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SEISMIC VULNERABILITY OF AIRPORT FACILITIES

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SUMMARY

The vulnerability of airports can be related to a variety of structural and non-structural systems. The loss of non-structural systems can be just as devastating to airport operations as structural failures. The risk to non-structural systems is their vulnerability to lower magnitude earthquakes. Such systems may sustain major damage at low magnitude seismic events even when all other airport systems remain undamaged and operational. Compounding the problem is the absence of any explicit seismic performance requirements for these types of systems.

The vulnerabilities of both structural and non-structural systems can be defined using the performance based method developed in this paper. In this method, three classification levels are used to determine the importance of each system. Once each system's importance is found, six classification criteria are applied to more specifically define each systems vulnerability. The six classification criteria include: General structural concerns, general non-structural concerns, life safety, cost, construction time and fragility. An example using the airport vulnerability classification system investigates the vulnerability of Mid-America airports threatened by the New Madrid Seismic Zone in the central United States.

The second aspect defines the logistical issues of an international airway modal network with respect to the infrastructure and critical nodes. The economic loss that may result if an airport were lost provides the incentive to develop retrofit solutions and codes providing seismic consideration for new airport systems. The impact of losing a single airport facility would be more devastating to the local transportation system and the local economy, but would also have significant national and international impact as well.

In order to prevent such a loss, an example retrofit of a Mid-America airport facility is presented. The retrofit provides an example of what can be done not only at Mid-America airports, but also airports across the world to reduce the vulnerability to earthquakes.

To exemplify the seismic vulnerability of airports across the world, a fragility curve tying the probability of airport functionality to earthquake peak ground accelerations is defined. An example fragility curve for Mid-America airports shows an example of the relationship both with and without retrofit.

INTRODUCTION

Seismic activity throughout the world poses a major threat to the global transportation infrastructure. Airports are one of the most important transportation networks that are vulnerable to earthquakes. Therefore, critical operations, systems and structures throughout the world's airports are identified, studied and modified in order to remain functional following a large to moderate seismic event. While life safety issues are important in determining the seismic vulnerability of an airport, the performance of airport systems must be considered in order to determine the consequences of losing the airport.

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In the United States, the New Madrid Seismic Zone poses the largest threat to Mid-America airports such as St. Louis' Lambert International and Memphis International airports. As illustrated below, these airports are a crucial part of the local, national and international transportation modal network.

FRAGILITY OF MID-AMERICA AIRPORTS

One way to define the vulnerability of an airport is to graph the fragility of its systems. The fragility of a system is defined as the ability of that system to perform with respect to a peak ground acceleration, spectral acceleration, spectral velocity, or other control variables[8]. The fragility of a system can be graphed with performance located on the y-axis and one of the above mentioned control variables located on the x-axis. The y-axis consists of different levels of performance. The levels can go from fully operational (no damage), to life safe (moderate to sever damage, no collapse), to total loss (complete collapse). The fragility can then be presented in an applicable manner, where the steeper and further to theleft the fragility curve, the more vulnerable the system. A graph showing the a typical fragility relationship is illustrated in Figure 1.

More specifically, the fragility of Mid-America airport facilities represents the relationship between the probability of maintaining airport operation to peak ground acceleration. Depending on the vulnerability and importance of the system, the amount of damage required to interrupt airport operations ranges from minor interference to full shutdown. Each component is represented by a step function or single point. The idea behind the single point is to show that each system goes from normal operation to some degree of damage resulting in a halt of airport operations. Depending on the vulnerability of each system determined using the previous criteria and operation levels, the single point may occur at relatively low peak ground accelerations, while others may be able to withstand shaking at high peak ground accelerations. Each fragility step function or single point can then be combined into a series of points, to which a smooth curve can be fitted to show the overall vulnerability of the Mid-America airport in question. An example of this will be shown in the conclusion of this paper.

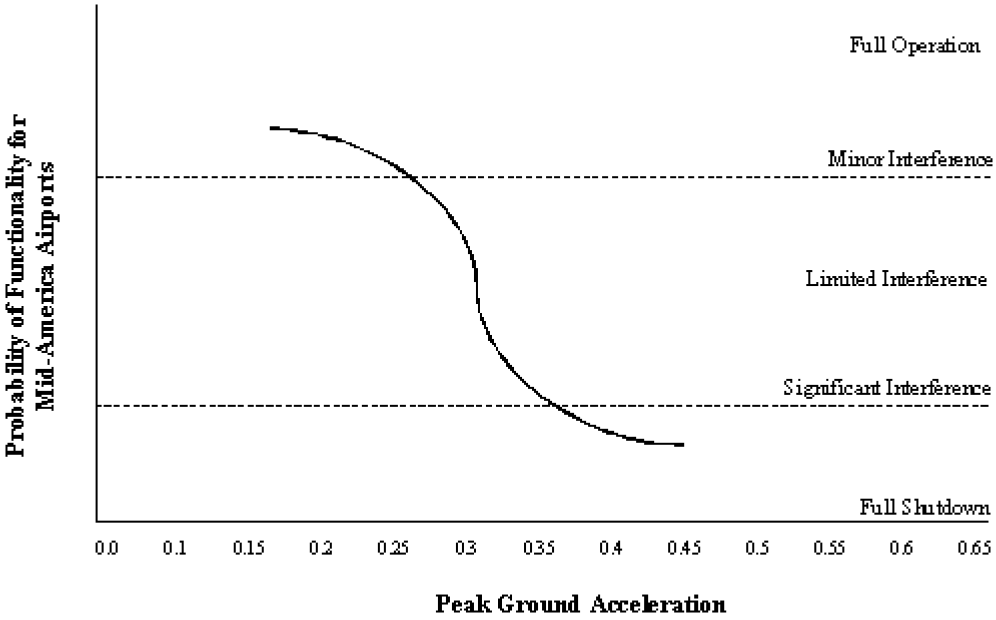


Figure 1. Typical Fragility Relationship

METHOD OF IDENTIFYING VULNERABLE COMPONENETS

Many studies only consider life safety when evaluating the seismic vulnerability of an airport. To keep airports operational, a performance based method of identifying vulnerable airport systems is necessary. In order to develop a performance based method of identifying seismically vulnerable systems, classification levels must be defined which describe and rate each system's performance and behaviour during and after an earthquake. In the following section, six classification criteria will be discussed and three classification levels of systems will be defined. Following this discussion will be a specific method of rating each system's seismic vulnerability based on the classifications and levels below.

Airport Facility Classification Levels

For airports both world-wide and in Mid-America, it is important to determine the role of each component in the operation of the airport. This section will define three levels, specific to airport systems, based on each system's importance to airport operations. While these three levels are only an extension of the six classifications defined later, they allow the engineer and owner/planner to gain a better understanding of which systems are the most vulnerable. All three of the levels may consist of systems, structural and non-structural, that, if lost, would render the airport inoperable for some period of time. The three classification levels are as follows:

Level A: This level consists of systems that are absolutely necessary to safely land and takeoff aircraft during or following a seismic event. This level would include facilities such as the control tower (not included in the scope of this study), voltage regulators powering runway lights, back-up power generators, runways, and any other system housing or consisting of vital communications.

Level B: This level consists of systems that are not necessary to land and takeoff aircraft during or following a seismic event, but are still vital to everyday airport operations. This level includes systems such as the baggage handling system, security systems, fuel supplies, and piping systems.

Level C: This level is similar to level B in the sense that the systems are not necessary to land and takeoff aircraft. It differs in the sense that collapse or loss of non-structural systems in this level may not effect the operation of the airport. This level includes systems such as storage facilities for aircraft, airport vehicles and non-vital supplies.

In general, systems in Level A would be expected to perform better than systems in Level B or Level C. The application of the three classification levels will be explained in later sections.

Airport Vulnerability Classification Criteria

To assess the vulnerability airport facilities, each airport system must be evaluated using a classification system describing that systems vulnerability under seismic loading. Six classification criteria have been developed in order to determine the vulnerability of each system. The six criteria are intended to cover all factors that determine how a system, structural or non-structural, will behave in an earthquake. The criteria include a system's general structural concerns, general non-structural concerns, life safety issues, cost, construction time, and fragility.

General structural concerns include torsion effects, plan irregularities, vertical irregularities, soft stories, soil conditions and short columns. **General non-structural concerns** include suspended components, unanchored components, components rigidly connected and resilient systems. The seismic vulnerability of non-structural systems is usually a product of how the system is installed. In a performance based study, such as this, **life safety** is just one factor involved in determining the overall seismic vulnerability of an airport system. This differs from most vulnerability studies that focus on life safety and not on a system's ability to function following a seismic event. If people inhabit the system under investigation at any point during day to day operation, there is a threat to life. To determine whether earthquake design measures should be considered during the implementation or retrofit of a system, the extra **cost and construction time** should be examined in detail. It is important to determine whether it is more economical to retrofit or to rebuild a system after it has been destroyed by an earthquake. The amount of time it takes to rebuild or to retrofit must also be considered. **Fragility** is explained in greater detail in previous sections.

Airport Vulnerability Classification Systems

The airport vulnerability classification system ties the three classification levels together with the six classification criteria to determine the vulnerability of a Mid-America airport component. The system is set up in a table format that allows an engineer to work with an owner or planner to identify vulnerable systems. The classification system is broken down into three tables. Table 1, vulnerability classification levels, is shown on the following page in Table 1. This table is used to determine which classification level the airport component in question fits into. The table has three columns; the first of which is used to describe the component under investigation. The second column is used to determine whether the component falls under level A, level B, or level C. The last column is left for comments so that the inspector can note how and why the component was assigned the level he or she gave. The information recorded in this table will be used again later in Table 3.

Table 1. Vulnerability Classification Levels

Component	**Classification Level (A, B or C)**	**Comments**

The second table is used to determine specifically the fragility level of the system under investigation. Table 2, fragility levels, illustrated below in Table 2, also consists of three columns showing the fragility levels of the components in question.. The first column defines the five different levels of airport functionality. The levels define the amount of damage that a system can undergo before it fails and causes the airport to shutdown for some period of time. The amount of damage it takes to reach this stage is different depending on which system is being investigated. The five levels include, full operation, minor interference, limited interference, significant interference and full shutdown. Full operation clearly is a condition where a component is performing as it is required following and earthquake, that is, no damage is present. Minor interference defines the fragility level at which limited damage to systems can be detected, but most system's operations remain unaffected. Limited interference is the case where most systems have undergone moderate damage, but a few of them continue to operate. Significant interference is the fragility level at which all systems have sustained major damage and many of them have failed. Full shutdown is the damage level at which all systems have suffered tremendous damage and each fails to operate.

Table 2. Fragility levels

Functionality	**Damage Assessment**	**Fragility**
Full Operation	System performs as intended following and earthquake. No damage present.	**I**
Minor Interference	Limited damage to systems can be detected. The majority of systems remain operational.	**II**
Limited Interference	Majority of systems sustain moderate damage. Some systems remain operational.	**III**
Significant Interference	All systems sustain major damage. Majority of systems fail.	**IV**
Full Shutdown	All systems sustain critical damage. All systems fail.	**V**

Although the damage levels are uniform for all systems, the amount of damage it takes for a system to shut down airport operations changes depending on the system being investigated. For a given peak ground acceleration, a system may be able to sustain major damage without halting airport operations. On the other hand only minor damage to a system may be enough to close the airport. For example, unreinforced masonry walls can withstand a significant amount of damage, up to the point of collapse, without threatening the day to day operations of airports. Baggage handling systems, however, require only limited damage before failure and eventual closing of some airport operations. While Limited interference may be the threshold for baggage systems, it may only be a life safe situation for the unreinforced masonry walls. Column 2 allows the engineer to decide at which level the damage sustained by a system after an earthquake will be enough to threaten the ability of a Mid-America airport, for example, to remain operational. The third column assigns a roman numerical value of I though V to the functionality level at which a system's failure will cause the termination of airport operations for a given peak ground acceleration. This numerical value will be referred to again in Table 3.

Table 3, overall vulnerability, illustrated in Table 3, ties together table 1 and Table 2 to define an overall seismic vulnerability of each airport system. Besides the information carried over from the first two tables, the third table also takes into account the other five airport system classification criteria. Table 3 consists of eight columns. Similar to Table 1, the first column of Table 3 describes the system in question. To define a system's seismic vulnerability, Table 3 gives a point value to each column, 2 through 7, in the table. Columns 2 and 3 are reserved for the classification level and fragility of a system found in Table 1 and Table 2 respectively. For the information from Table 1, a point is given for each classification level. For level A, one point is assigned, for level B two points are assigned and for level C, three points are assigned. For column three, the number of points assigned is equal to the reverse point value of the defined level of fragility. So for level I, a point value of five is assigned, while for level V, a value of one is given. Columns four through seven represent the remaining classification criteria which include general structural concerns(GSC), general non-structural concerns(GNSC), life safety factors(LSF), cost and construction time(CCT). Each of these columns is assigned a value based on the vulnerability of each system with respect to each criterion. The values range from zero to three. The more vulnerable a system is to a given criteria, the higher the value given. For example, baggage systems are not affected by general structural concerns, so a value of zero would be assigned to the column headed GSC. Baggage systems are quite vulnerable to general non-structural concerns, therefore a value of 3 would be assigned to the column headed GNSC. The final column is for the overall vulnerability of a system. The value placed in this column is the addition of the values found in columns two through seven. The higher the value in column eight, the more vulnerable the system.

Table 3. Overall Vulnerability

Component	Classification Level(A, B or C)	Fragility	GSC	GNSC	LS	CCT	Overall Vulnerability

Mid-America airports threatened by the New Madrid Seismic Zone were examined using the airport vulnerability classification system to illustrate the use of these tables. Five systems, both structural and non-structural, were identified as vulnerable. The five systems include baggage systems, fire sprinkler systems, electrical equipment, back-up power generators and unreinforced masonry walls. The vulnerability of each of these systems is presented in the conclusion of this paper.

RETROFIT OF VULNERABLE COMPONENTS

The loss of airport facilities, as illustrated below, can devastate airway modal networks. Retrofit design considerations can be implemented to reduce the vulnerably of airports to seismic events. In order to prevent the loss of airport operations due to failure of the five identified vulnerable components following an earthquake, an example retrofit scheme was developed for Mid-America airports. This retrofit scheme is used to illustrate steps that can be taken at Mid-America airports to eliminate problems that currently exist with respect to seismic activity. The example retrofit is for a back-up power generator building that houses both the back-up power generator and voltage regulators for a Mid-America airport. This building was chosen due to the fact that it houses both structural and non-structural members and has a high seismic vulnerability. The design includes a retrofit for the voltage regulators in which a base plate with a bolt hole pattern is used to keep the previously unanchored regulators from sliding or overturning. Both an interior and exterior steel frame were designed to tie back the unreinforced masonry walls and to better connect the heavy roof diaphragm to the walls. A basic retrofit design was also developed to eliminate the problem with the back-up power generator's exhaust and fuel supply. If the retrofit scheme were implemented, the overall fragility of the airport could be reduced, drastically decreasing the threat of airport shut-down.

IMPACT OF LOSING MID-AMERICA AIRPORT

To be able to justify the retrofit of airport systems at the world's airports facing the threat of earthquakes, the consequences of losing an airport must be defined. It will not be worth the extra cost of retrofit to the decision makers if the losses due to the shutdown of airport operations are not known. Because airports have such an impact on the overall transportation modal network, their ability to operate during and after an earthquake is imperative.

This point can be illustrated by describing the importance of Mid-America's airports to not only the local economy, but also the national and international airway network. Lambert St. Louis International Airport has a $5.1 Billion annual economic impact on the St. Louis Region and the airport employs over 19,000 people through airlines, vendors, service companies, and the City of St. Louis[12]. According to the airport, Lambert International sees over 45,000,000 people per year. That is approximately 125,000 people per day. St. Louis Lambert International Airport receives half of its revenue from concessions that operate on airport property[1]. Not only would a shut-down due to an earthquake devastate the local economy due to the inability of delivering supplies, but also due to the inability of the workers and the airport to make money during the down time. While specifics regarding the local impact of losing Memphis International were not readily available, the airport faces many of the same economic issues as St. Louis Lambert International. According to the FAA/DOT database, Memphis International is responsible for an approximately $4.8 Billion regional impact. The impact that these airports have on the local economies results in an even bigger impact on the national and international transportation modal network. The importance of Mid-America's airports with respect to the national and international airway networks is illustrated below in Figure 2.

ACI world ranking based on total cargo:	Memphis International #1
ACI world ranking based on total aircraft movements:	St. Louis Lambert International #9
ACI world ranking based on total passengers:	St. Louis Lambert International #15

*ACI refers to Airport Councils International

Figure 2. Importance of Mid-America Airports.

CONCLUSIONS

Seismic activity threatens airports world-wide. International airports all have a major impact not only on their local and national transportation networks, but all transportation networks world-wide. The impact of losing an international airport goes beyond the loss of life. Economic losses must also be considered. While making an airport life safe is the first priority, further steps must be taken to protect the global airway network. In order to take the next step, the vulnerability of airports to seismic events must be investigated from a performance based point of view. The results of this study, as illustrated below, provide a performance based alternative to defining the seismic vulnerability of airport facilities.

1. Method of identifying vulnerable airport systems (Table 4).

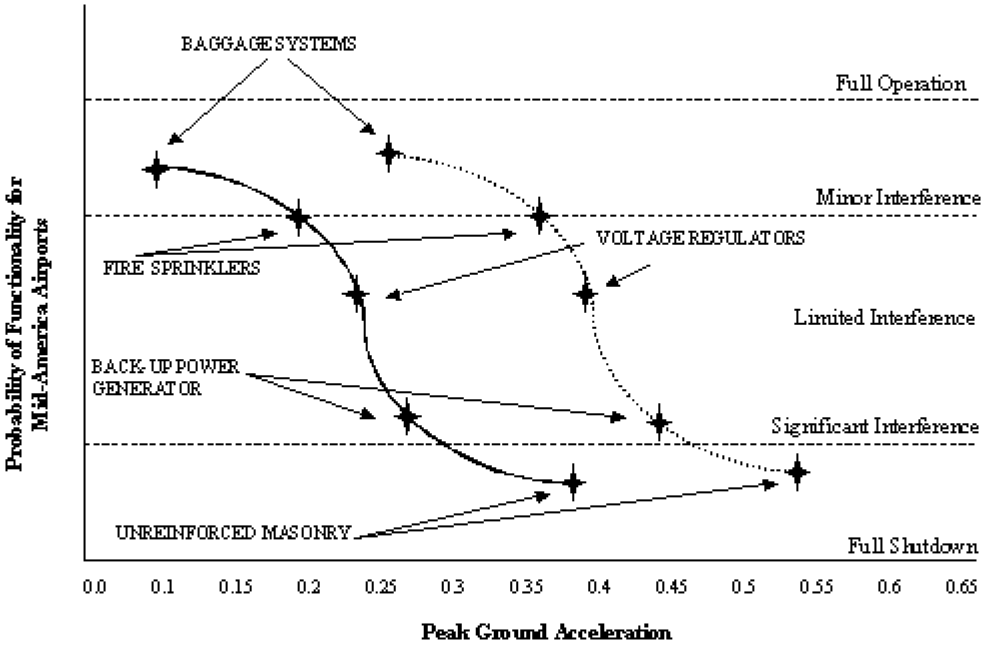
2. Economic importance of international airports (Figure 2).

3. Seismic retrofit of identified vulnerable airport systems.

4. Example of overall airport fragility curve: Mid-America airports (Figure 3).

Table 4. Overall Vulnerability of Mid-America Airport Systems

Component	Classification Level(A, B or C)	Fragility	GSC	GNSC	LS	CCT	Overall Vulnerability
unreinforced Masonry	A – 3 points	2 points	3	3	3	3	17/20
Power Generator	A – 3 points	4 points	0	3	3	3	16/20
Voltage Regulator	A – 3 points	3 points	0	3	3	3	15/20
Fire Sprinklers	A – 3 points	3 points	0	3	3	3	15/20
Baggage Systems	B – 2 points	4 points	0	3	1	3	13/20



*Grey dashed curve denotes vulnerability with retrofit.

Figure 3. Overall airport fragility curve (with and without retrofit).

REFERENCES

[1] Airport Authority. 1999. *Airport Authority Revenues.* St. Louis, Missouri. http://stlouis.missouri.org/government/budget99/execsum/airport.html.

[2] Barclay, Charles. 1998. *America's Future in Airport Infrastructures.* AAAE.

[3] Building Seismic Safety Council for the Federal Emergency Management Agency. 1994. *NEHRP Recommended Provisions for Seismic Regulations for New Buildings,* Part 2: Commentary. 1994 Edition. Washington D.C.: Government Printing Office.

[4] Court, Anthony B., Mervyn J. Kowalsky. 1998. *Performance-Based Engineering of Buildings-a Displacement Design Approach: Proceedings of the Elsevier Structural Engineering World Wide Conference 1998.* T109-1.

[5] Hall, John F. 1995. *Earthquake Spectra: Northridge Earthquake of January 17th, 1994, Reconnaissance Report.* Volume 1. Oakland, California: Earthquake Engineering Research Institute.

[6] Huggins, Richard M., Roland L. Sharpe. 1998. *A Seismic Assessment System which Provides an Increased Scope of Practice and Excellent Client Utility: Proceedings of the Elsevier Structural World Wide Conference 1998.* P319-4.

[8] Islam, Saiful Ph.D. 1998. *Seismic Evaluation of Existing Building Using Performance Based Approach: Proceedings of the Elsevier Structural Engineering World Wide Conference 1998.* T187-6.

[9] Lambert St. Louis International Airport. 1999. *General Information about Lambert.* St. Louis, Missouri. http://www.lambert-stlouis.com/facts.html.

[10] Memphis International Airport. 1999. *Memphis International Airport.* http://www.memphisguide.com/MIA.html.

[11] Naeim, Farzad. 1989. *The Seismic Design Handbook.* New York: Chapman and Hall.

[12] Rojahn, Christopher, A. Gerald Brady and Robert A. Bruce. 1999. *ATC-21-T: Rapid Visual Screening of Buildings for Potential Seismic Hazards.* Washington D.C.: Government Printing Office.

[13] Schiff, Anshel J. 1995. *Northridge Earthquake: lifeline performance and post earthquake response.* Technical Council on Lifeline Earthquake Engineering. New York: American Society of Civil Engineers.

[14] Shinozuka, Masanobu. 1998. *Conceptual Framework for Seismic Design and Retrofit Guidelines for Lifeline Systems: Proceedings of the Elsevier Structural Engineering World Wide Conference 1998.* T123-1.

[15] Woodward-Clyde Consultants. 1997. *Seismic Risk Analysis PHASE 1: Lambert-St. Louis International Airport.* PART 1-Executive summary, introduction and source of work. St. Louis, MO.