is critical in understanding the remaining strength of the building and its response to wind loading. Also, by measuring the existing wind loading and the resulting movement, some projections of movement in higher wind speeds can be roughly projected.

7. Initiate a request for legal support from the engineering firm's and the general constructor's attorneys. While the initial thrust will be in contracts and construction law, other legal specialties, such as environmental, will also be drawn into the melee - the scope of which is outside the bounds of this study. However, there is one goal on which the emergency manager must focus. That, stated quite simply, is to keep the engineers and constructors on the job and avoid a shutdown over liability issues. This exercise showed the willingness of the engineers and their executives, as well as the general constructors and their executives, to aggressively take on this problem in a hypothetical exercise. The one and only issue that finally daunted some participants was the prospect of exposing their firm to unprotected legal liability. This almost certainly would require immediate and aggressive government intervention.
8. Initiate contact with the client's executives and their insurance company, because the ultimate loss will be the client's. For this reason, the engineer and general constructor should establish clear lines of communication for major decisions. Because of the complexity of the issue, it is unlikely that the owner or his insurance company would interfere in most decisions short of implosion. However it is obvious that keeping them informed of the building's condition and possible additional damage necessitated by emergency repairs may reduce the likelihood of post-incident litigation. In most cases, the building manager or the management company will provide much of this interface and actually make the contacts and set up meetings if necessary.
9. Initiate contact with law enforcement representatives. Local law enforcement may defer to the FBI in this case. However, there have been notorious incidents where the

two law enforcement groups clashed on crime sites, one of which was the 1993 WTC incident. In that case, the FBI threatened to arrest local New York Police Department detectives and forced them from the site. The lesson is that law enforcement controls the site under their authority over crime scenes, so the engineering and emergency management personnel should be prepared to make a powerful and well-presented case for their activities on site. It is important to recognize that many FBI agents are lawyers and do not bluff easily. They will protect the integrity of the crime scene at all costs. It is very likely that the only argument that will gain access to the damaged column is the threat that building deterioration or collapse will destroy the crime scene. It must also be remembered that there has never been a high rise incident in which an effort was made to save the building from total destruction and that the devastating domino model is generally unknown (although readily understandable even by those without architectural, engineering or construction expertise). All of these ideas will have to be explained effectively and succinctly.

10. Plan an initial meeting with the entire emergency response organization. This meeting is primarily to get decision makers together with the general constructor and all subcontractor managers and supervisors. The purpose of the meeting is to identify players and devise an incident action plan. As noted earlier, the players would also include surveyors, building management, and law enforcement representatives. One important function of the latter would be to explain the crime scene site protocol that everyone must understand. Lawyers and insurance company representatives may or may not be present depending on circumstances and relationships.
11. Initiate a floor loading and condition review of the damaged floors. Like the survey information this is basic information that will determine access to the most severely damaged area so emergency assessments can be performed. This work could probably be done by experienced steelworker supervisors or engineers.
12. Initiate a rapid but systematic survey of damage to the building structure by a team of engineers and steelworkers. This survey should be planned to be completed in hours, not days, so multiple teams might be necessary. Photos should be taken of the damage so floor and column lines can be clearly identified and their locations confirmed. If

there is a potential for progressive failure due to wind movement, either live or TV observation of the area should be immediately instituted.

The purpose of these actions is to furnish critical engineering data for use in determining the level of damage to the wind frame, any gravity loading issues such as debris or P-Delta shifts, or progressive failures leading to greater risks. From this information, the engineers will make the major decisions concerning temporary bracing, reduction of wind loading, and emergency repairs of damaged connections.

7.5.1.1 Temporary Mitigation Measures for Rigid Steel Frame

This exercise identified a number of expedient mitigation measures that can be used to stabilize a rigid steel framed building. These are:

1. Repair, raise as possible, and reconnect severed columns after checking any increased loading of adjacent columns caused by the pure tension action of failed wind beams. Reinforce damaged connections and brace deep girders.
2. Add X or K bracing to the damaged wind frame by welding or temporary cabling. Remove windows and interior partitions to reduce wind loading on upper floors of the building.
3. Install shoring under damaged floors to reduce the chance of collapse.
4. Weld/shore damaged wind beams if feasible.
5. Increase the capacity of overloaded columns adjacent to the damage.
6. Remove debris where feasible.
7. Review the option of implosion if necessary.

The actions listed above are believed to be the most practical of the options that participants listed for expedient mitigation. Two other options were explored by participants and listed in Tables 3 and 4, but were not included in final strategies due to lack of time for implementation or technical difficulties. These strategies or combinations were used in the decision flow charts for Strategies 3 through 8 and can be viewed as an actual checklist for an event such as the scenario for this exercise.

7.5.2 Task 2: Team Organization for Expedient Hazard Mitigation Operations

All steel framed high-rise buildings suffering a crippling blow are going to require basically the same response for expedient mitigation decisions. Collectively, the engineers and constructors have outlined a response that includes the following as a minimum: an engineering team, a construction team with a general contractor, a steel subcontractor(s), a steel fabricator, an electrician, a surveying team, and a materials testing company. This team will involve a minimum of fifteen people plus the actual skilled labor required for repairing the building. The labor force could be from twenty to two hundred workers at any given time (see Figure 8 for team composition for external impacts on the engineering decision maker).

One of the central problems of expedient hazard mitigation for a steel framed high-rise building is the responsibility that falls on a single individual to make the D1 decision to react to the initial events and initiate mobilization. Although the key decision has been discussed from an engineering perspective, it is actually a safety decision by the building owner. There is a need for an initial financial commitment that will cause confusion and delay if the owner is not immediately approached with rational and solid business reasons for any expedient mitigation actions. It is a major impediment to expedient hazard mitigation and must be addressed.

If the average cost per worker is $150.00 an hour and an hourly average of 100 workers are committed for 48 hours, the total labor cost is $730,000 for this cost category alone. A tool and material cost of one-third of that amount is normal, resulting in a total of approximately $1,000,000 for the expedient mitigation effort. This is not a decision that can be made by a building manager, who is likely to be the individual who initiates the engineering response. However, even if only two buildings collapse, a total loss of over a billion dollars is not unlikely. Indeed, the loss of WTC 7 alone was that amount. Thus, the expenditure is in a ratio of one dollar spent to save $1,000. This estimate of $1 million for expedient hazard mitigation does not include the cost of permanent repairs that could run well beyond one hundred million dollars. Even so, the savings would still approach a billion dollars. While we can assume that this ratio is acceptable to most CFOs, providing the detailed argument to proceed in a format satisfactory to the financial decision maker is an undertaking that may require a concentrated professional effort in several fields. One of the early lessons most business bureaucrats learn is to never rush into a decision. This maxim can and probably will backfire in a fast-moving, high-risk situation such as described in this exercise. The strategies for resolving this decision-making dilemma will require advance planning and education of owners or, more practically, firm government intervention. Unfortunately, the government agencies that have historically had some responsibility in this area show no awareness of the issue. The government thinks of a repair response in weeks, when hours may be required to save the building. As is too often the case, planning will be dictated by bitter experience. It appears difficult at this point to avoid a possibly fatal paralysis in expedient decision-making such as occurred at the WTC in 2001.

7.5.3 Task 3: Adjustments to the Decision Model

Although the normative decision model appears to be valid, there are three areas where adjustments are warranted.

First are the D1 and D2 decisions, which are a combination of engineering and financial choices. Once the engineering decision maker(s) determine D1 and D2, they must convince the owner or government agencies of the wisdom of the selected expedient mitigation actions and gain approval for the financial commitment that accompanies the decision to implement one or more of them. Therefore, the expediency of these decisions is absolutely controlled by the owner of the building, his insurance company and/or government entities with available funding. The engineer's role is one of gaining authorization to begin the process of mobilization and implementation. The normative model could be adjusted to show the outside control of the decision and reflect the accompanying process.

Second is the mobilization of constructors and support personnel starting at the D2 decision point. This is too complex a matter for engineers to effectively organize on site while performing their primary role of making engineering design decisions. The actual mobilization should be largely predetermined and triggered by the D2, D3 and D4 decisions and patterned to fit each action with conditional adjustments determined by constructions managers on site. Thus, entirely different specialists, subcontractors, and materials lists might be called upon depending on the direction of each decision. The constructor's mobilization point could be reflected in an adjunct to the flow diagram with details of who is mobilized down each decision path.

Third, Strategy 7 terminated in one case with the building surviving without intervention, but then being demolished. This was not anticipated and should be added to the chart.

7.5.4 Task 4: Identify Critical Engineering Programs for Analysis of Damaged Structure

One of the most important issues identified in this exercise is the lack of a specific approach for programming computer strategies to this problem. As discussed earlier, the participants in the exercise did not identify any specific pre-programming for the structural assessment of the building. They did, however, repeatedly refer to using engineering programs. The underlying issue was a lack of concept of how to move forward with the analysis. This problem was discussed in Section 6.4.3 where it was noted that structural engineering is a mathematical topography with a known landscape. A damaged building is outside the boundaries of that well-established discipline. Therefore, the most basic principles of an approach to such a problem for expedient mitigation are either not established or at least at not being taught in our schools of engineering. The development of such a program is a key requirement of expedient hazard mitigation and its development should be a cornerstone for an effective response to the imminent failure of a steel framed high-rise structure.

8. CONCLUSIONS

8.1 Concluding the Proposed Decision Flow Chart

The Decision Flow Chart for Expedient Hazard Mitigation appears to be accurate, but deserves additional detail. First is a financial control module for initial engineering decisions D1 and D2 that estimates the cost of the engagement of the engineers and technicians to survey the problem. This is followed by the costs of mobilization of construction personnel for the actual repair. The owner and his insurance company exert this control initially, although government agencies, such as DHS, FEMA, USACE, and NIST, might have long-term involvement. The engineer at this early stage is primarily an advocate for financial mobilization to accomplish the goals of expedient mitigation. For the scenario in this study, the two day cost of an effective response appear to be at least a million dollars, assuming the mobilization of two to four hundred skilled trades (e.g. welders, construction managers, surveyors, engineers and other specialists).

Second, the efficient mobilization of these personnel and consultants for expedient mitigation requires pre-planning and should be tied to individual decision points at D1, D2 and D3. Mobilization management should be a partnership between engineers and constructors (the latter are actually better equipped for the task).

The responses identified in the flow charts for Strategies 1 through 8 (Figures 10-17) by participants in the exercise produced five different strategies to the expedient mitigation problem (the additional three charts reflect varying approximations to permanent strategies). Engineers chose four of the five strategies. The fifth was chosen by a single constructor. This difference reflected divergent opinions among participants as to the condition of the building and even which aspect of the problem required attention. This divergence was grounded in a lack of a single coherent approach to calculate the strength of the damaged building or the circumstances and consequences of this failure. Further confirmation of this lack of consensus on a strategy was the variance in judgments about the lateral strength of the damaged building, from less than 40 mph to over 80 mph (see Table 11). Table 12 further emphasized this dissension where opinions on the likelihood of total collapse within 24 hours varied from 0% to 50%, even among the engineers with 20 or more years of experience. Other data reflected this disagreement and engineers' estimates of time to "properly analyze" the building for expedient mitigation varied from hours to over a week. There was no evidence of misunderstanding the problem or the questions. However, there was strong evidence of a lack of a single coherent approach to the calculations (assessment of the problem) even though the damage was clearly visible and explained in writing with a complete set of plans for reference. Strategies for expedient mitigation were further scattered by questions concerning legal liability and possible loss of professional liability insurance. All of these factors combined to produce the variations of eight strategies shown on the flow diagrams.

These results have two implications. First, the engineering discipline as a whole is very inconsistent in such a scenario. Even the most experienced engineers and executives disagreed on how to proceed, which might lead to over-reaction in the case of a scenario similar to this exercise. In any event, such disagreement will almost certainly delay the initiation of mitigation action. In turn, such delay is likely to decrease the probability of successfully stabilizing the damaged building. Emergency management personnel, faced with wildly varying opinions from engineers, will probably err on the side of safety and evacuate large areas of the Central Business District. The over-reaction could lead to tens of thousands of workers in some of our largest, most prestigious companies and professional firms being forced out of their offices. This evacuation will be exacerbated by the lack of planning for expedient mitigation and the building may be left unstable for many days or weeks. In an extreme situation, hundreds of thousands of work-hours could be lost, because the number of work hours lost increases exponentially with the radius of the evacuated area. (See Figure 18).

However, the ultimate issue is much greater. The compromising of high-rises as power symbols and secure bastions of American business could lead to the abandonment of the architectural form. A few companies have already abandoned the Central Business Districts for “campus” environments on the outskirts of our cities. Moreover, an unknown portion of the workforce is uncomfortable in high-rises at the present time. At which point does lost work, a primal fear of heights, and a shrinking workforce willing to work above the ground drive a company to seek lodging elsewhere?

25	26	27	28	29	30	31	3 Blocks
48	9	10	11	12	13	32	2 Blocks (Recommended)
47	24	1	2	3	14	33	1 Block
46	23	8	X	4	15	34	Subject Building
45	22	7	6	5	16	35	
44	21	20	19	18	17	36	
43	42	41	40	39	38	37	

Figure 18 - Theoretical Grid Showing Buildings Impacted by Evacuation Orders. D2 Decision Recommendation to Incident Commander, Evacuation Radius – Costs. The number of blocks impacted by an evacuation order of 1, 2, or 3 blocks in addition to subject building.

One Block Evacuation Clears 8 Blocks

Two Block Evacuation Clears 24 Additional Blocks (Table 15)

Three Block Evacuation Clears Additional 48 Blocks

If a high-rise district houses an average of 1,000 people per block, then a two block evacuation called for by the average engineering participant will clear 24 blocks in addition to the subject building. Thus, 24 x 1,000 = 24,000 personnel evacuated for one week = 24,000 x 40 hours = 960,000 hours or approximately one million labor hours lost each week. Assuming employee cost in a typical high-rise building is $50 an hour, the loss is $50,000,000 a week from evacuation costs alone. These estimates are very conservative for a major Central Business District.

What happens to a city whose high-rises no longer have a value as real-estate? What happens to a country whose power symbols are violated beyond use?

8.2 Conclusions

The results of this exercise support several conclusions and participants' responses have suggested some areas for future discussion:

1. Engineers are less likely than constructors to recommend immediate implosion, presumably because their education gives them greater understanding of the inherent strength of the building. (Emergency Assessment)
2. Greater education may reduce the likelihood of unjustified extreme reactions to an emergency. (Emergency Assessment)
3. There is evidence that even top experts do not explore all the available options. A protocol to encourage full exploration of options is needed, such as a team approach to the problem, by laying out more ideas for action and options for strategies. (Hazard Operations)
4. There also appear to be great advantages in a team approach to evaluating the damage to the building. The constructors intuitively move in directions that did not occur to engineers, such as immediate movement of surveyors to the site. Introduction of team engineering expertise may also help reduce extreme reactions. (Emergency Assessment)
5. Executives show a more consistent decision method and results than working professionals. (Incident Management)
6. Pre-event research into specific repair concepts for emergency use may greatly reduce repair time and assist decision making in an emergency. (Hazard Operations)
7. There was absolute agreement among all participants to take control at the site and not remotely. (Emergency Assessment)
8. Locating and assembling structural documents of record may be a serious problem. (Emergency Assessment and Hazard Operations)
9. Most participants showed a great moral commitment to assist in such a situation, even in the face of reminders of their personal and corporate liability risks (Incident Management).
10. The threat of cancellation of insurance for professional liability can stop the job if other protection is not immediately provided. (Incident Management)

11. There is great variation in participants' judgments of the survival potential of the damaged structure. Engineering methods to streamline this calculation are badly needed. (Emergency Assessment and Hazard Operations)
12. There were no available professional resources that participants could turn to for assistance with this exercise. (Hazard Operations)
13. The potential for domino failure could cause the evacuation of dozens of blocks with huge long-term labor costs (Figure 18). (Population Protection)

8.3 Planning for a Future Incident

From these conclusions, several areas of planning are suggested.

1. The engineering profession thrives on prior planning for problems, or at least the basic elements of problems. Table 17 clearly showed tremendous disagreement on how to analyze the problem. In this exercise, new calculation concepts were mentioned by at least two participants. These and other approaches need to be explored and expanded prior to their need in some future emergency. Appropriate software for analysis needs to be researched and concepts of likely situations developed. Such prior planning could reduce the possibility of rapid evacuations of large areas caused by a lack of information. But the inverse is even more important, to recognize a deteriorating situation in time to allow the evacuation of tens of thousands of endangered tenants in nearby high-rises.
2. The issue of domino failure requires a serious review. Professionals have widely varying opinions of the likelihood of a series of buildings collapsing in sequence. Is it a real possibility? If so, what can be done about it? This issue has severe implications for evacuation radius (Figure 18).
3. Response teams of qualified high-rise experts need to be identified in advance, and arrangements made to utilize their knowledge in a crisis. Concepts about how such teams would function nationally should be explored because current emergency teams are not focused on high-rises. This exercise showed substantial differences in judgment that could not be clearly attributed to discipline, education or experience. On the other hand, the team concept should help ensure that prior experience does not lead to

abridgements in the decision-making process by the most experienced individuals as reported in previous research.

4. The lists of key emergency assessment and incident management action items and expedient mitigation options need to be highly detailed for use by the response teams and qualified for various locations and types of structures. This detailing is important even with experts because there was repeated evidence that the most experienced individuals tended to take shortcuts to arrive at decisions consistent with prior experience. The procedures outlined in these lists will help ensure that all items receive at least nominal attention. This prior planning will combine with the team concept to further ensure some balance in the decision-making beyond snap judgments.
5. A central repository of major high-rise plans, specifications and calculations needs to be established for every major city. Surprisingly, structural plans are often incomplete or unavailable.
6. Research on actual levels of American workers' fear of high-rises needs to be initiated. This baseline information will be valuable in the future to understand the evolving business impact of damage to high-rises and plan the future or non-future of high-rises. If companies cannot entice skilled workers into high-rises after a future series of attacks, the high-rise real estate market will collapse.
7. There is a need to establish blanket liability protection for engineers and constructors that can be implemented in less than an hour. This exercise showed a great willingness of participants to take risks, but this one issue alone proved capable of stopping the best of intentions.
8. All planning efforts need to remember that the primary issue that separates the production of human-initiated disasters from all others is the concept of flexibility of the initiation. In a natural disaster, engineering strategies will block future reoccurrence of the disaster. If well visualized, even related issues may become moot. In human-initiated disasters, intelligent adversaries will constantly be seeking to circumvent any fixed solution to the risk. Fixed, evident solutions can be circumvented if the result is sufficient. New York City's Freedom Tower is not a solution; it is simply a new problem. Its protections may be circumvented, as were the extensive security

measures at WTC I and II. Secrecy of strategies for current problems may be a partial defense against the creation of new problems.

If the high rise power symbols of our society are compromised, what does it mean to city planning? Do the concentric rings of beltways and intersecting freeways funneling millions of vehicles into American Central Business Districts still make sense or does the corporate campus outside the city show the way for a new era of architectural planning. The exercise showed this scenario is capable of rendering major confusion and disorder in America's Central Business Districts. A modicum of preplanning at negligible cost could change the outcome in some future reality.

9. The most extreme responses for possible collapse comes from individuals with the least education in high-rise engineering. This education level is probably similar to fire department emergency decision makers. The reaction by the fire department personnel should be explored, especially in light of the New York Fire Department response in WTC 7.
10. In terms of comprehensiveness, no single individual identified even half of all of the solutions that the sample generated collectively. Of the major solutions, a maximum of 66% of engineers identified any one option. In a sample of this small size, it is difficult to discuss firm conclusions about the differences between engineers and constructors, among levels of education, and among years of experience in Tables 6 and 7. Nonetheless, the differences among these categories of participants are almost all smaller (usually much smaller) than 30%. Consequently, decisions about expedient hazard mitigation in situations like this should not be improvised by a single individual and perhaps, not even by a small team. Nor, as some might suppose, should it necessarily be composed exclusively of Ph.D. engineers with 20-plus years of experience (who tended to focus in on one solution). The best outcome will require both advanced planning/analysis and improvisation by a large, diverse team.

GLOSSARY

Windframe – A high-rise steel frame with welded joints, designed to resist lateral forces such as wind.

Windbeam – An external beam of a high-rise windframe, typically deep and relatively narrow, fully welded to its supporting columns. Such beams, with their exterior columns comprise a rigid steel wind frame.

Normative – Relating to anticipated "normal" responses.

Shoring – Individual, temporary steel posts with telescoping heads that are placed under floors or floor beams to transfer the load to a lower level of the building. Loads can be transferred through multiple floors as required for gravity loads.

Bracing – Refers to temporary steel members or cables in an "X" or "K" pattern that stabilize a building against lateral loads such as winds.

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APPENDIX A

BUILDING PHOTOGRAPHS

Photo #1

West elevation- H Hour plus 45 minutes

Building: 40 floors 1 million Sq. Ft. Photo is from ground.

Comment 1: Column line C on 21st floor is severed.

Comment 2: Wind is 15 to 25 mph.

Photo #2

West elevation- H hour plus 1 hour

Floors-18 thru 32.Photo is from building across street.

Comment 1: Column C is severed on 21st floor.

Comment 2: Girders above 21 have plastic failure at first and third quarter points.

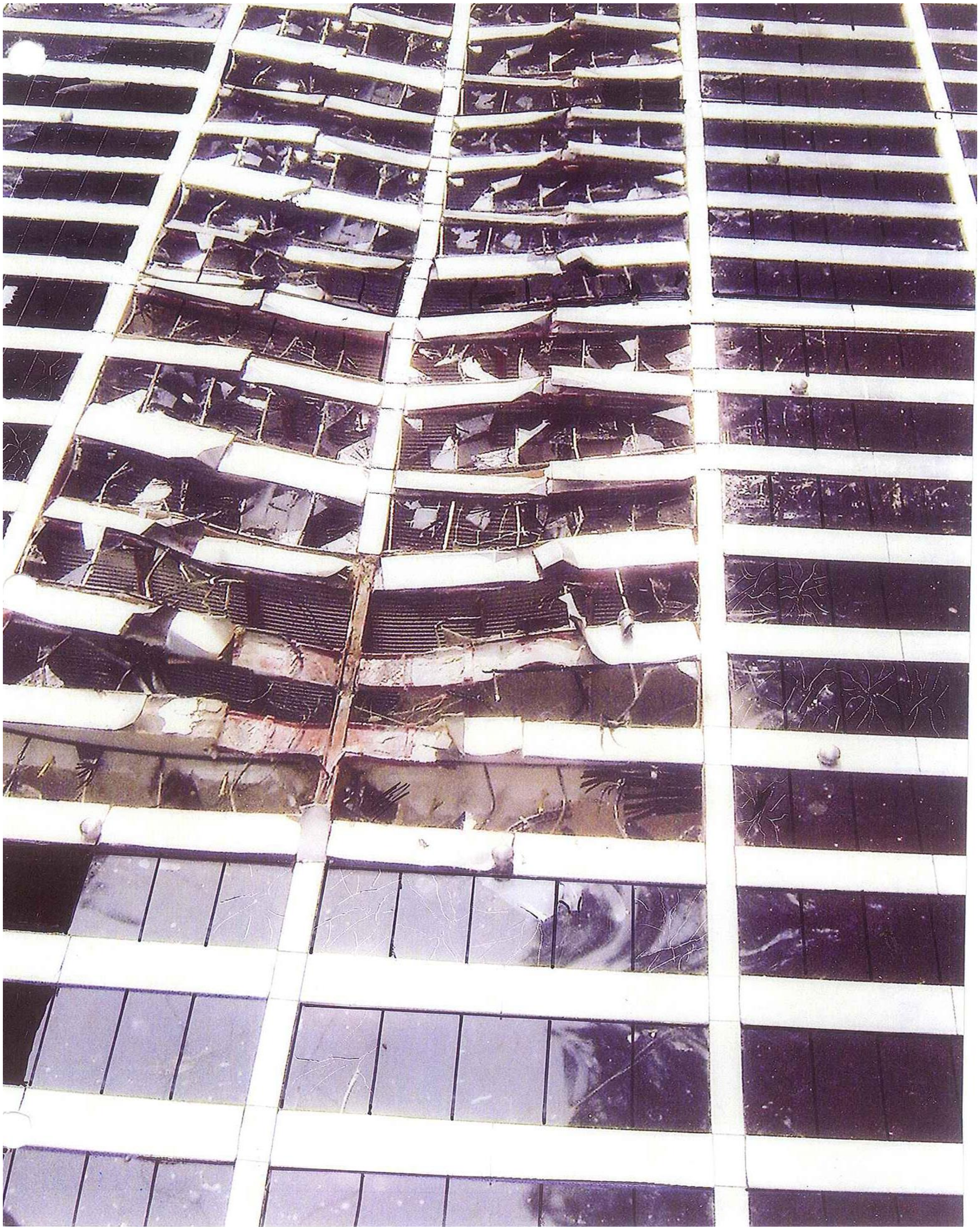


Photo #3

H hour plus 1 hour

Floors 20, 21 and 22. Photo is from building across street.

Comment 1: Column has 5' section missing.

Comment 2: Girder is 2/3 severed at column.

Comment 3: Girder severance is slowly progressing as building moves under wind loading.

Comment 4: Girders have plastic failure at approximately quarter points.

Comment 5: White coating is spray on asbestos fireproofing.

Comment 6: Floor decks on 21 and 22 have failed around severed Column C.

Comment 7: Column has shifted out of alignment 5 to 6 inches.

Photo #4

Floors 20 thru 24. Photo is from building across street.

Comment 1: Floors 21 and 22 have deck failure around severed column.

Comment 2: Collapsed ceilings and debris make access to severed column difficult.

Comment 3: 22nd floor beam 10' off column line C (to left) has severed at girder B-C and fallen to 21st floor with floor deck (see photos 5, 6, 7 for additional views). Failure is visible as black hole immediately to left of column C on floor 22.

Photo #5

H-Hour plus 1 ½ hours

Floors 20 thru 24. Photo is from building across street.

Comment 1: Black hole to left of column C on 22nd floor is from failure of WF beam at girder. Collapsed deck is visible to left of column C on 21st floor. Metal across hole is air conditioning trunk line.

Comment 2: Re: Plastic deformation of girders, note that photo is deceptive, actual plastic points are near third points.

Comment 3: Angle cuts of steel cutting charges are visible on left side of severed column.

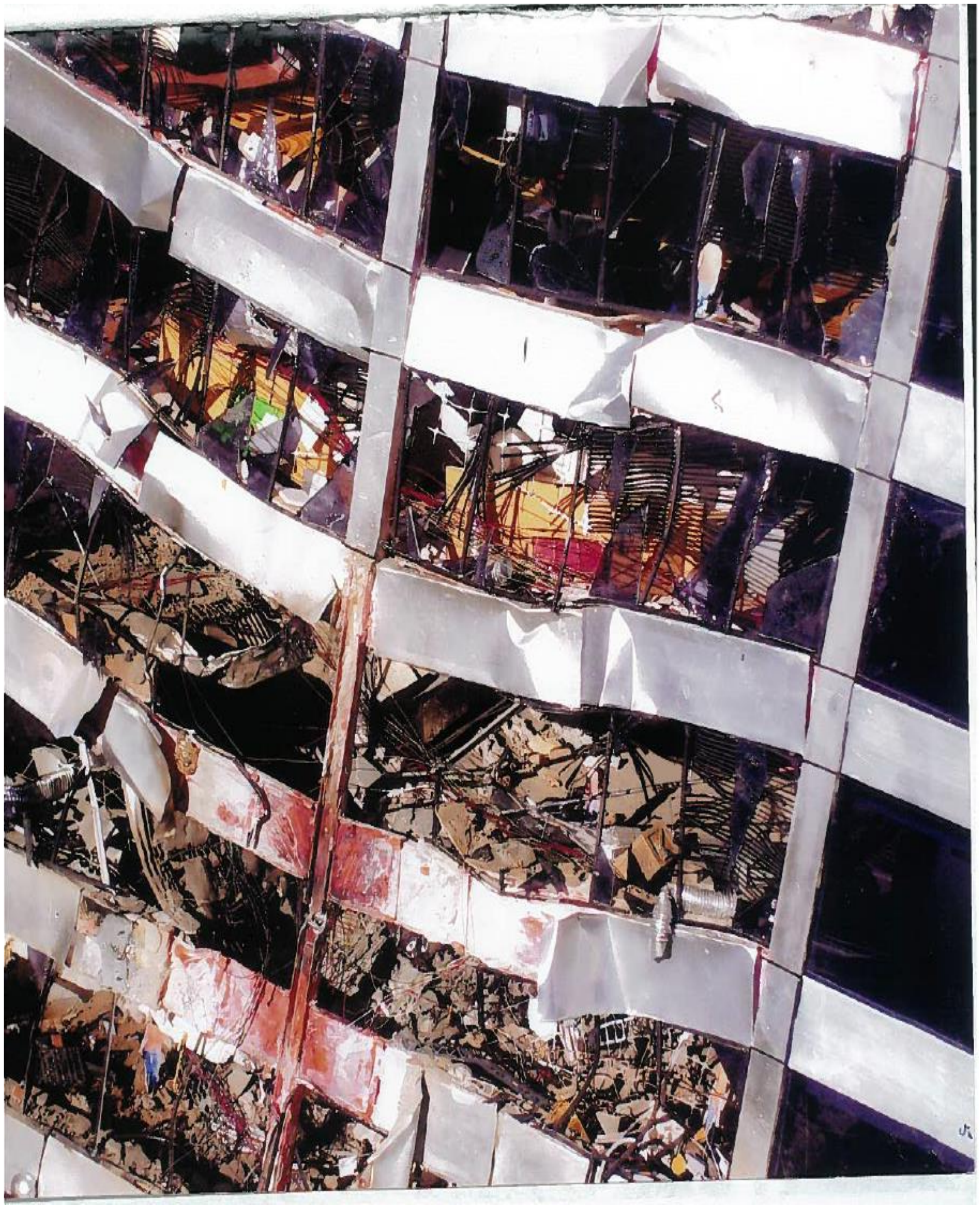


Photo #6

H Hour plus 1 ½ hours

Floors 20, 21 and 22. Photo is from building across street.

Comment 1: Center of picture is collapsed deck from 22nd floor beam failure.

Comment 2: 21st floor girder shows damage from 22nd floor WF beam collapse 10’ to left side of severed column.

Comment 3: Angled cut of steel is visible on left side of severed column.

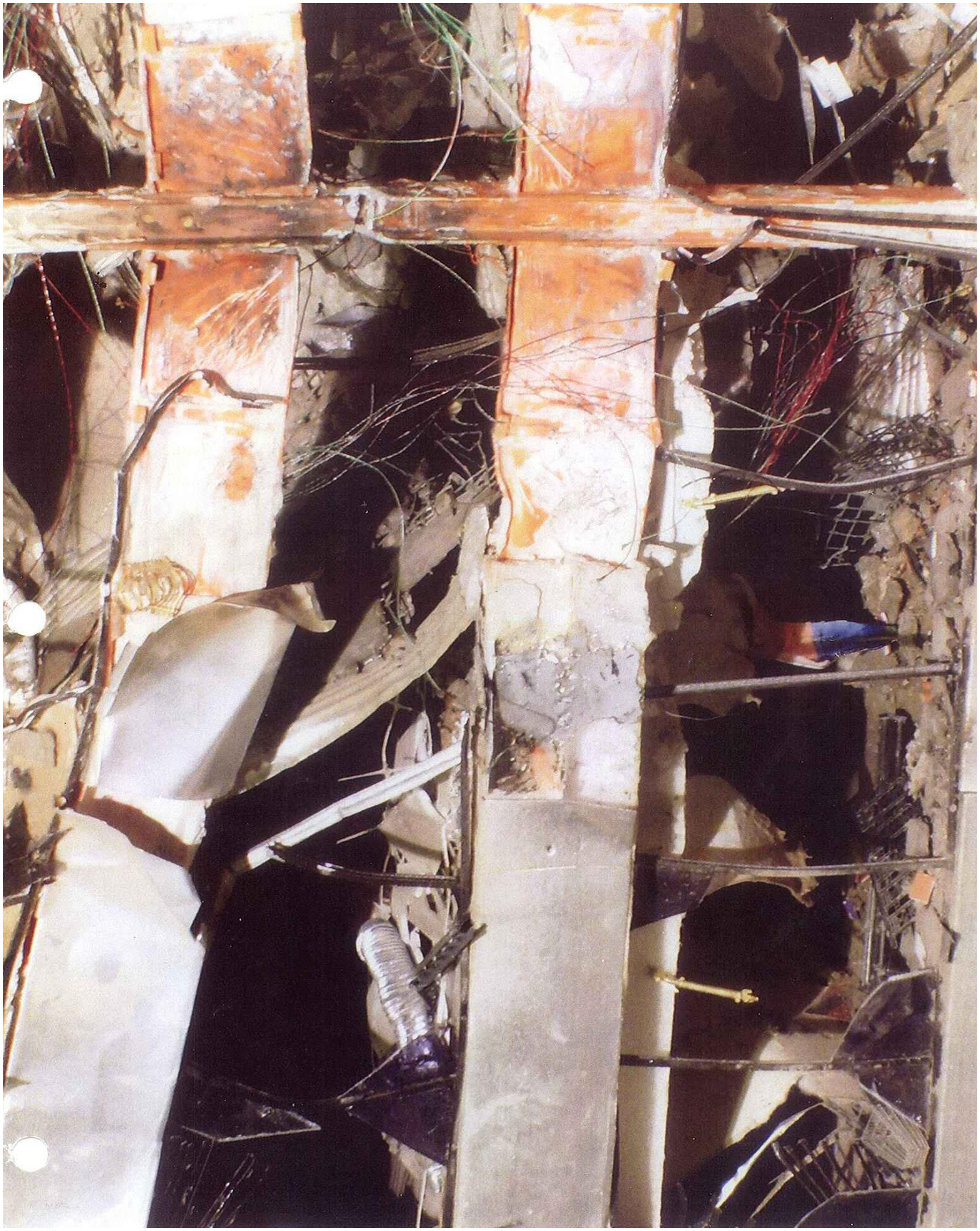


Photo #7

H hour plus 1 ½ hours

Floors 20, 21 and 22. Photo is from 35th floor of building across street.

Comment 1: Angled cut of steel is visible on severed column.

Photo #8

H hour plus 1 ½ hours

Floors 21 and 22. Photo is from news helicopter.

Comment 1: WF beams on Column Line C are visible behind severed column, floor decks are gone on both 21 and 22 around damaged column.

Comment 2: WF beam to left of visible beam on 22 is severed at girder and has fallen.

Photo #9

H hour plus 1 ½ hours

Floor 22. Photo is from building across street.

Comment 1: Disrupted stainless skin and interior windowsill reloading friable asbestos into building and exterior.

Photo # 10

H Hour plus 1 ½ hours

Floor 25. Photo is from building across street.

Comment 1: Floor on background is cracked along column line C and is probably unsound.

Photo # 11

H hour plus 1 ½ hours

Floor 24. Photo is from building across street.

Comment 1 : Floor in background shows crack along column line C and is probably unsound.

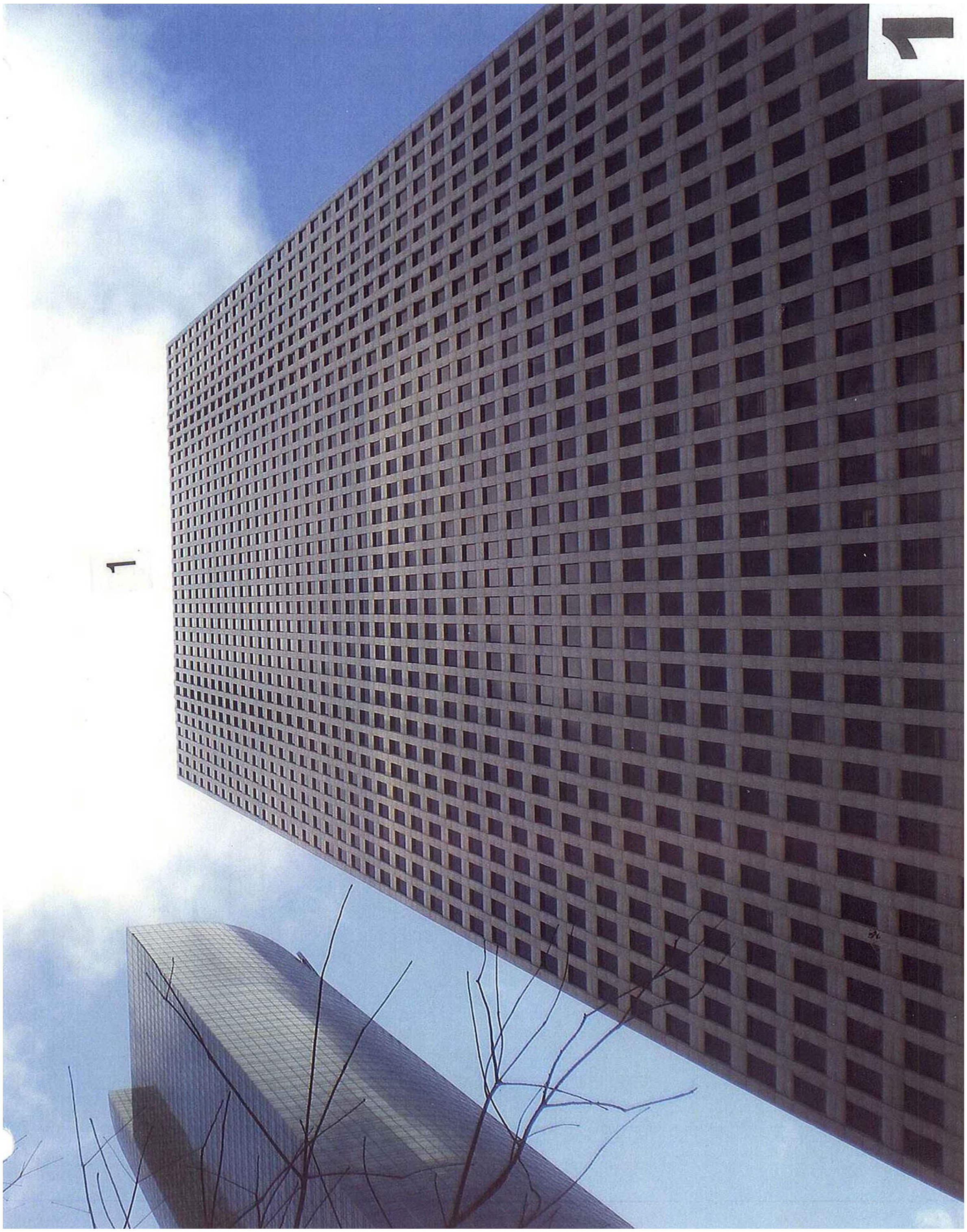
Comment 2: All floors above this level can be assumed to have similar damage with severe cracking along column line C.

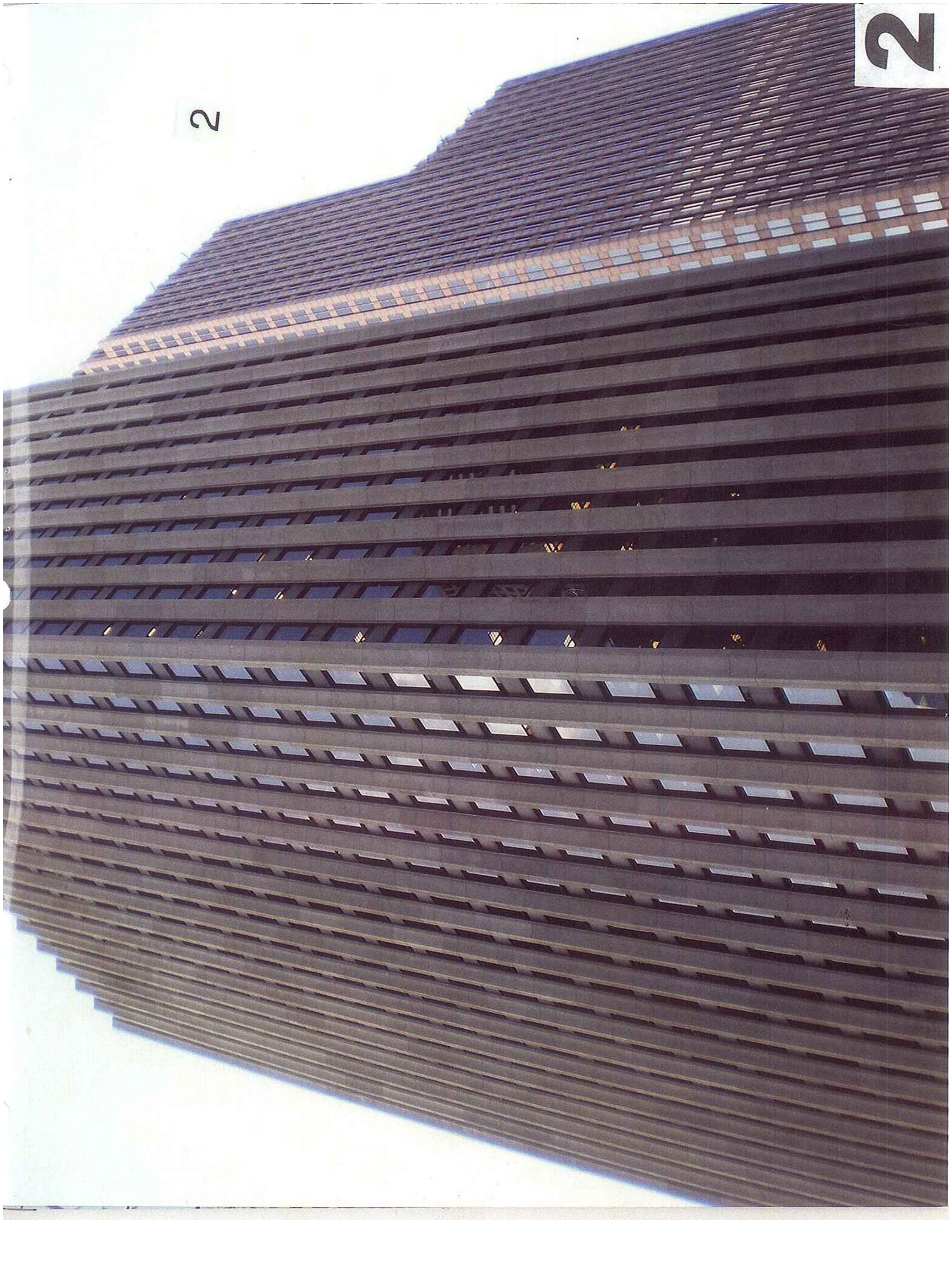
APPENDIX B

BUILDING LOCATION MAP

APPENDIX C

NEIGHBORING BUILDING PHOTOGRAPHS

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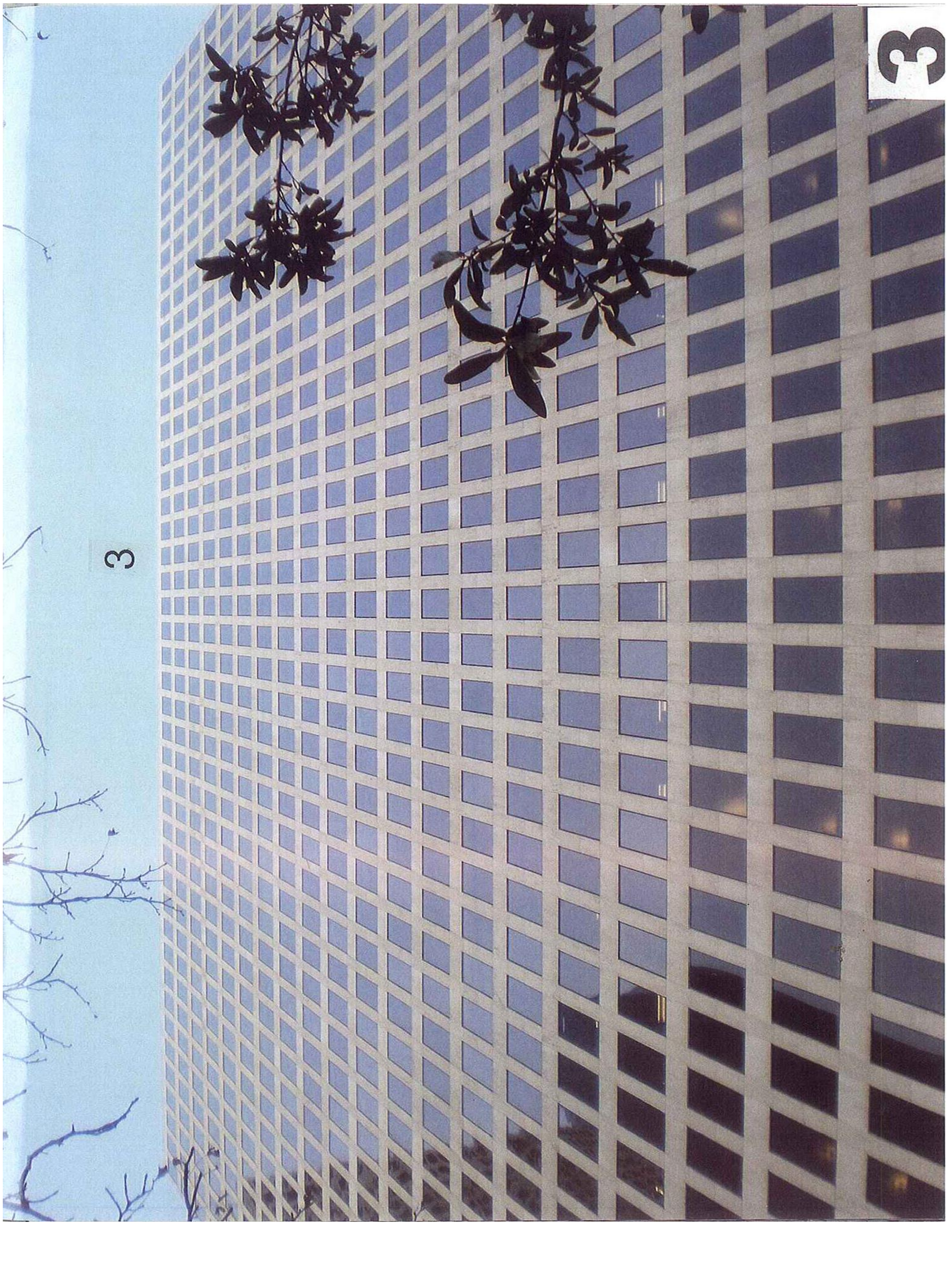
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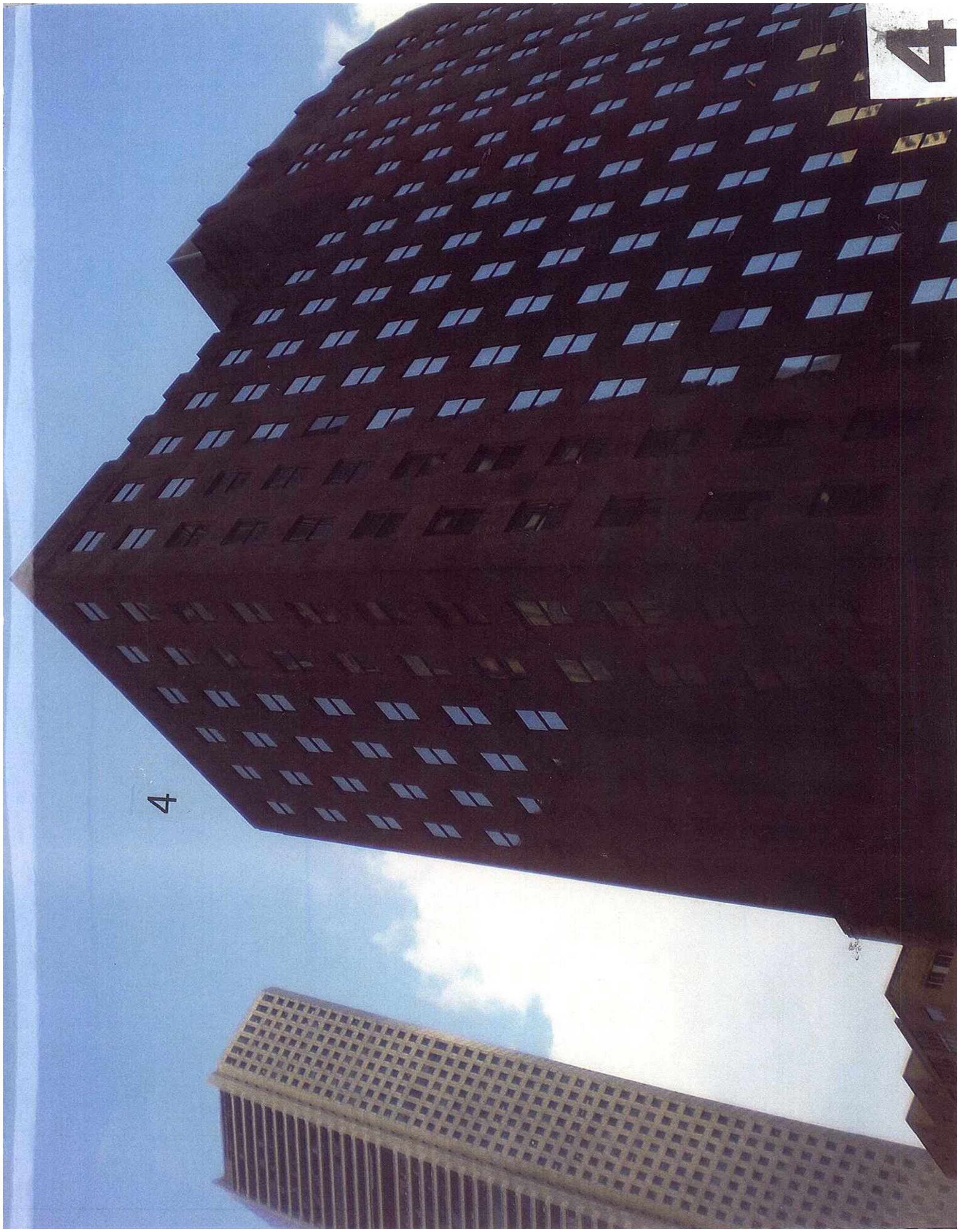
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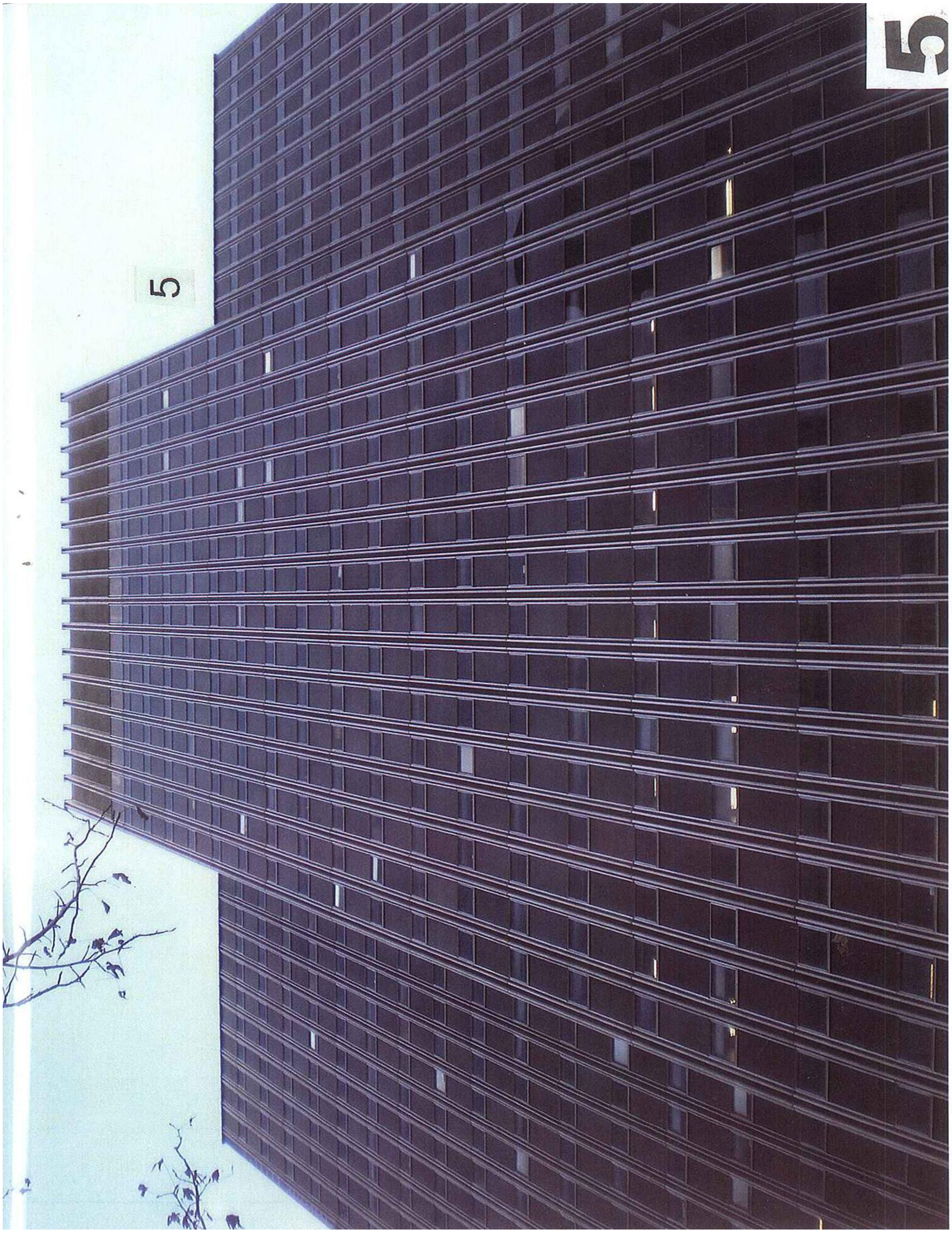
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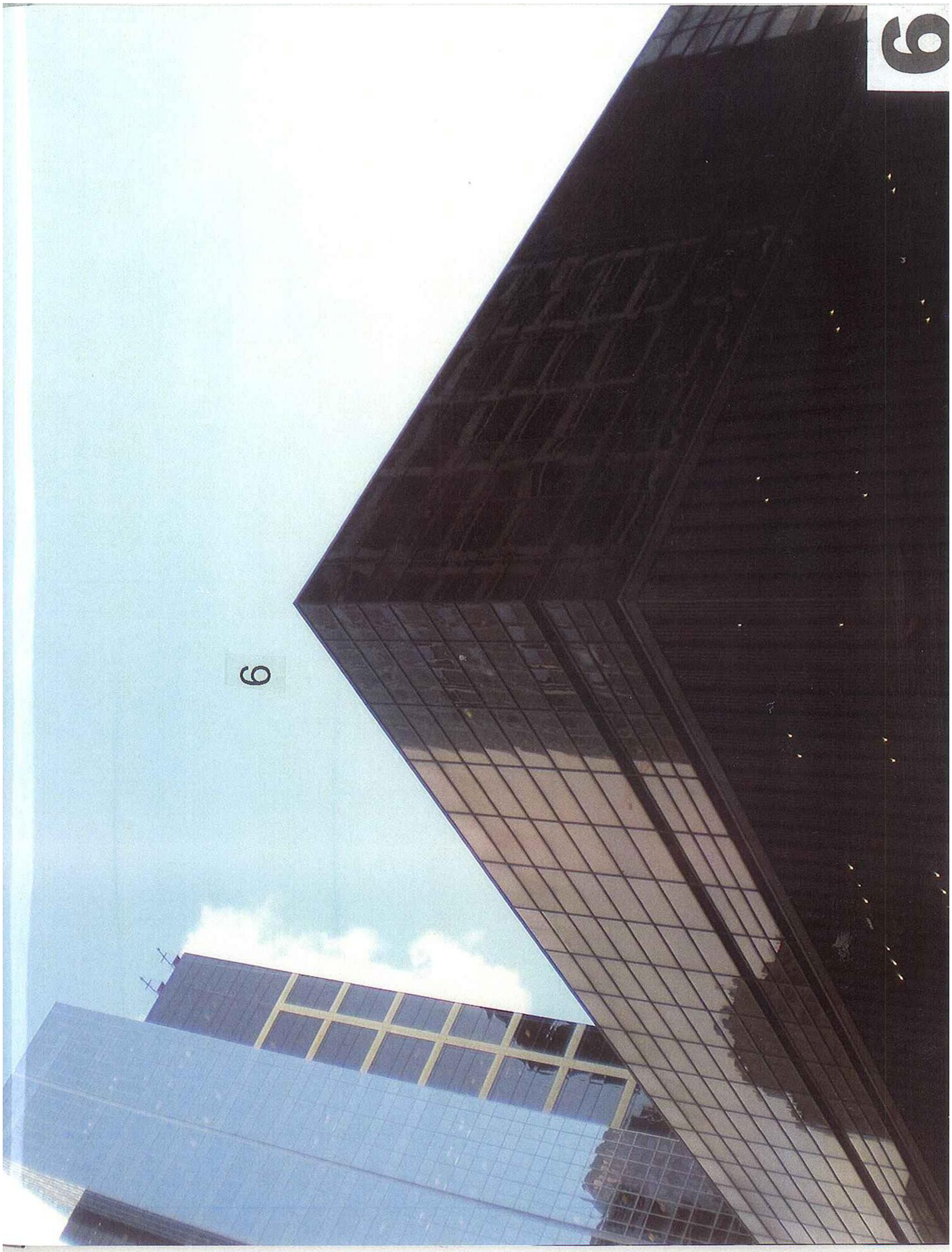

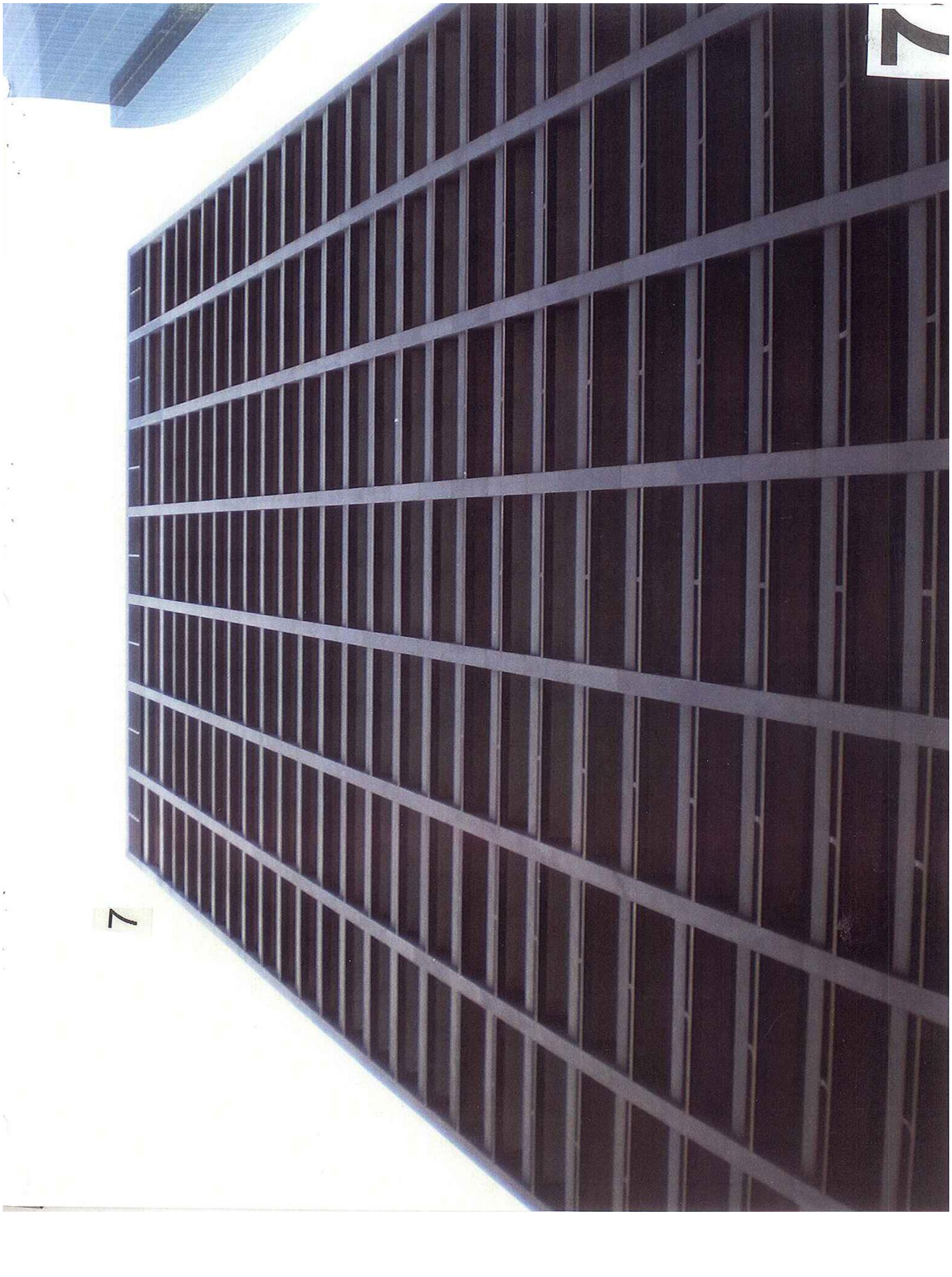

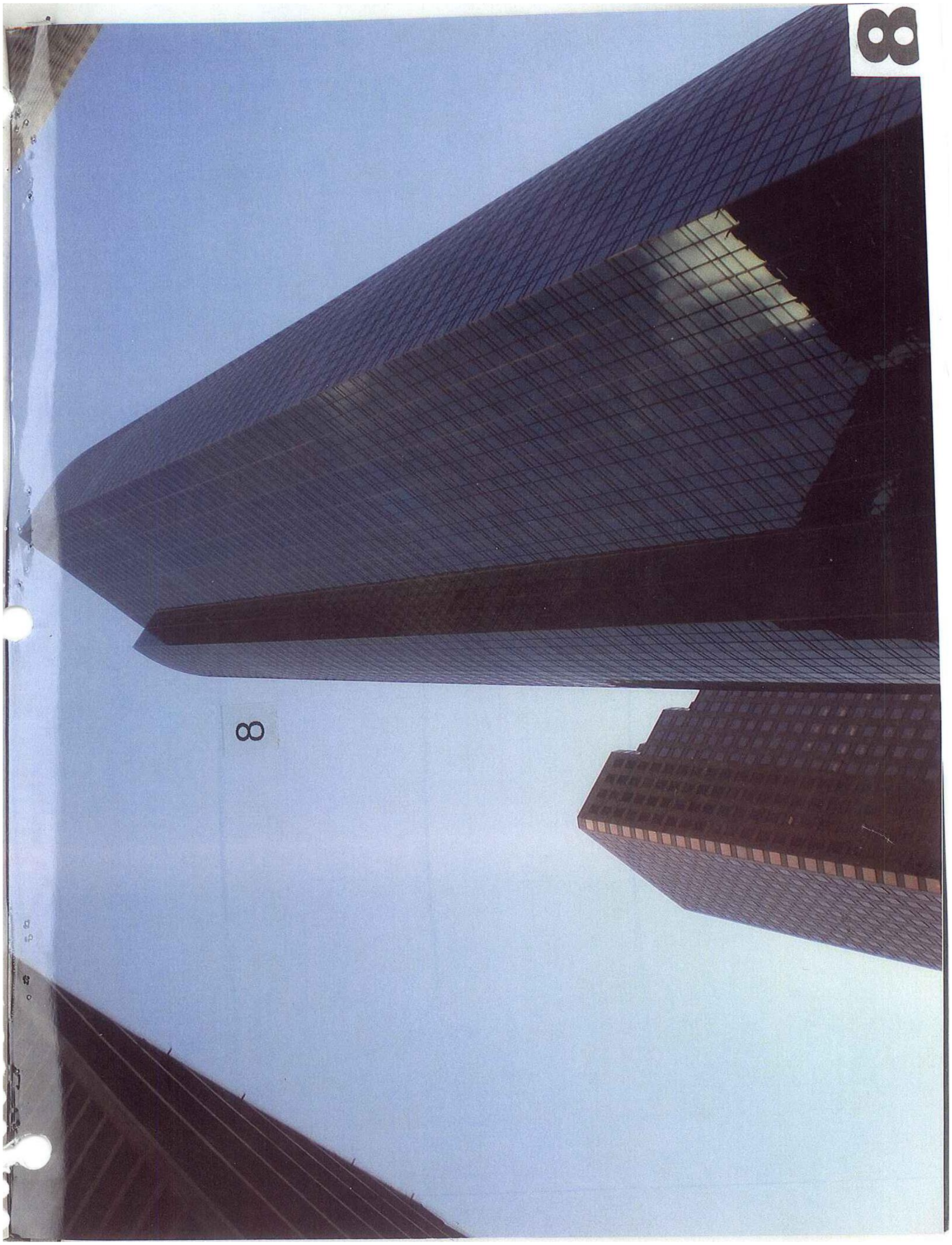
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APPENDIX D

SCENARIO

CONSENT FORM

Expedient Mitigation for a Structurally Compromised
Tall Building: A Decision Model for Crisis Managers
(A Doctoral Dissertation)

Introduction

The purpose of this form is to provide you information that may affect your decision as to whether or not to participate in this research study. If you decide to participate in this study, this form will also be used to record your consent.

You have been asked to participate in a research study concerning decision-making by structural experts in a high-rise scenario. You were selected for your knowledge of high-rise buildings. A total of 24 subjects have been asked to participate in the study. The purpose of the study is to furnish authoritative information to Incident Commanders and Government Emergency Managers about questions that could occur in certain types of high-rise building emergencies.

What will I be asked to do?

If you agree to be in this study, you will be asked questions of professional opinion that might be asked by the fire department incident commander, by local and state crisis managers and the owner of the building, as well as other concerned parties. The questions generally do not have right or wrong answers, but call for professional opinions and explanations. The questions will be in written form and the responses will primarily be multiple choice or a range of choices with some discussion questions.

The study will take about two hours for the initial exercise plus one more hour several weeks later to explain the results to you and obtain your professional opinion about the validity of the information gained.

What are the risks involved in this study?

Risks associated with your participation in the study are minimal and not greater than those associated with daily life.

What are the possible benefits of this study?

The possible benefits of participation are understanding issues that may arise in certain emergencies and questions that may be asked by emergency managers.

Do I have to participate?

No. Your participation is voluntary. You may decide not to participate or to withdraw at any time without our current or future relations with Texas A&M University being affected.

Will I be compensated?
A $100 honorarium will be paid on reviewing the results approximately one month after the questionnaire is completed.

Who will know about my participation in this research study?
This study is confidential. The records of this study will be kept private. No identifiers linking you to the study will be included in any sort of report that might be published, regardless of the report's security classification. Research records will be stored at Texas A&M University and only Gene Robertson, and Dr. Michael Lindell, will have access to the records. The transcripts and questionnaires will be destroyed two years after completion of the study.

Whom do I contact with questions about the research?
You can contact Gene Robertson at (832) 287-9053 or Dr. Mike Lindell at (979) 862-3969 with any questions about this study.

Whom do I contact about my rights as a research participant?
This research study has been reviewed by the Human Subjects' Protection Program and/or the Institutional Review Board at Texas A&M University. For research-related problems or questions regarding your rights as a research participant, you can contact these offices at (979) 458-4067 or irb@tamu.edu.

Signature
Please be sure you have read the above information, asked questions and received answers to your satisfaction. You will be given a copy of the consent form for your records. By signing this document, you consent to participate in this study.

Signature of Participant:__________________________ **Date**: _________________

Printed Name: ___________________________________

Signature of Person Obtaining Consent__________________________ **Date:**__________

Printed Name: ___________________________________

EXERCISE GUIDE

1. Sign two consent form sand remove from booklet.
2. Provide one copy of consent form to subject
3. Place one copy of consent form in envelope
4. Fill out professional background
5. Review professional background
6. Have question list ready
7. Provide blue pen
8. Start clock at 0:00
9. Have subject note time at end of Section 1
10. Switch to red pen
11. Provide:
    a. White photo book
    b. Green photo book
    c. Set of plans and poster
12. Have subject note time at end of Section 2
13. Switch to green pen
14. Have subject note times at end of 3 and 4
15. Have subject note time at end of 5
16. Switch to red pencil for any additional notes
17. Staple question list in booklet
18. Have subject write code on back of booklet
19. Staple booklet shut
20. Collect:
    a. Consent form
    b. Questionnaire booklet
    c. White photo book
    d. Green photo book
    e. Set of plans and poster
    f. Clock
    g. Pens and pencil
    h. (This) Exercise Guide

PROFESSIONAL BACKGROUND

Please answer as accurately as possible and do not hesitate to ask for clarification if needed. The information is anonymous. Do not include your name. Although the following information may be definitive, it will be held confidential.

1. My age bracket is:
   20-25   26 – 30   31 – 40   41 – 50   51 – 60   61+

2. My degrees and subjects (Civil Engineering, Architecture, Construction, etc.):
   - ☐ Bachelors ______________________________
   - ☐ Masters ______________________________
   - ☐ PhD. ______________________________

3. My total years of design or construction experience are:
   1 – 5   6 – 10   11 – 20   21- 30   31+

4. My total years of experience with high rises are:
   1 – 5   6 – 10   11 – 20   21- 30   31+

5. For the last three years, my primary role has been: (check no more than 2 boxes)
   - ☐ Student
   - ☐ The daily preparation of construction documents
   - ☐ Company executive; (CEO, President, V.P.)
   - ☐ Management of construction
   - ☐ Other (specify) ______________________________

6. In relating to high rises, my specialty is: (Place numbers 104 in boxes with 1 as your most familiar and 4 as least).
   - ☐ High rise structural design
   - ☐ High rise architectural design
   - ☐ High rise construction management
   - ☐ High rise facilities management

INSTRUCTION SHEET
(Retain throughout exercise)

The following exercise consists of five sections. The questions include short lists and multiple-choice questions. You will have two hours (or more if you wish) to review, answer and change your answers. Two hours is approximately the length of time assumed for the real events and decision-making issues to occur. The scenario and questions are intended to be realistic and are not intended to revolve around hidden clues or tricks.

The information from this exercise will be summarized (without identifying individuals) and in a few weeks, the questions will be discussed with you and the other participants as a group to obtain a better understanding of the issues imbedded in the answers. This study is not about correctness, but rather of the range of judgments and opinions by knowledgeable individuals about a complex subject.

Most important, treat all issues as you would in reality. If you would refuse a request, then answer accordingly. If you would make a demand, write it down. You may discuss the issue with the representative in the room.

Some sections will be time noted for purposes of determining the time necessary to comprehend and complete that portion of the problem.

Write on the back of your sheet if you need more space. Please note "over" on the front of your sheet. If you wish to delete material, please draw a single line through the deleted words.

During the exercise, photographs showing the subject building and neighboring buildings will be furnished, as will a set of structural plans for reference.

When you are satisfied that you understand the above information, please proceed with the exercise by starting the clock.

Section 1

Please do not review other sections until you have completed the preceding section

Use blue pen

Engineers Scenario (Retain throughout exercise)

I The Scenario

All questions are based on the following scenario. Please study it to understand the environment of the exercise and feel free to ask questions for clarification.

Your own office environment is exactly as it really is.

You are in your office at 3:50 PM on a Sunday afternoon having just wrapped up a project for a Monday afternoon presentation. As you are walking out the door the main phone line rings and you pick it up at the receptionists' desk. A downtown building manager for whom your firm does extensive work says there was an explosion in his forty-story building at about 3:00 PM. There appears to be serious structural damage to the exterior column line on the twenty-first floor. He is currently driving to the building with a police escort from the Woodlands and asks for a structural engineer to meet him at the building to assess the damage. He says he has a set of structural plans at the building in his office, which he believes is accessible. He further says the fire department and police are on the scene as well as his senior building engineer.

The building manager says he must have an answer to the question of how soon can your firm have a structural engineer on the scene. You believe you are about fifteen minutes from the damaged building, but this is not your usual client. The client's engineer is on vacation in Europe. His experience is comparable to your own. You do not immediately know where any of your other structural engineers with high-rise experience are. You do know that the damaged high rise is rigid framed steel and was designed by an out of town engineering firm over thirty years ago, but your firm has performed work in the building for the last twenty years and has copies of the original plans and specifications.

SECTION 1

1. TIME 4:00 PM. Your reply to the building manager's request for an Engineer to come to the site immediately is:

2. Once you have disconnected, you intend to promptly take the following actions:

3. You are unable to immediately locate your CEO or any of your firm's experienced high-rise engineers other than yourself. You leave messages for all of them. You do, however, locate two of your capable young engineers and a senior computer draftsman all of whom live within a half-hour of either your office or downtown. Your directions to them are:

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END OF SECTION 1

End Section 1

Time:____________________

Please return blue pen

Section 2

Use red pen

If you wish to go back and make changes to Section 1, use red pen. If you wish to delete wording, use a single red line to mark out.

Continuation of Scenario (Retain throughout exercise)

Following your actions at the office, you are driving to the building to meet the building manager. You have not yet located another engineer with substantial high-rise experience. You turn on your car radio and hear a news account of the damaged building. An on the scene reporter says that authorities have stated that experts are on the way to perform a structural evaluation of the building. As you approach downtown, you can see damage to the subject building as shown in Figure 1. You notice that the trees along the road are blowing in a breeze fifteen to twenty-five miles an hour.

One minute later, you are stopped at a police roadblock six blocks from the building. You observe that reporters are being denied access. You identify yourself and the officer immediately clears you to report to the Fire Department Incident Commander in the lobby of the damaged building and provides an escort. As you approach the building you can see a large field of broken glass from the upper window walls on the plaza. You also notice what appears to be a large piece of distorted H section on the plaza perhaps five feet long. You find the Incident Commander (a District Fire Chief), an assistant Police Chief, the building manager, and the building owner's Vice President in an intense discussion around the lobby security desk with various subordinates and others, about 20 in all. On introduction, they greet you with relief. The building owner's Vice President defers to you to take charge representing their interests in his presence.

The Incident Commander gives you the following brief report on what is known.

None of the high-rise traction elevators are operational although the hydraulic elevators to the three story underground garage are working. The speculation by the building manager is that power to the roof top switchgear was interrupted when the floor dropped. The building engineer on duty reports that the shafts and guide rails appear to be intact although uneven at some points. He believes the elevators can be operated, though perhaps at reduced speed, if power is restored. Reducing the speed is a simple adjustment. An elevator electrician is working to restore elevator service.

Some water and sewer lines were ruptured necessitating shutting off water pumps.

Some fire sprinklers were activated by the explosion and ruptures in the vertical risers necessitated shutting down the fire pumps.

Power for lighting and wall plugs appear to be out above the twentieth floor but working on lower levels.

A single point of failure (an explosion) apparently occurred on the twenty-first floor at an exterior column. The column dropped several feet and the floors above sagged into the shallow V of the photograph. What is supporting the column and floors now is not clear.

Reports are sketchy, but state that chunks of floor concrete are still occasionally falling and the area near the severed column is very difficult to reach due to a tangle of furnishings, collapsed ceiling, wiring and large holes in the floor for several feet around the damaged column.

As the Incident Commander completes your briefing, a structural engineer you recognize as employed by the City Plan Checking Office walks over from the fire stair and introduces himself.

The Incident Commander suggests that rather than attempting to access the damaged floor that the group should observe the point of failure from the building directly across the street. The group makes a quick visit and observes the damage from several levels, trying to find angles to see details in the building. At one point, the Incident Commander has to ask his police escort to remove a television camera crew doing a live feed so that you may access the best vantage point to observe the severed column. From this visit several photos are made (Figures 2 through 11). In particular observe that Photo 7 is a close-up of the severed column and shows that a section of several feet is missing from the column and the top cut appears to be resting on the stub of the column. The city engineer who was downtown at the time of the explosion tells you that he had climbed to the 21st floor before you arrived and managed to observe the severed column from about twenty feet away for about fifteen minutes. Twice he thought he saw the top section of the column lifting up from the stub an inch or two and then easing back into its present position. He said the movement was apparently related to wind gusts but was infrequent. He also thought he saw crushed grooves in the opposing steel surfaces that were perhaps resisting the top surface from sliding off. This grooving was not visible from across the street but the engineer said he estimates the grooves as a fraction of an inch deep. Photo 7 shows some detail.

Upon returning to the building, the building manager provides the set of structural drawings that you have in front of you. The manager says critical drawings are up to date.

SECTION 2

4. Having furnished this information, the Incident Commander says he knows you haven't had a chance to study the situation, but asks you to judge if it is safe for fire department searchers to continue looking for two missing individuals on the upper floors. There are also a dozen police officers collecting evidence in the building and the FBI is on the way. The building manager adds that his elevator electrician has left the building and is refusing to return without assurance that the building will not collapse. The manager adds that the electrician's cousin died in the World Trade Center and he is concerned that other critical personnel are about to flee the building.

Your answer is:

____

____

____

5. The CEO of your firm returns your earlier call. He is in Istanbul. You brief him and he expresses concern about liability issues but gives you authority to use your own judgment, but to keep him informed of major decisions. He furnishes you the firm's lawyer's phone numbers and suggests you contact them when appropriate. After this discussion you proceed to:

____

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6. Your cell phone rings and your firm's most experienced high-rise engineer is on the phone (If you are the most experienced then this is the next most experienced). He is the only experienced high-rise engineer you have been able to contact. You brief him on the situation and your actions. He informs you he is seventy-five miles north of downtown near I-45 but can leave immediately. He has a cell phone with him but no computer. He states I-45 is jammed with traffic at least 50 miles out from downtown. He then asks your opinion of what he should do. You glance at a clock; the time is now 5 PM. You reply:

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END OF SECTION 2

End Section 2

Time:____________________

Please return red pen

Sections 3, 4 and 5

Use green pen

If you wish to go back and make changes to sections one or two, use green pen. If you wish to delete wording, use a single green line through the words you wish to delete.

SECTION 3

7. The Incident Commander informs you that the incident is on national news, and that commentators are speculating about the risk of the building collapsing. The Incident Commander also informs you that the Weather Channel is projecting windstorms and possibly high winds of 60 mph for Tuesday night (48 hours). The Incident Commander asks if you have any suggestions for actions that should be taken. You respond:

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8. At this point, the City Fire Chief walks up to the group while talking on his cell phone. He disconnects and tells the Incident Commander that the mayor is involved and that his conversation with the mayor was just interrupted by a call from the Governor. He speculates that the Governor is offering assistance; perhaps even to activate state disaster teams. He hands the event commander a list and they step away for a discussion. The Incident Commander turns to you and shows you a list of ten questions. (These are the basic questions formatted for computer analysis).

8. (1.) What is your estimate of maximum windstorm wind gusts the damaged building could survive? Assume thirty minutes of wind measured by standard Weather Service criteria at 30 feet of elevation. Assume the wind would be centered on the South side of the building. The damaged side of the building is the West side). Circle one:

40 MPH or less 50 MPH 60 MPH 70 MPH 80MPH+

Comments:____

____

8. (2) Given the information available, how likely is it that the building will collapse in the next 24 hours, assuming winds that do not exceed 25 MPH (at 30 feet elevation).

Circle one:

0% 25% 50% 75% 100%

8. (3) Given the information available, how much forewarning of collapse would there be, assuming high winds were not involved. Circle one:

NONE A FEW SECONDS A MINUTE

AN HOUR PROBABLY NOT PREDICTABLE

8. (4) What activities or occurrences, other than high winds, do you foresee possibly endangering the building while it is damaged?

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8. (5) Assuming you believed the collapse of the building to be possible during business hours on Monday, how large an area do you believe should be evacuated in terms of city blocks radius from the building? Circle one.

1 2 3 4 5 6 7 8 9 10+

Comments ____

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8. (6) Assuming that the building were to topple against a similar building across the street and in the direction of a continuous line of high rise buildings, what is the possibility that a collapse could result in a series of building failures like a line of dominos? Circle one:

0% 25% 50% 75% 100%

Comments ____

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8. (7) If this building were to collapse under a 60 MPH East wind as described in question 11, how do you believe the building would collapse? Circle one:

COLLAPSE VERTICALLY (WTC) TOPPLE FROM BASE

TOPPLE FROM 21st FLOOR NO IDEA

OTHER (comments below)

Comments ____

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8. (8) How much time would it take to properly analyze the structural condition of the building for temporary repairs?

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8. (9) What significant information about either the building's condition or the situation do you need to continue your analysis. Please list.

8. (10) If your firm's insurer were to void this project's liability coverage, would you continue to serve as consultant? Please explain what you would require to continue.

END OF SECTION 3

Please proceed to Section 4

Time ________________________

SECTION 4

9. How small a package could conceal plastic explosive (C4) capable of severing an 18-inch H section with 1.5 inch flanges in two places? Assume 50 KSI steel.

Circle one:

PURSE SMALL BRIEFCASE LARGE BRIEFCASE

SMALL SUITECASE LARGE SUITECASE

10. You observed that an 18-inch H section five feet long was blown completely out of the building. In your opinion, how long would it have taken one trained individual to quietly set such explosive charges (including the relatively quiet removal of gypsum board wall and fire insulation) that would produce this result? Circle one:

½ HOUR 1 HOUR 2 HOURS 4 HOURS 8 HOURS

END OF SECTION 4

Please proceed to Section 5

Time ______________________________

SECTION 5

II Key Decisions and Solutions

Assuming that you have agreed to proceed with the engineering for a solution to the problem, several key decisions must be made.

Decision #1: A yes/no decision for an engineering/construction response to impending storm winds. Would you initiate work to increase the building's ability to survive anticipated storm winds of 60 MPH (measured at 30 ft) expected in 48 hours. Circle one:

YES NO (No Decision is a NO)

Decision #2A: What possible solutions would you review that might reduce the chance of the building collapsing uncontrolled during the windstorm in 48 hours. Please list and number your ideas.

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Decision #3: Assuming you decided to initiate some action, which of your ideas would you use. Please explain your reasons briefly.

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Decision #4: Assuming that the building survives the coming storm, do you believe the building can be permanently repaired? Please circle one. If yes, briefly state how you would approach the repair of the collapsed portion.

YES NO

If yes, explain:

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Decision #5: If decision #2 had been not to attempt to stabilize the building, are there other possible 48 hour alternatives to reduce risk to surrounding buildings from a catastrophic collapse during the wind storm? Please list any other options, remembering that the full resources of local, state and federal government have been offered to you.

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END OF SECTION 5

END OF EXERCISE, ALL OF YOUR SHEETS ARE AVAILABLE. PLEASE REVIEW ALL OF YOUR ANSWERS AND MAKE ANY CHANGES YOU WISH WITH THE RED PENCIL.

APPENDIX E

ORIGINAL CALCULATIONS

(DELETED FOR CAUSE)

APPENDIX F

EXTENDED DOMINO THEORY

(DELETED FOR CAUSE)