Fire Technology, 43, 107–122, 2007

DOI: 10.1007/s10694-006-8433-5

An Intelligent Evacuation, Rescue and Recovery Concept

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Abstract. Recent terrorist incidents have demonstrated that personnel responsible for decision-making in post-attack and structural fire evacuation, rescue and recovery (ERR) activities can significantly benefit from an expert decision support system. In this paper, a concept is proposed for such an expert system that, through the use of sensor technology, can permit real-time assessment of the extent of blast and fire damage to a building, can recommend immediate actions that can be taken to mitigate the situation and prevent further deterioration, can monitor the growth and spread of fire and smoke, and can be used to aid the rescue workers and evacuees in rescue efforts and safe egress. This comprehensive system, once fully operational, can be used for training, blast damage assessment (BDA), target vulnerability assessment (TVA), pre-event emergency preparedness planning, and post-attack ERR operations. The key capabilities of this system stem from the electronic integration of two critical components: a near real-time intelligent BDA/TVA tool and on-line ERR-related optimization techniques. The implementation of this concept will support faster and more efficient evacuation of a building, ship, or other large structure in the event of military attack, fire, natural disaster, chemical attack, discovery of hazardous materials or biological agents, or other circumstances warranting quick escape.

1. Motivation and System Overview

Numerous terrorist incidents against US facilities (e.g. Saudi Arabia (Khobar Towers), Kenya and Tanzania (U.S. Embassies), Oklahoma (Murrah Federal Building), Persian Gulf (USS Cole), New York (World Trade Center (1993, 2001)) and Washington, D.C. (Pentagon)) over the last decade or so have demonstrated that personnel responsible for decision-making in post-attack and structural fire evacuation, rescue and recovery (ERR) activities can significantly benefit from computer-based modeling and decision support systems [1, 2]. In this paper, we describe a concept for an intelligent evacuation, rescue and recovery (IERR) computer-based system for large buildings or similar facilities that will enable continuous assessment of processes associated with a general force protection program and will provide dynamically updated instruction for on-line operations in response

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to evolving conditions and further threats or attacks aimed at the facility. Specifically, it will: permit real-time assessment of the extent of blast and fire damage to the building structures; monitor the growth and spread of fire, smoke and other hazards; recommend immediate actions that should be taken to mitigate the situation and prevent further deterioration; and will aid rescue workers and evacuees in rescue efforts and safe egress. In addition to its utility for on-line post-attack and structural fire ERR operations, the system will enable training, full-scale blast (and fire) damage assessment (BDA), target vulnerability assessment (TVA), and pre-event emergency preparedness planning. These capabilities are integrated into a comprehensive system for both civilian and military facilities. The implementation of this concept will support faster and more efficient evacuation of a building in the event of military attack, fire, natural disaster, chemical attack, discovery of hazardous materials or biological agents, or other circumstances warranting quick escape.

The key capabilities of the IERR system stem from the electronic integration of two critical components: a real-time BDA/TVA tool, referred to herein as the damage assessment tool, and on-line ERR-related optimization techniques. The former component will be used for providing real-time analyses of the current and predicted future operational capacity of a building and its circulation systems (i.e. means of egress). The latter will employ this information in providing dynamically updated optimal instructions for the evacuees and rescue workers. Specifically, it will be used to determine optimal and robust (i.e. likely to remain optimal or nearly optimal even under variable conditions) tactical and operational strategies for rapidly evacuating a large damaged building, e.g. a burning building or a building that has come under attack by enemy or natural catastrophe.

Circumstances immediately following post-blast events and that arise in a structural fire are physically hostile and mentally confusing. While advice from experts concerning evacuation, rescue and recovery is critical immediately following such events, needed experts may not be on-site at the time of the blast and/or fire, may have only limited (if any) access to observe and collect data due to safety concerns, or may not be able to provide instantaneous post-attack or structural fire analyses (i.e. analyses of the fire's impact on structural stability) as such analyses may require extensive data collection and computation. Response personnel typically rely on firefighters and fire officers at the scene of a building fire to, in real-time, detect structural fire damage that may lead to collapse of the building or entrapment of fire personnel [3]. It is inconceivable to expect that such real-time collapse analyses be conducted by personnel who are unfamiliar with the particular structure, who are not trained in structural engineering, and who are urgently needed for rescue and recovery operations. There are myriads of instances where such dangers go undetected and fire fighters have, as a result of building collapse, perished. To enable investigators who may or may not have expertise in structural analyses to conduct on-line post-event damage assessment and to provide real-time guidance to evacuees and rescue workers, the IERR system employs sensor technology and intelligent computational tools, embedded in an electronically integrated and automated system.

Post-attack conditions, or conditions concurrent with a structural fire, are often characterized by dangers that strengthen and spread over time [4]. Such circumstances induce the possibility that sections of the building may become inaccessible or impaired (i.e. unable to operate at full capacity) during the course of the evacuation. Thus, successful egress may be inhibited by partial or complete failure of key escape paths, as may occur if a stairwell were to become impassible due to smoke. Even if we know the exact location and characteristics of the blast, or the origins of the fire, one cannot know how the situation will progress with certainty. It is crucial to explicitly consider the dynamic and uncertain nature of conditions within the circulation systems of the building in providing instructions to evacuees and rescue workers.

Consideration of the dynamic and uncertain nature of near-term future operational capacity in determination of the evacuation path strategies will give rise to robust intermediate evacuation plans with lower probability of failure than paths determined otherwise. Instructions that do not consider the evolution of damage to the building over time and threats of probable additional destruction and deterioration can result in suboptimal decisions that can lead to unnecessary imposed risk and unnecessary lost lives. As the IERR system enables such consideration, resulting instructions will explicitly consider the imposed risk of potential means of egress and will, thus, instruct the evacuees to move along paths with low risk of failure (i.e. low likelihood of being trapped or of exposure to carbon monoxide and other lethal gases) and not simply the paths with the lowest traversal times.

2. The Damage Assessment Component

The IERR system relies on a damage assessment component to provide predictions on near-term structural performance, load carrying capacity and reliability in response to extreme loads resulting from an explosion, structural fire, or similar event. In such circumstances, the immediate and yet unrealized responses of the building are difficult to predict, as they depend on the magnitude and location of the explosion and building properties.

Damage assessment is composed of a number of steps that are designed to assist in (1) identification of an existing condition, referred to as symptom observation [5], (2) condition and severity diagnosis, (3) cause (in terms of structural changes) recognition, and (4) treatment identification. Through this process, it is possible to then map symptom observations to possible failure modes. By inferring a sequence of events that may have caused the observed symptoms or conditions, damage assessment can determine the current structural condition, potential unrealized damage as existing loads are redistributed throughout the building, as well as near-term future operational capacities of the building structures.

Several works have addressed the creation of expert systems for damage assessment of key infrastructure components, such as protective structures, bridges and roadways ([5] through [17]). Some of these expert systems' goals stop short of suggesting treatments and may only assess damage states or speculate the cause of damage.

These expert systems differ, not only in their goals, but in the way each of these steps is carried out and in how information employed within the system is modeled. For example, many authors propose the use of fuzzy-set representation to model observed symptoms, including inspector confidence/certainty in symptom type and severity. A benefit of fuzzy representation is that it can handle the subjective nature of inspector opinions and imprecision in empirical data. Thus, it can be used to combine quantitative and qualitative descriptors in making inferences regarding current conditions and modes of damage [6, 9–11]. Such fuzzy set representations can be embedded in higher-level algorithms, such as neural networks [15], Petri nets [16–18], genetic algorithms [14], and specially designed rule-based systems [7–9] to provide decision support, e.g. providing serviceability ratings and treatment recommendations. Krauthammer et al. [13] proposed a combined symbolic-numeric approach to damage assessment that does not rely on fuzzy set theory, but nonetheless addresses the uncertainties present in accurately describing observed symptoms, estimating causes of failure that lead to the observed damage and in determining future structural capacities (similar to serviceability ratings).

An expert damage assessment tool is an essential component of the IERR system described in this paper. Specifically, the damage assessment tool will (recognize symptoms of failure modes as they arise (e.g. as damage is incurred as a consequence of a blast and/or fire), will determine the condition of the building structures based on these symptoms, including sequence and location of structural responses, and will identify possible failure modes that lead to the damage. The primary goals of the tool are two-fold: to provide treatment recommendations to be used in recovery efforts and to assess the current conditions and predict future resistive capacity of the building as a consequence of the observed damage modes. This latter capability will enable prediction of the continued (and yet unrealized) response of the building to any future loading events, further fire damage, and/or progressive collapse for use in predicting circulation systems capacities and other related attributes.

The ability to, in real-time, detect failure in the building structures, assess its cause and predict near-term future performance of the building and its circulation systems in the proposed IERR concept is enabled through the use of sensor technology, real-time data processing techniques and computer-based modeling. This differs from the techniques described previously, where it is typically assumed that symptoms observation is made through visual inspection and empirical testing. With the exception of collapse assessment conducted by fire personnel at the scene of a fire, these largely manual procedures are conducted off-line. This is acceptable for the majority of applications, as most of these procedures were developed primarily for use in maintenance and management of infrastructure components and systems over a long time period or in assessing a building for future occupancy in post-fire analyses. However, such manual procedures will not suffice for on-line use as described herein.

In the IERR system, information on the current state of the structure, including orientation (to detect a change in geometric configuration), temperature, pressure, strain, toxic gas concentrations, deflection and acceleration, as well as forecasts for near-term failure of the structure and any of its components, is received via sensor technology. The structural response to a typical high explosive (HE) event can be divided into two phases: the initial blast-induced damage phase, i.e. a very short blast phase, lasting up to 50 milliseconds (or longer for large amounts of HE or in the event of a nuclear explosion) and the much longer post-blast phase lasting on the order of minutes (nearly an hour in some recent events). The rate at which the data acquisition system transmits the signals from the sensors to the damage assessment component must be fast enough to operate in both phases; signals must be sent frequently (as fast as 10^6 readings per second per channel) during the first phase and much less frequently during the second phase. High speed data acquisition systems that can acquire, digitize and transmit data at sufficiently fast rates to support the needs of the IERR system are widely available.

Signals can be analyzed in both the time and frequency domains to identify characteristic signatures that indicate a shift from one behavior mode to another. The structural damage assessment capability is performed based on data recorded by these sensors using computer codes, DSAS [19] and ABAQUS [20]. Numerically, DSAS can be used to assess the response of individual structural elements to blast, shock, or impact. Sensor data can be used directly for damage assessment, as described later, herein, and for the validation of numerical analyses (e.g. comparing the computed and measured structural deformations). For a numerical analysis, the user may select an option to perform either fully nonlinear single-degree-of-freedom (SDOF) or Timoshenko beam analyses of selected structural elements. These analyses are performed by solving the dynamic equilibrium equations that contain the externally applied dynamic loads and the internal structural resistances associated with all relevant resistance mechanisms (i.e. flexure, shear, axial forces, etc.). The applied loads are defined based on a specific explosive incident, while the internal structural resistances are based on load-deflection or moment-rotation relationships that address appropriate equilibrium, compatibility, and material models. The analysis provides detailed behavior time histories (e.g. loads, moments, internal strains and stresses, diagonal and/or direct shear effects, deflections, or support reactions and/or rotations). These results are used for assessing damage in the selected structural elements that is performed in accordance with damage definitions in typical design practices (e.g. [21, 22]) and by employing advanced concepts of pressure-impulse (P-I) diagrams [23]. Fire effects can be included by modifying the material properties for the associated temperature changes in the affected structural elements.

Design damage criteria are based on the magnitude of structural deformation under the applied loads (e.g. magnitude of the support rotations or structural deflections). For example, light damage is associated with support rotations of under two degrees, moderate damage with rotations between two and five degrees, and heavy damage with rotations between five and twelve degrees. The P-I approach is much more specific, since one can derive P-I curves for any level of structural response (e.g., initial cracking, reinforcement yielding, or reinforcement rupture). The pressure and impulse for an explosive incident are uniquely defined by the explosive charge weight and distance to the structural element [21, 22], and they are represented by a point on the P-I diagram. If the point is on or above the P-I curve, it indicates that the load will cause the structural element to reach or exceed the damage criterion used for that curve. If the point is below the curve, the load will not cause the structure to reach that damage criterion. Once the localized damage is defined by sensor data and numerical analyses, one can assess its effect on both the circulation system and follow up structural analyses. Such information can be fed into an AI capability (e.g. [13]) for automatic damage assessment that defines the state of a structure at the end of the blast event. The damage evolution that follows the blast event can rely on additional sensor data alone; however, predicting structural behavior after the blast requires the use of more advanced analyses.

The use of an advanced finite element code, such as ABAQUS, for a comprehensive progressive collapse analysis of the entire building, was described in [24]. In such analyses, a damaged structural element is removed from the three-dimensional model of the building, and the damaged structural model is allowed to respond to the applied loads (i.e. any combination of gravity loads and/or temperature changes associated with a post-attack fire). The corresponding sequence of additional damage is noted and used to define the damage evolution in the building.

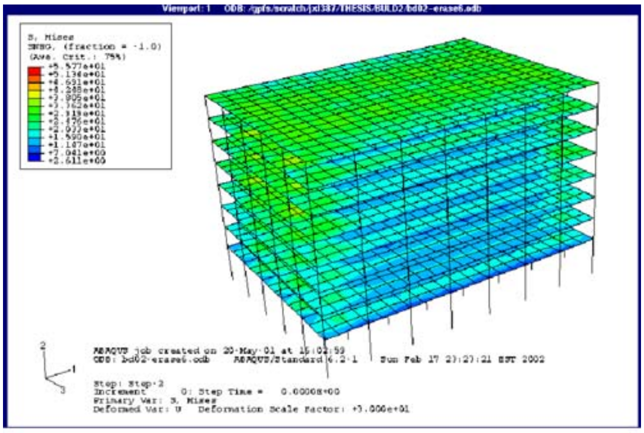
Sensor technology can also aid in detecting, tracking and predicting hazard evolution (e.g. fire growth and spread) throughout the circulation systems. Smoke, heat, flame, temperature, humidity, air quality, air movement, and gas sensors can be employed to predict the heat release rate of a fire, flashover potential, presence of toxic gases, conditions of limited visibility and other hazards. Numerous emerging technologies (e.g. distributed fiber optic temperature sensors for heat detection, optical smoke detectors, thermal video camera systems and other computer vision technologies, synchronized chemical sensors, and multi-sensing detectors) and advanced methods for employing these technologies (e.g. pattern recognition algorithms, image processing, neural networks and other analysis tools) exist that, in addition to many widely used technologies, can support such detection under extreme conditions. A review of many of these technologies and metholodologies for employing these technologies for fire detection can be found in [25]. A sensor-driven fire detection model employing data from multiple heterogeneous detectors is proposed and analyzed in [26]. Multi-function sensors for fire detection are described in detail in [27]. Both [26] and [27] describe detection systems that by simultaneously analyzing information concerning multiple hazard signatures can lead to reduced false alarm rates and increased ability to track and predict fire growth and spread. A sensor-driven fire detection model that simultaneously analyzes data from multiple signatures at a central fire control panel as conceptualized in these works will be employed within the IERR system.

Information concerning the state of the structure or evolution of fire and smoke will be used to predict current and likely future conditions of the circulation systems. For example, such technology could be used to assess instantaneous measures of stress intensities that could be used to determine which structural components (e.g. columns) failed and to forecast if and when other parts of the building might also fail. Predictions of near-term structural damage or spread and dispersion of fire and smoke can be used to forecast stairwell and corridor closures or blockages, as well as other incidents that could prevent or inhibit egress or endanger fire personnel.

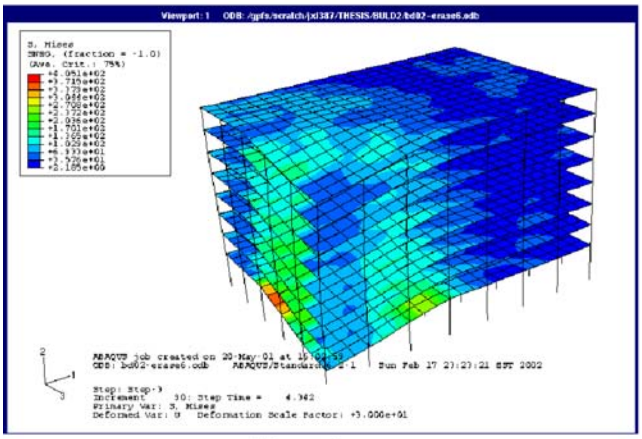
Figure 1 depicts an eight-story building that has been damaged by removing corner columns at one corner, as might occur if the building were to be subjected to a blast in that vicinity. Within seconds of removal of these columns, the stresses shift away from the corner and are redistributed throughout the building. There is then a response by the structures to this redistribution. Subsequent swaying and interactions within the structures take place and within minutes (or perhaps as long as a few hours), the remaining structural elements could begin to fail. This type of failure may occur very quickly or may be gradual, depending on the building's and the load's characteristics, as well as the damage evolution. Figure 1 shows the stress intensities before and four seconds after the columns were removed, indicating that the stress intensities begin to redistribute throughout the structure in response to the structural changes.

Similar circumstances might arise from accidents or as a consequence of fire. For example, in the Ronan Point collapse, a gas explosion in a kitchen created a lateral impact load that took down a load-bearing wall. The floor above that was supported by this wall collapsed, created an impact load on the floor below and successive collapse of the underlying floors ensued [28, 29]. Even without an explosion, structural fires can cause changes in loading, which can lead to collapse. An in-depth description of various types of building collapse that may result from structural fire is provided in [3].

Whether the structural damage is caused by a malicious attack or by an accidental occurrence, knowledge of actual and predicted failure in the building structures and of the growth and spread of fire and smoke that often follows a blast of this nature can be used to detect and predict reduced capacities and failure in portions of the circulation systems.



(a) pre-damage



(b) post-damage

Figure 1. Stress intensities in an eight-story building.

The optimization component of the expert system described next employs this information in providing dynamically updated robust and optimal instructions for the evacuees.

3. Providing Optimal ERR Instructions

The IERR system can be used to address both emergency preparedness planning and real-time execution. Tactical preparedness concerns involve, in part, the selection of carefully planned *a priori* evacuation paths and path finding assistance for the rescue workers that consider the inherent dynamic and uncertain nature of conditions that exist in emergency situations requiring evacuation. Operational concerns address the on-line determination of evacuation and rescue paths (to aid in safe egress or in seeking refuge), as well as operational assistance in recovery efforts. These are updated in real-time as actual conditions of the building structures and circulation systems are revealed and predictions related to risk of continued failure concerning the structural members and portions of the circulation systems are updated. Such on-line instructions could be provided by various means. For example, changeable message signs, photoluminescent signage or voice evacuation systems could be used to provide path-finding assistance to the evacuees. Allocation of tasks, including specific instructions or assistance, could be transmitted to the rescue workers via two-way audio-visual devices. Emergency transponders could be used to send notification of need for assistance and information on current location. The location of the evacuees and rescue workers at all points within the building might be monitored or broadcast when triggered through the use of RFID (radio frequency identification tags) or cameras and other security technology. Further, in addition to employing other technologies used in fire and smoke detection discussed in Section 2, mobile sensors may be worn by a sample of people from whom additional information on conditions (including smoke infiltration and time to traverse corridors or stairwells) can be accessed.

The optimization techniques developed for use in this system exploit a network representation of the evacuation problem. In such a representation, the network represents the layout of the circulation systems of the building, where nodes correspond with locations inside the building (such as offices, meeting rooms, lobbies, lavatories, building exits, and corridor intersections) and arcs correspond with the passageways that connect these locations (such as staircases, elevator shafts, doorways, corridors and ramps). A cost is often associated with the use of an arc. In evacuation problems, the cost is typically in terms of the time it takes to traverse the arc, known as the arc traversal time. When large numbers of people must be evacuated from the building simultaneously, issues concerning capacity of the network arcs arise. The capacity of an arc is the number of people that can pass through the associated passageway per unit of time. The arc capacities are dependent upon the size and type of passageway that the arcs represent. Arc traversal times are a function of the arc capacities and the number of people simultaneously using the arcs. The nodes at which the people are located when the evacuation begins are called source nodes and the exits are referred to as sink nodes.

Figure 2 depicts a simplified network representation of a building (the Pentagon is shown in the figure as an example). A more detailed and accurate representation could be derived with information on the actual corridors, offices, etc. Here, a node was used to represent

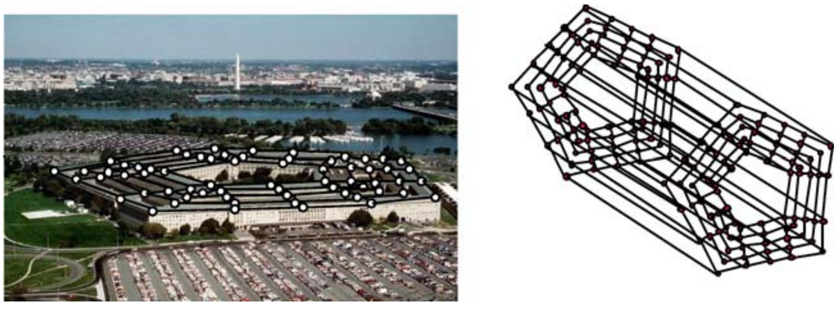


Figure 2. The circulation systems of the Pentagon can be modeled as a network.

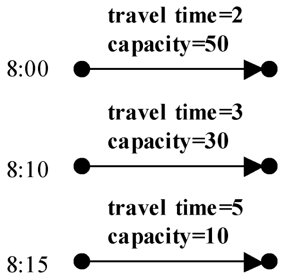


Figure 3. Time-varying arc attributes.

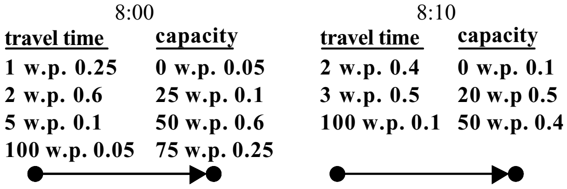


Figure 4. Time-varying and probabilistic arc attributes.

each location where a decision as to where to move next might need to be taken. If it is possible to move directly between these two locations without coming to another decision point, the two nodes were connected by an arc. Such a representation for a single story is given in the left portion of Figure 2. To represent this three-dimensional system, it is necessary to model each floor and then to provide links between floors where elevators, stairwells, or ramps connect the floors. The associated network representation for two stories (making certain assumptions about the whereabouts of the stairwells, etc.) is given in the right portion of Figure 2. The network representation for the actual circulation systems of this building would be far more complex with significantly more nodes and arcs. See, for example, Ahuja et al. [30] for additional background on the use of network representation for network flow applications.

In many emergency situations warranting evacuation, the arc capacities may decrease over time (e.g. as a fire and smoke spreads through a building) and traversal times will likely increase as conditions in the building worsen. Visibility may become increasingly inhibited due to smoke and loss of power and passageways may become impaired or completely obstructed over time. Thus, the arc attributes (traversal times and capacities) are time-varying quantities. This is shown in Figure 3 for a single directed arc.

Even if one could surmise that conditions may worsen, and hence, capacity along the network arcs may be reduced or traversal times may increase, one cannot predict these quantities with certainty. This is because such probabilities depend on the location and strength of the blast or fire and the structural design of the building. An example for the same arc as shown in Figure 3 is given in Figure 4, where the random arc travel times and capacities are discrete random variables. The possible times or capacities and their associated probabilities are indicated. The damage assessment component enables computation of these future likelihoods through its predictions related to: future structural capacity; existence of untenable conditions; and the reliability of these predictions.

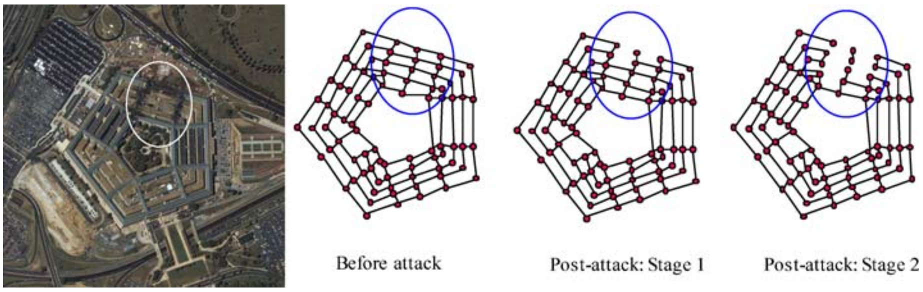


Figure 5. Hypothetical post-attack scenario for the Pentagon.

For illustrative purposes only, Figure 5 depicts a hypothetical example of the damage evolution to the Pentagon after the September 11, 2001 attack. In the left-most portion, a circle is drawn around the location of the damage.

Given this damage and the network representation of the circulation systems of a single story of the Pentagon prior to the attack as created in Figure 2, Figure 5 gives a possible scenario with respect to the damage to the buildings as it relates to the network structure. In the pre-attack figure, all arcs are intact. Seconds after the attack (post-attack stage 1), several of the corridors could have been destroyed or completely disabled, shown as arcs that are completely missing from the representation (treated as arc failure in the network algorithms). As time evolved, fire and smoke likely spread, additional structural damage ensued and the network representation might have been better depicted as it is in the post-attack stage 2 of Figure 5. Additionally, the capacities of some of the remaining arcs likely decreased to a portion of their ideal values and the travel times likely increased accordingly.

With intelligent technologies and real-time optimization techniques that have been developed or are under development for use in this IERR system, it is possible to quickly determine on-line evacuation plans given the current and predicted state of the building structures and the location of fire and smoke and other conditions that reduce egress capacity and rescue capabilities. Such instructions will also explicitly consider the probable ways that the damage might evolve, being careful not to route an evacuee or rescue worker to an arc that will have a high likelihood of failing by the time the evacuee or rescue worker arrives at that location.

Optimization techniques for determining robust on-line evacuation instructions that explicitly consider the inherent dynamic and uncertain nature of future capacities and arc traversal times, as predicted by the damage assessment component of the IERR system, have been developed (e.g. [31–33]) or are under development. Previously existing approaches seek to optimize a system objective and, thus, may suggest that one person take a high risk path for the good of the whole. Opasanon and Miller-Hooks [34] formulated the Safest Escape (SEscape) problem and proposed an exact algorithm, the SEscape algorithm, for its solution. The SEscape algorithm seeks the set of paths and evacuee assignment to paths that maximizes the minimum path probability of successful arrival at the sink of supply (i.e. evacuees) originating at multiple source nodes given time-varying arc travel times and stochastic and time-varying arc capacities. Solutions obtained via the SEscape algorithm ensure that the risk incurred by any evacuee who is forced to take the greatest risk is minimized (i.e. his or her probability of successful escape is maximized). Additional objectives have been considered in [33] and in other on going research efforts for providing optimal instructions in an evacuation network with stochastic and time-varying arc capacities and travel times: minimize the time by which the last evacuee egresses, minimize total time for evacuation, and maximize the expected flow.

Computational efficiency is critical for on-line use. An efficient and exact reoptimization algorithm that begins from the prior optimal solution and, given multiple heterogeneous changes to the arc costs and capacities, determines the updated optimal routing instructions has been developed. The technique is based on concepts of dual ascent and capacity scaling algorithms and was developed specifically for use in the IERR system. Significant computational savings can be achieved as compared with existing techniques (all of which start from scratch). In an effort to develop techniques that are both quick enough for use on-line and that explicitly address the complexities of the problem, heuristics have been developed. A noisy genetic algorithm developed for this purpose has also been extended to simultaneously address multiple objectives.

These techniques, like all other related network optimization algorithms, assume that instructions can, with respect to this application, force evacuees to split up at intermediate locations even if they arrive at a common point in time. As most evacuees would balk at such instructions, and because the IERR system enables provision of common instructions, simple heuristics for rapidly updating routing instructions that consider issues of shared information and fairness in terms of risk exposure and that explicitly consider the stochastic and time-varying nature of future conditions are currently under development for use in the IERR system.

4. System Design and Functionality

A flow diagram depicting the logic of the IERR system is provided in Figure 6. The system is comprised of two main components: the damage assessment component and the ERR optimization component. Briefly, the system continuously monitors for changes in structural state by comparing sensor and numerical data with background data, as described previously. The background data provides a benchmark for pre-event conditions. The data is processed and analyzed in an effort to recognize symptoms that would indicate that damage might have occurred. If damage symptoms are detected, this information is passed to the damage assessment tool, where conditions are assessed and possible causes are identified.

The damage assessment tool provides suggested treatments for use in recovery efforts and predicts likely present and future resistive capacities of the building. If predictions of near-term effects are not significantly different from prior estimates, the system continues to monitor sensor and other incoming data for symptoms of damage. If, on the other hand, the predictions indicate significant changes from prior conditions, the severity of the predictions is assessed. The predictions are used to update forecasts of capacity, travel time and other attribute estimates for the network representation of the circulation systems. If failure of key structural components is imminent and complete collapse of the structure is forecasted for the very near future, paths are provided to the evacuees and jeopardy instructions suggesting immediate withdrawal are relayed to the rescue workers. This information is employed by

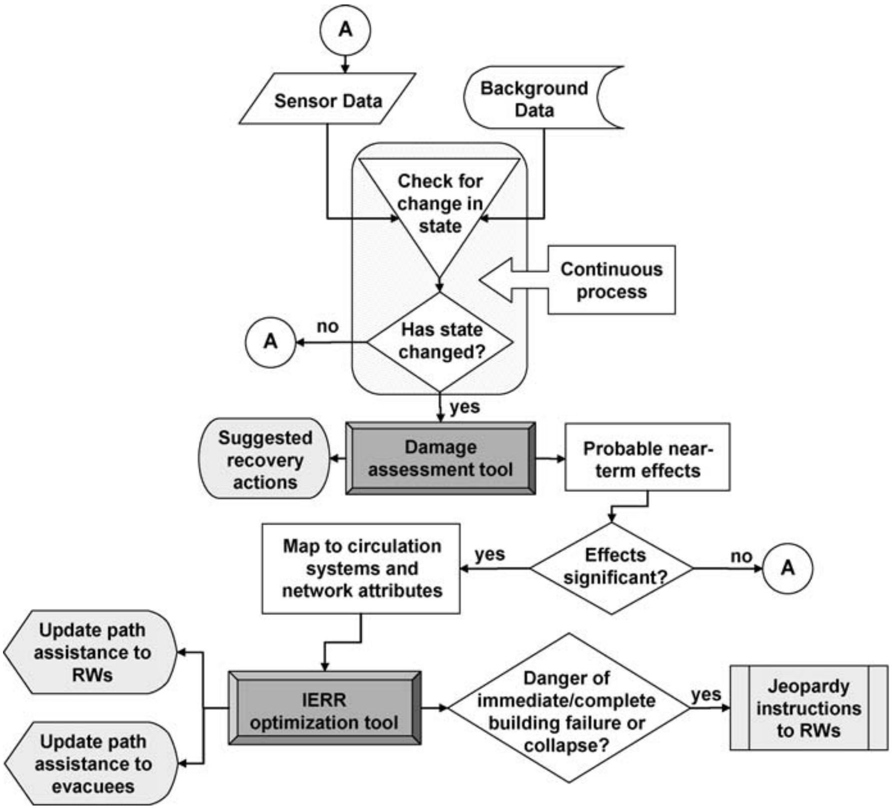


Figure 6. Flow diagram of IERR system.

the techniques comprising the ERR optimization tool to update path assistance to both evacuees and rescue workers.

While not depicted in Figure 6, this tool will also check for network connectivity. If the network is disconnected, it is possible that some evacuees may be trapped. When such an event is detected, the system will choose an optimal location for temporary refuge, referred to as a safe haven, will route the trapped evacuees to this location and will determine optimal instructions for rescue workers for creating a path to the safe haven.

5. Conclusions and Discussion

In this paper, we introduce an intelligent evacuation, rescue and recovery concept that exploits recent developments in communication and location technologies. Its key capabilities to provide real-time damage assessment, target vulnerability assessment, emergency preparedness assessment and on-line assistance with evacuation, rescue and recovery are enabled through the unification of ideas and techniques from multiple disciplines, including structural and forensic engineering, fire engineering, operations research and computer science. The inherent benefits of this electronically integrated and automated system are processes with reduced labor intensity, increased consistency, and increased speed of response over current approaches. Such a system will ensure quality and reliability of required processes. It will enable operational planners and their technical support personnel to effectively and objectively exchange information on specific situations and to rapidly plan and execute operations to meet complicated variable emergency conditions with lower resource requirements.

By explicitly considering the inherent stochastic and dynamic nature of future conditions and by further employing information on current and near-term performance of a building or facility and its circulation systems, it will enable sophisticated techniques that will result in robust decisions. Evacuation plans that are robust and that are quickly updated in response to evolving conditions and predictions of future conditions will aid evacuees and rescue workers in avoiding potentially high risk situations. For example, traditional evacuation planning would ignore the likelihood of a fire moving through a corridor or down a stairwell. If the probability of such a situation arising at particular points in time in the future is considered, a path that would use the associated corridor or stairwell at a time with high likelihood of failure could be avoided.

Additional benefits will be derived from on-line evacuation assistance, because evacuees are not always familiar with their environment, and thus, may be missing critical pieces of information, such as the layout of the building. This is particularly important when the posted evacuation routes become blocked or impassible. These evacuees would greatly benefit from on-line assistance in safe egress. The IERR system can be employed in evaluating existing evacuation plans and in identifying potentially high-risk circumstances that might prohibit successful evacuation. It will further provide on-line assistance to rescue workers in safe construction and demolition activities for ventilation, recovery efforts and access to trapped evacuees. And will alert rescue workers to hazards, including impending structural collapse. Faster and more efficient evacuation of a building that would result from employing this system can permit recovery efforts to begin quickly. Thus, the use of this concept will result in reduction in the number of injured persons, lost lives, risk of exposure, and number of trapped evacuees, and will lead to improved building operations.

Benefits of the proposed system also stem from the integration of technologies for receiving and transmitting real-time information to and from persons within the building. For example, the use of devices for determining the location of people within the building, along with information on the operational capacity of the circulation systems, can aid rescue workers in quickly finding trapped evacuees. Even without such technologies for locating people within the building, such a system can provide predictive measures on possible hospitable locations, such as voids, in which living evacuees or rescue workers may be trapped. The system could have foreseen the imminent collapse of the World Trade Center buildings, could have informed rescue workers of the urgent need for quick escape prior to collapse and could have guided the evacuees along paths with greater likelihood of safe egress.

Tenability criteria are employed in routing the evacuees or any rescue worker whose oxygen supply has run out or who is not suited with proper heat shields. While the techniques described in Section 3 can take into account such tenability criteria, how to address the additive effects of repeated exposure over a short period to carbon monoxide or other toxic gases requires further investigation. Moreover, optimization-based techniques that explicitly handle uncertainties in oxygen availability are needed, because how quickly oxygen supplies are depleted depends on factors, e.g. how much oxygen the rescue worker takes in with each breath or how many breaths he or she will take over a given period, that cannot be measured precisely.

To ensure that the IERR system can operate in harsh post-attack or fire environments, it is critical to maintain communication with the sensors, evacuees and rescue workers. In addition to selecting technologies that can operate in extreme conditions, the sensor and communication equipment should be positioned with sufficient redundancy to guarantee that even if the building sustains its maximum designed damage, the equipment will remain operational.

An initial system prototype of the IERR concept has been developed in a simulation test-bed employing FlexSim visual simulation software (a state-of-the-art discrete-event simulator) to provide a preliminary demonstration of its core technical capabilities and benefits [35]. Serious technical risk can be overcome through the development of a prototype system in its various stages and through extensive off-line testing. The prototype can also provide the foundation for a test-bed in which proposed methodologies and other system components can be assessed. Such a test-bed will provide a means for assessing a nearly exhaustive set of "what-if" scenarios through the simulation of random events. Through repeated replications of possible scenarios, one can assess the capabilities, responsiveness and quality of solution provided by the actual system. It will further provide a platform for assessing the benefits of deploying such a system.

Acknowledgments

This work was supported by NSF grant CMS 0348552 and Engineering Research and Development Center ERDC -WES of the United States Army through the Protective Technology Center at Pennsylvania State University. This support is gratefully acknowledged but implies no endorsement of the findings.

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