THESIS

# PERFORMANCE BASED DESIGN OF WOODFRAME STRUCTURES FOR FLOODING

Submitted by

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WE HEREBY RECOMMEND THAT THIS THESIS, PREPARED UNDER OUR SUPERVISION BY MASON TAGGART, ENTITLED "PERFORMANCE BASED DESIGN OF WOODFRAME STRUCTURES FOR FLOODING" BE ACCEPTED AS FULFILLING, IN PART, THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

Committee on Graduate Work

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## ABSTRACT OF THESIS


## PERFORMANCE BASED DESIGN OF WOODFRAME STRUCTURES FOR FLOODING

In 2005 Hurricane Katrina demonstrated how devastating flood waters can be to residential structures. Obviously, life safety of the inhabitants is the most critical issue for residential buildings followed by financial (property) loss due to water damage. This paper presents a methodology, software, and several examples for the design of wood frame residential structures for for flood. The methodology is based on probabilistic flood hazard and provides the owner and engineer with a fragility for annualized loss or for loss over the anticipated/expected lifetime of the building. The primary purpose of this information is to aid in decision making during the planning, construction or retrofit/repair process. The approach is based on known properties of wood and housing products, and when not available, reasonable interpretations/assumptions were used based on discussion with colleagues in the wood and/or housing industry.



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# 1. Introduction

Performance-based design of woodframe structures was originally perceived in the 1970's as part of HUD's Operation Breakthrough. Since that time little progress has been made with a few notable exceptions such as floor system dynamics, i.e. bounce, and fire performance ratings. The Structural Engineering Institute (SEI) of the American Society of Civil Engineers (ASCE) funded a Special Project headed by the Committee on the Reliability-Based Design of Wood Structures entitled "The Next Step for ASCE 16: Performance-Based Design of Wood Structures". The purpose of that project was to begin a prestandard document for performance-based design of wood structures. This thesis represents the effort put forth for flooding hazards.

Greater than 75% of declared Federal disasters are a result of flooding. According to FEMA, the average annual losses due to flooding in the United States are over 2.4 billion dollars and tragically often results in the loss of life. Damage to infrastructure and loss of productivity account for significant additional financial costs. Life safety is the primary concern with any natural disaster and in the case of flooding the issue of life safety is addressed through the ASCE 7 standard (ASCE 7 (2006)), as well as through the advent and enhancement of early warning systems, i.e. technology. Aside from life safety, however, emphasis is needed to abate the staggering economic losses due to flooding. While there are diverse means whereby flood damage may be reduced, there is great need to provide potential property owners with information regarding specific flood risks thus allowing them to make informed decisions as to the level of protection they would like with regard to the potential for financial losses, i.e. risk. Information needs to be made available which quantifies the probability of flooding and associated damage to a structure with and without damage mitigation techniques incorporated.

Performance based design (PBD has been proposed as an effective process for the design of buildings for extreme events. PBD is an engineering approach wherein performance objectives for the building are selected by those who will own or use the building and then calculations are made based on various hazards and various building designs in order to obtain a design that meets those performance objectives in the best way. This procedure lends itself well to the use of probabilistic analysis wherein a specific probability of exceedance (PE) is associated with the performance objectives, following which various building designs are probabilistically evaluated to determine which of those fall within the acceptable range of probabilities. Probabilistic calculation of building performance is the ideal choice for extreme events, such as flooding, due to the uncertain nature of the events themselves, making PBD a desirable design approach (see figure 1). From left to right, Figure 1 shows the gathering of performance objectives followed by information regarding the details of a preliminary building design, probabilistic flood characteristics, and probabilistic construction cost data. This information can then be combined and an analysis performed to calculate the performance of the building based on the specific design, expected flooding conditions, and expected costs of repair of items damaged in during flooding. The building performance can then be compared with the initial performance objectives and a determination made as to whether or not the design meets those objectives. If it does not, the preliminary building design can be altered and the process repeated until the building performance does meet the performance objectives.

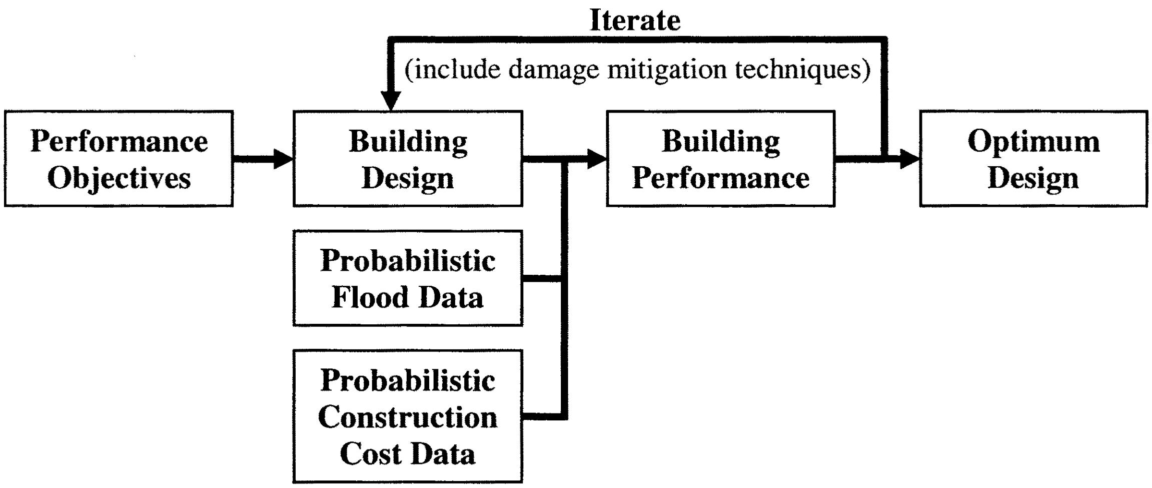


**Figure 1. Performance Based Design Process for Flooding**

The purpose of this study is to develop a process, applying a PBD approach, to provide potential or current property owners with information concerning probable monetary losses due to flood damage for various building and site designs, thus allowing them to make informed cost-benefit decisions on viable flood damage mitigation techniques which may be incorporated into the design thereby reducing flood damage costs. In increasing order of importance, the standard performance objectives for extreme events as discussed in the 1st Invitational Workshop on Performance-Based Design of Woodframe Structures (van de lindt, 2005) include: (1) occupant comfort, (2) continued occupancy, (3) manageable loss or acceptable damage, (4) injury or life safety and (5) structural integrity or collapse. The PBD process for the design of a structure to meet structural integrity performance objectives for a flooding event would be similar to the processes used for earthquake or high wind events except that the critical loads result from water pressure rather than wind pressure or ground motion. In addition, unlike earthquake or extreme wind events, there is often greater warning time for flooding events wherein occupants are often instructed to move to an alternate location rather than to seek refuge in their own homes. As a result of these two factors, this study will focus on the next most critical performance objective for extreme events which is that of manageable loss or acceptable damage and will consider only low velocity flooding conditions. This study suggests a process which can be used to estimate damage to a specific structure based on flood depth and duration and which is a framework meant to be added upon as more information becomes available. There is a dearth of information which links flood depth and duration to specific building system damage and there is uncertainty in the prediction of flooding as well as in specific costs of repair or replacement of building systems. The methodology proposed in this study allows for integration of new and more reliable information which will constantly improve the accuracy of flood damage estimation without any significant change in procedure.

# 2. Literature Review

This literature review focuses on four areas: (1) the study of performance based design, (2) flood damage estimation considerations, (3) flood risk quantification and (4) potential flood damage mitigation techniques. These areas of focus are of significant importance in the development of a methodology for performance based design of residential structures for flooding.

## *2.1 Performance Based Design*

The basic theory of performance based design has been the subject of varying degrees of attention in the building industry for over 30 years. One of the most significant advantages is that it allows a designer to have more freedom in the design process to determine the appropriate performance objectives for a specific building, to determine what factors will have an effect on those performance objectives, and how to quantify that relationship. Using this method, the designer can make educated and informed design decisions based on the effects that these factors have on the probability of achieving each specified performance objective. This allows the design procedure to be specifically tailored to the type, use and location of each building, producing the ideal design for a specific structure rather than using a standard procedure which may over design in some cases and under design in other cases. Performance based design typically involves a probabilistic approach to design which is especially valuable in the cases of natural disasters such as flooding wherein the probability of occurrence may be relatively low but the potential damage, i.e. consequences, due to an occurrence are likely to be very high. A useful approach to performance based design for conditions of great uncertainty is that of assembly-based vulnerability (ABV). This approach is meant to be used in the analysis of a specific building rather than the categorical analysis of a general building type. The ABV approach takes into account the location of the structure in the probabilistic generation of risk parameters such as flood depth, accounts for the damage resistance of various building components, simulates damage to various building components, estimates the cost of repair of building components using probabilistic repair values, and through numerous iterations, generates a probability distribution of expected losses over time. Through changes in input parameters, this method can then be used to make educated cost-benefit decisions through the evaluation of any number of potential building or site modifications – essentially informed design.

Rosowsky and Ellingwood (2002) discussed the migration from standard design procedures to performance based engineering for wood frame housing. They provided a background of load and resistance factor design (LRFD) and a commentary on it's strengths and shortcomings, establishing the need to build upon the lessons learned from the development of LRFD and other such procedures and continue forward to the development of a truly performance based design process. A significant focus of their study was associated with the value of the performance based design process for buildings subjected to natural disasters and the authors assert that natural disaster damage mitigation is an important current focus of the building design industry. The authors suggest that, whereas standard design processes were derived mainly for the purpose of life safety, a performance based methodology could address items such as enhancements in durability and reduction in maintenance costs, as well as reduction in risk of death, injury and property damage from extreme natural hazards. The authors define the fragility to be the conditional limit state probability as conditioned on the demand on the system and attest that, while fragility is less informative than a fully coupled risk analysis, it is beneficial, and considering the limited availability of accurate fully probabilistic descriptions of hazards, it may be preferable in many cases. The authors provide a simple example of fragility curve generation involving the failure of a standard residential flooring system and provide suggestions as to how this example might be followed with a number of building components and systems to generate fragility information which could be then used in performance based engineering. The authors state that there is a considerable gap in current knowledge and information available for the purpose of an immediate change to a completely performance based design process. The main deficiency is the lack of information which links the qualitative performance objectives to quantitative information such as structural response behavior. Another shortcoming is the lack of data encompassing limit state probabilities and performance of residential structural systems as well as any methodology for determining such. The authors assert that a move to performance based engineering will improve the durability of the housing stock as a result of increased ability to resist loads caused by natural hazards and reduce economic losses resulting from damage caused by natural hazards.

Porter et al (2001), proposed the value and use of assembly-based vulnerability. The authors provide an overview of the basic methodology of ABV in the specific case of a seismic risk as shown in Figure 2.

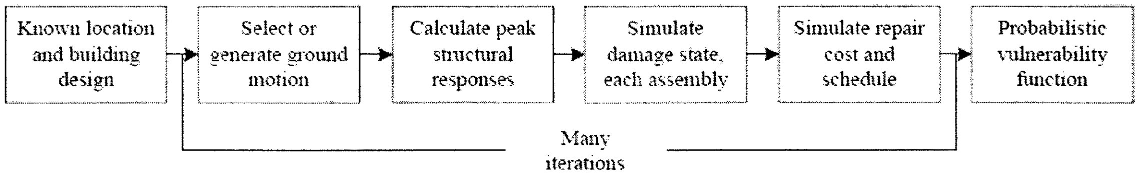

**Figure 2. Steps of the ABV methodology (Excepted in part from Porter et al., 2001)**

The information required to perform this type of analysis includes building design, ground-motion selection, and general unit repair costs. The calculations required are the structural analysis of the building and components, damage to building assemblies, repair cost of assemblies due to specific damage, other monetary cost considerations and the total cost of repairs. Through a number of trials, this information can be combined to produce a vulnerability function which provides a representation of monetary risk over time. The authors assert that the ABV approach is ideal because the process is necessarily probabilistic to account for the inherent uncertainties associated with imperfect knowledge of the timing and nature of a seismic event, the response of a structure and the costs to repair the damage; and therefore, seismic risk management decisions essentially rely on the consideration and quantification of uncertain parameters. The authors discuss how ABV is easily integrated into performance based design. They state that, while current codes focus nearly exclusively on the structural components of a building as they relate to life-safety and serviceability, the detail associated with ABV would allow one to determine the specific damage to both structural and non-structural components and thus provide the ability to more accurately compare the expected performance of a building with the performance objectives previously set forth. The authors also demonstrate the important link required between qualitative performance objectives and the qualitative data which can be generated using assembly based vulnerability as show in Table 1.

**Table 1. Illustrative translation of qualitative performance terminology (Excerpted in part from Porter et al, 2001)**

| Qualitative term | Translation | Example |
|---|---|---|
| Negligible, few, little | 0 - 1% | "Generally negligible [ceiling] damage:" less than 1% of ceiling area is damaged. |
| Some, minor | 1 – 10% | "Some cracked [glazing] panes; none broken:" Between 1% and 10% of lites visibly cracked; no glass fallout. |
| Distributed | 10 – 30% | "Distributed [partition] damage:" between 10% and 30% of partitions need patching, painting or repair, measured by lineal feet. |
| Many | 30 – 60% | "Many fractures at [steel moment frame] connections:" between 30% and 60% of connections suffer rejectable damage. |
| Most | 60 – 100% | "Most [HVAC equipment] units do not operate:" at least 60% of HVAC components inoperative. |

## *2.2 Flood Damage Estimation Considerations*

To predict flood damage one must determine limit states in which building systems are considered to have failed. A failure may be that the building system requires repair, partial replacement or a total replacement. It must then be determined what nature of flooding is necessary to cause such a failure, i.e., a specific flood depth, duration, contaminants, debris, velocity etcetera. The link between the building system failure limit states and the flood parameters noted above is of significant importance in accurate estimation of flood damage but, although some excellent work has been done, there is a general dearth of data on this subject. If one can overcome this dearth of information and determine the point at which a limit state for a specific building system is reached, it is then necessary that the cost of replacement be calculated. The cost of repair or replacement will include all labor, materials, overhead, transportation and equipment use by each contractor for both removal of the damaged system and installation of the new system including any extra efforts associated with integration of the new system into the old system. There is uncertainty in all aspects of the flood damage estimations including uncertainty in the nature and frequency of flooding, uncertainty in the relation between the nature of flooding and specific damage to building systems which will be sustained as well as uncertainty in the cost of repair or replacement of those building systems. As a result of the uncertainty of this issue, a probabilistic approach to the solution is needed.

In the study, Field Testing of Energy-Efficient Flood-Damage-Resistant Residential Envelope Systems (Aglan et al., 2004), numerous residential building systems subjected to controlled flooding were examined. The main purpose of this study was to investigate the flood damage resistance of various building materials and methods and determine which are best suited for use in areas with higher flooding probabilities. The main study included the construction of five 8 foot by 8 foot (243 cm by 243 cm) structures, each of which was subjected to flooding and two follow up tests which were conducted in order to further previous findings. A set of two tests were done on structures considered to be constructed using standard residential construction materials and techniques, one of which was constructed as a slab on grade while the other was constructed with a crawl space (See Figure 3). The next set of two tests were also for both a slab on grade structure and a structure with a crawl space; however, these two tests were performed using materials and methods which were hoped to demonstrate greater flood damage resistance. The final test was performed on a slab on grade structure and was for the purpose of determining the feasibility of dry flood proofing wherein measures are taken in the attempt to prevent the entrance of water into the interior of the structure during flooding conditions as shown in Figure 4.

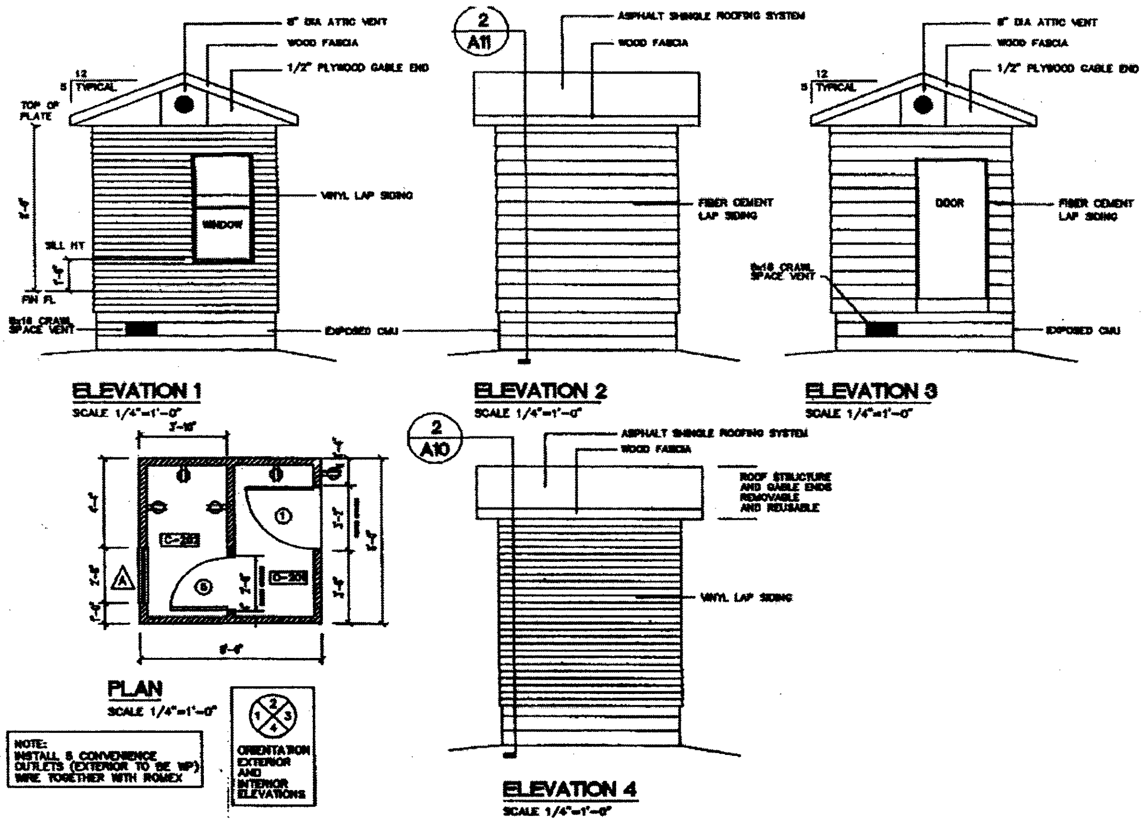


**Figure 3. Plan and elevation view for crawl space module (Excerpted from Aglan et al., 2004)**

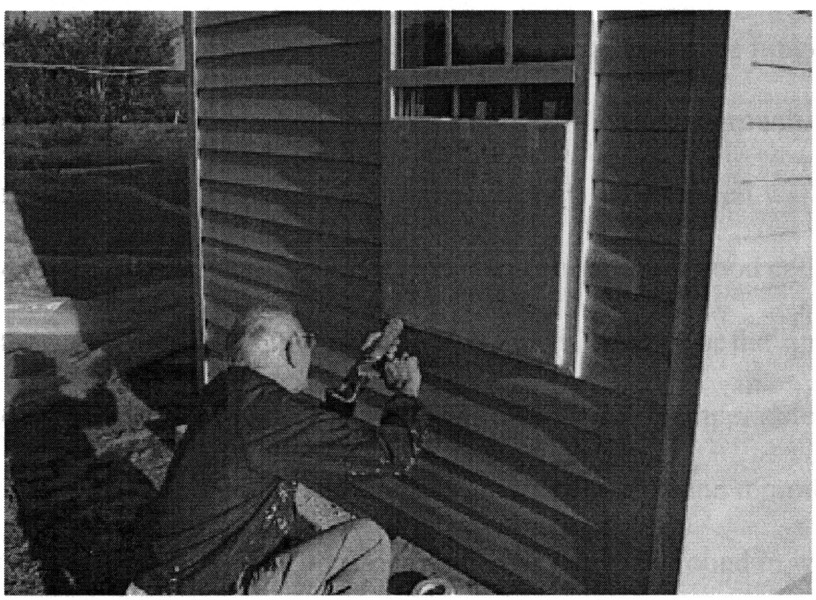

**Figure 4. Placement of a flood proofing dam over window (Excerpted from Aglan et al., 2004)**

From this final test it was determined that dry flood proofing is not a reasonable flood mitigation technique since the authors considered that their efforts in dry flood proofing were superior to those which would be adopted by most home owners or contractors and that these efforts were insufficient to prevent the entrance of flood water into the structure. The five testes noted above included subjection of each structure to a three day flooding event in two foot (61 cm) deep flooding conditions. The building systems included in the study were: siding, sheathing, insulation, housewrap, interior wall board, paint, ceramic tile, doors, windows, electrical system, concrete slab, carpet and pad, sheet vinyl, plywood subflooring, wood joists, and wood flooring. Each of these was studied in detail considering damage sustained during flooding, the susceptibility of the material to mold growth, drying time and repairability. Various mitigation and remediation procedures were also considered. The authors present their findings in detail and make recommendations as to the specific types of building systems included in their study which provide the most ideal flood damage resistance.

Carll and Highley (1999) conducted a study entitled Decay of Wood and Wood-Based Products Above Ground in Buildings. This study focuses on the fungi which cause decay in wood and the conditions which promote or inhibit its growth. The authors discussed three categories of fungi: those that feed directly on wood cell walls and thus degrade the wood, those that secrete enzymes which depolymerize wood cell walls and thus degrade the wood and those that obtain food from cell cavities or the surface of the wood and have little effect on the strength of the wood. Various temperature and moisture conditions were studied as they relate to both the growth and reproduction of the fungi and this information was related to conditions that might be found in walls, attics, crawl spaces and decks. A significant finding of the study was the verification of a common previously asserted fact that fungal growth is completely inhibited below a 20% moisture content in wood.

## *2.3 Flood Risk Quantification*

The greatest uncertainty in flood damage estimation is the nature of the flood itself including variability in return period, depth, duration, velocity, contaminants and debris. There is an extreme deficiency in information or procedures which would allow an accurate quantification of flood velocity, contaminants or debris in a specific area in any way other than basic rational judgment made by a study of the topography and nature of the area. For example a structure built in a canyon versus on the plains could be assumed to be susceptible to a higher velocity of flooding and greater damage through impact of floating debris but there is little data to quantify the specific velocity of flooding, probability of impact by debris and forces due to the impact by debris. There has been, however, much effort to quantify the extent of a flood with a 1% annual probability (100 year flood) and a flood with a 0.2% annual probability (500 year flood). There are maps indicating the reach of floods with these probabilities and from the use of these maps in conjunction with topographic maps, one can calculate the depth of flooding of each of these floods at a specific location. In addition, using these two floods with associated probabilities and depths, one can generate a probability density function (PDF) and cumulative distribution function (CDF) for the specific location to calculate flood return periods from various flood depths. In order to generate these statistical distributions it is necessary to determine the type of distribution which will best fit actual flooding occurrences. There has been much research in this area with a wide variety of differing conclusions. While research continues to find a distribution type that will yield the most accurate flooding predictions, the Gumbel distribution is generally accepted as a reasonable estimating tool.

The Federal Emergency Management Agency (FEMA) provides a number or resources giving information regarding natural disasters including flooding. FEMA provides public flood maps across the entire United States which can be either purchased or accessed on the internet (See Figure 5). These flood maps include the extents of a 1% annual probability flood, a 0.2% annual probability flood and various other data which might be useful for building design which accounts for potential flooding.

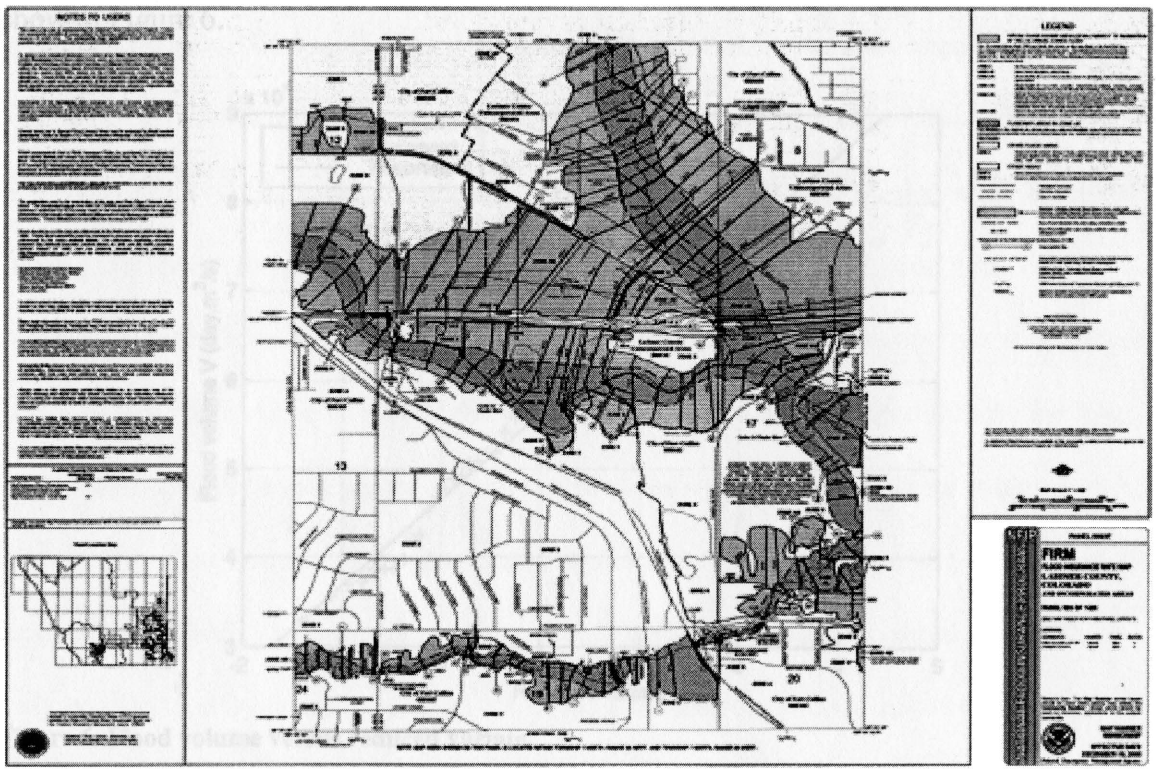

**Figure 5. FEMA flood map (item number 08069C0983F)**

Yue et al (1999) studied the application of the Gumbel distribution to flooding in their article entitled The Gumbel Mixed Model for Flood Frequency Analysis. The study considers the application of a bivariate extreme value distribution with Gumbel marginal distributions to estimate flood volume, duration and peak. The authors describe the model in detail and then consider the application of the model to a specific location, namely the Ashuapmushuan basin located in Canada in the province of Quebec. The region was chosen based the existence of annual flooding conditions and data available quantifying those flooding conditions. The authors consider the joint distributions of flood volume and peak, and flood volume and duration and the value of the Gumbel mixed model in the analysis of these distributions. The authors conclude that the process is valid based on the observation that the values obtained through use of the theoretical model are reasonably close to those actually observed in the actual case considered, as is show in Figure 6.

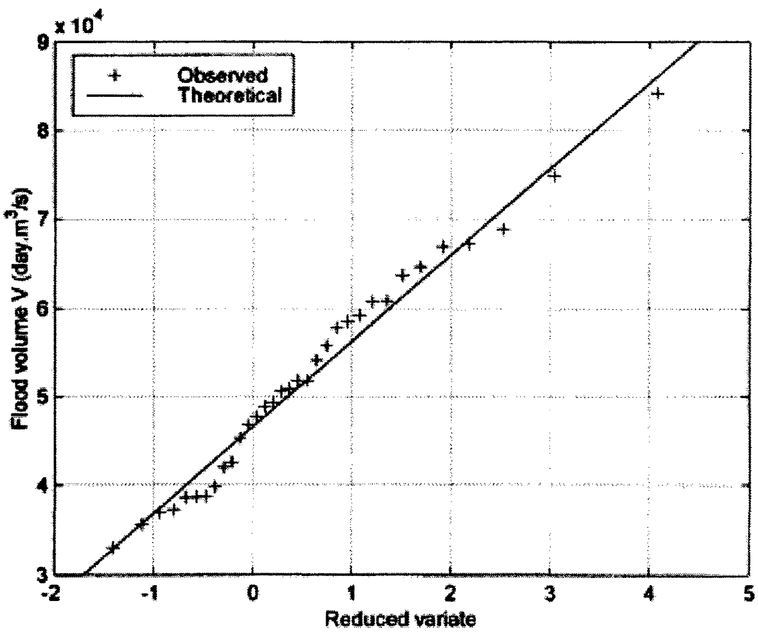


**Figure 6. Flood volume versus reduced variate**

## *2.4 Flood Damage Mitigation Techniques*

As construction continues in flood prone areas where land is typically less expensive near coastal areas, alternative construction materials and methods are desirable to reduce the cost of flood damage. Potential flood damage mitigation techniques are nearly endless and the variation in cost of implementation ranges from no additional cost to extreme measures which, even if one hundred percent effective, would never achieve a widely acceptable payback period. There are, however, some techniques which tend to be widely published and are circumstantially considered to achieve a reasonable return on investment. The most straightforward of these, in theory, is the technique of raising the height of some building item in order to reduce the probability that it will come in contact with flood waters. One technique is to raise the level of the entire structure to avoid flooding; this also has the potential of not only reducing flood damage to the structure but of preventing flood damage to contents. Another commonly published method is that of raising electrical components including outlets, switches, meter and panel box. Finally one can raise the level of some household appliances such as the washing machine, dryer, water heater and furnace to reduce the probability of flood damage, particularly for low level floods which have a higher occurrence probability. In addition to the methods involving raising building items are methods which use different materials engineered to have greater flood damage resistance or provide greater protection to those items which may be damaged by flooding. This type of material and/or product innovation was exactly what HUD envisioned in Operation Breakthrough in the 1970's (Performance criteria resource document for innovative construction, Report NBSIR 77-1316 National Institute of Standards and Technology, Washington, DC (available from NTIS)).

Design Guidelines for Flood Damage Reduction, FEMA-15 (1981), provides a variety of information including causes of flooding and processes, policies and programs related to flood damage reduction and their effects, as well as community and individual structure design considerations for flood damage mitigation. The authors discuss the consideration of site drainage with an objective that site runoff after development should not exceed that of pre-development runoff if possible. Factors affecting placement of buildings on a site are discussed as well as the potential for restructuring the topography and of using retaining walls or levees to make the site more ideal. The authors discuss dry flood proofing approaches and the additional forces acting on a structure due to the resultant water pressure on the exterior of the structure as shown in Figure 7.

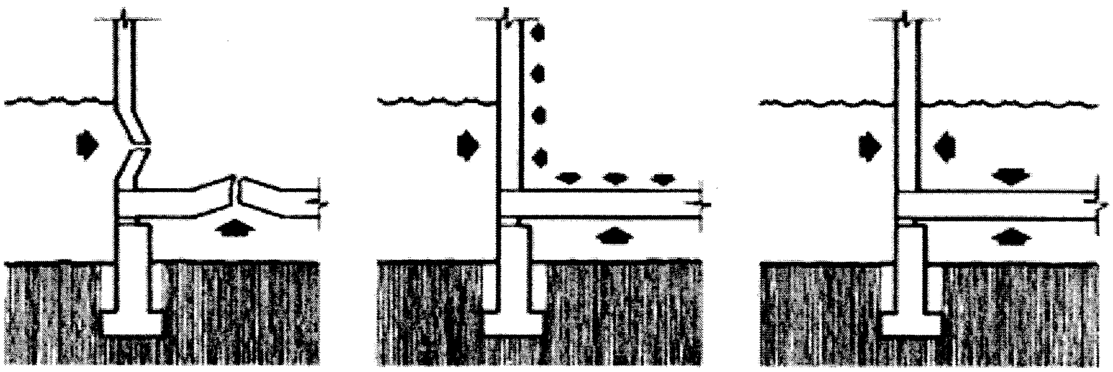

**Figure 7. Illustration of need to balance water pressure through increased structural capacity or allowing water to enter the building to prevent structural damage (excerpted from FEMA-15 (1981)**

A number of methods of raising buildings are suggested including those that required a change in topography and those accomplished through the use of piers or posts. Another suggestion put forth by the authors is the modification of the internal spatial organization of the building so as to place those rooms which are likely to have items of higher value in areas of the building which are less likely to be affected by flooding. The authors briefly mention the advantage of construction using water resistant materials. The design of foundations and mechanical systems is also considered along with wet flood proofing techniques.

As discussed previously the Field Testing of Energy-Efficient Flood-Damage-Resistant Residential Envelope Systems, Aglan et al (2004), includes testing of a structure with both standard construction and flood damage resistant construction. One of the most significant findings was the need to remove any construction material which may significantly impede the drying time of the structure and thereby promote mold growth and other adverse affects of long term exposure to water and humidity. The materials which are the primary cause of these problems are carpeting and fiberglass insulation. It was found that the removal of these or use of alternate materials allowed proper drying of other building materials, the replacement of which would be much more costly. A foam type insulation was studied which allowed proper drying of other materials without the removal of the insulation thereby alleviating the need to remove drywall in order to access the insulation (see Figure 8).

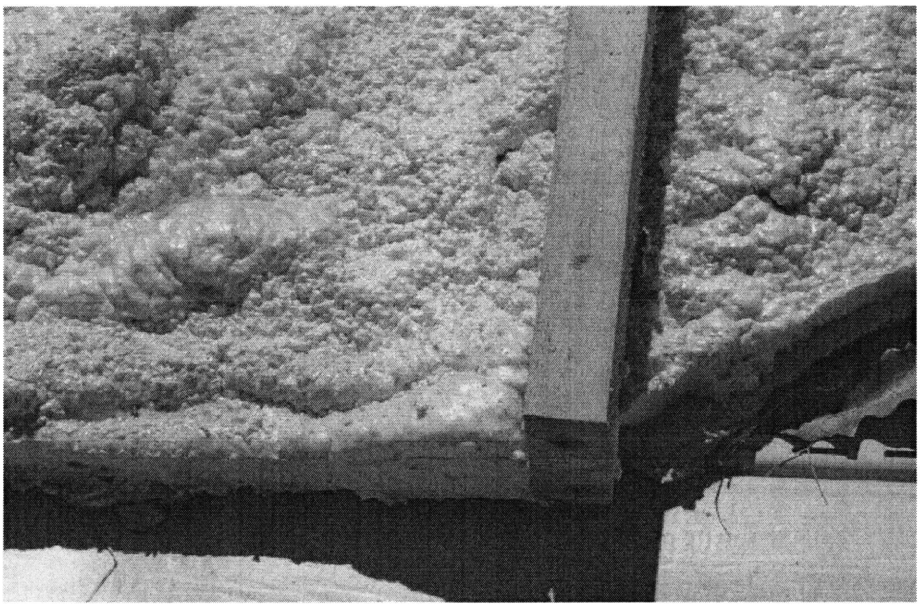

**Figure 8. Autopsy of foam insulation 15 months after flooding showing no mold or severe staining (Excerpted from Aglan et al., 2004)**

The study also showed that the use of vinyl or cement fiber siding was preferable to the use of hardboard siding and could be easily returned to pre-flood conditions through washing alone. Fiberglass and metal doors as well were easily restored to pre-flood conditions whereas a variety of wood interior doors were found to be damaged beyond cost effective repair.

# 3. Performance Based Design

Performance based design (PBD) is an engineering approach which allows qualitative performance objectives set by building occupants, owners or the public to be related to the quantitative evaluation of building design alternatives as the building is subjected to various hazards without prescribing a specific technical solution (Ellingwood, 1998). In other words, those who will own or occupy the building decide upon various ways in which they would like the building to perform such as the continued occupancy after a moderate seismic event or minimal repair costs after a 100 year flood event. These qualitative objectives are then matched with specific quantitative measures of various building systems and in turn a determination is made as to the extent of the hazard required to force these systems to these failure limits. The probability of reaching this specific hazard level is calculated and a determination made as to whether or not this failure probability is low enough to conclude that the design meets the performance objectives previously established. If not, the process is repeated with various building designs until the performance objectives are considered to be met based on an acceptable probability of failure. It should be noted that rather than discuss these probabilities as probabilities of failure, the values are subtracted from unity and called exceedance values. An exceedance probability which would be considered acceptable may be highly variable as for example the need for continued occupancy during and after some hazard would be of much greater importance for a hospital than for an office building.

There are several important distinctions between the performance-based design methodology and the traditional engineering design approach. Current building codes are generally based only on life safety performance objectives and do not thoroughly consider other performance objectives which may be generally desirable, such as serviceability or durability. Objectives which may be specific to a customer/owner, location, occupancy or building design are typically not considered in traditional force-based design. In addition, current codes usually prescribe a single method to determine the successful achievement of performance objectives and do not allow the engineer to judge the optimal process by which a design problem may be solved. Traditional engineering design also generally defines failure of the system based on the failure of a single member (e.g., if a single beam fails, the floor is considered to have failed). This, however, is often inaccurate especially in light-frame wood assemblies where the system performance is significantly affected by load sharing, the partially composite action of members and sheathing, and connection behavior (Rosowsky and Ellingwood 2002). By not prescribing a specific design procedure, the performance based design approach allows the designer to take these effects into account through system-level analysis according to the most current relevant information.

The process of assembly based vulnerability (ABV), fits closely into the PBD approach and is applicable to the evaluation of building design for extreme events. ABV is a process by which performance based design may be implemented methodologically accounting for the location of the building, the specific characteristics of an extreme event, the effect of those extreme event characteristics on various building components, the damage sustained by various building components, and the cost of repair of those damaged components. This method prescribes a Monte Carlo type simulation to generate a probabilistic vulnerability function. The ABV model is followed in this study in that the process prescribes the choice of a location, estimation of flood depth and duration at that location, the interaction between the flood duration and depth on damage to building components, the damage sustained by components, the cost of repair of building components and the generation of a fragility curve to demonstrate the results. Table 2 shows the implementation of this process for flooding as compared with that proposed by Porter et al., 2001.

**Table 2. ABV process proposed by Porter et al., 2001 versus process used in this study**

| ABV proposed process | Associated process used for this study |
|---|---|
| Known location and building design | Location used with FEMA flood maps to generate flood depth associated probabilities.<br>Location used to obtain knowledge of probable flood duration.<br>Building design known and various mean values of building dimensions and quantities understood. |
| ***Begin Iteration*** | ***Begin Iteration*** |
| Select general ground motion | Increment flood depth<br>Choose flood duration |
| Calculate peak structural responses | Determine which building items will come in contact with flood waters |
| Simulate damage state of each assembly | Determine area damaged and the relative amount of repair or replacement which is needed |
| Simulate repair cost and schedule | Determine costs associated with repair of damaged building components |
| ***End Iteration*** | ***End Iteration*** |
| Generate probabilistic vulnerability function | Generate fragility curves showing probable damage versus flood depth |

The performance based design process necessitates probabilistic analyses, which are especially applicable to building design for extreme events considering the uncertainty inherent in the timing and nature of the hazards, strength and durability of materials, and cost of repair or replacement of damaged items. PBD requires a link between the qualitative performance objectives and quantitative building response and this link generally involves some level of uncertainty (often quite large). PBD also requires a link between the nature of an extreme event and the building response which also involves uncertainty. These qualities of PBD along with the aforementioned uncertainties demonstrate the value of a probabilistic approach to solving building design problems relating to extreme events.

The first step in a PBD solution is to consider appropriate performance objectives. Specific performance objectives may be chosen for each specific building and situation; however, there are some general performance objectives which would be applicable to most buildings as noted in Table 3.

**Table 3. General performance objectives**

| Performance objective: | Considered herein: | Reason: |
|---|---|---|
| Occupant Comfort | No | Not applicable for flooding |
| Continued Occupancy | No | Generally less important than other considerations / Process for manageable loss could be modified to consider this (make changes as a second step rather than a primary investigation) / Limitation of damages generally leads to improvements in this area |
| Manageable Loss / Damage | Yes | Economic losses due to flooding are enormous (2.4 billion in the United States annually) / There is currently no process to allow building owners or occupants to make educated design decisions based on flood damage probabilities for their specific structure and location |
| Injury / Life Safety | No | Covered by ASCE 7 for non-PBD / Covered by advances in early warning systems / Closely related to PBD process for wind or seismic events |
| General Structural Integrity / Collapse | No | Closely related to PBD process for wind or seismic events |

As shown in Table 3, this study focuses on providing the building owner or occupant the ability to make design choices based on the *manageable loss* performance objective. For the case of flooding, the probability of economic losses can be calculated based on various design choices, especially those which are effective in mitigating flood damage, and this can be weighed against the initial cost of the various design options, providing valuable cost-benefit information which will aid in making design and retrofit decisions.

Another main step in PBD is to quantify the hazard. Due to the uncertain nature of extreme events, a probabilistic quantification is desirable, especially for a flooding hazard which varies significantly with each flooding event (See Table 4).

**Table 4. Load types caused by a flooding extreme event**

| Load type: | Damage caused by: | Considered herein: |
|---|---|---|
| Flood Depth | Absorption of water | Yes |
| Flood Duration | Absorption of water | Yes |
| Flood Velocity | Force of water | No |
| Flood Debris | Force of debris carried by water | No |
| Flood Contaminants | Absorption or adhesion of contaminants carried by water | No |

The commonly available data associated with flooding is flood depth which is, of course, based on local topography and drainage. There have been extensive efforts made to determine the extents of a 100 year flood (a flood with an annual probability of occurrence of 0.01) and a 500 year flood (a flood with an annual probability of occurrence of 0.002), and from these extents along with local topographic information it is possible to ascertain the expected depth of flooding. There have also been some efforts to quantify the probability of flood duration and flood velocity. However, this information is not generally available to designers. Certainly a more accurate quantification of the nature of a specific flood expected in a specific location would be extremely valuable. Recall the purpose of this study is to propose a process for PBD for flooding, accounting for flood depth and duration, which could easily be adapted to include more accurate flooding information with respect to depth, duration and contaminants; and, with limited effort, could be combined with a modified structural analysis PBD process as prescribed for seismic or wind events to account for velocity and debris.

The next step is to establish a link between the characteristics of the extreme event and the damage sustained by the building.. For the case of seismic, wind or flood velocity, this link is based on the structural response of a building to loadings due to ground motion or air or water pressures; however, for the case of flood depth and duration, this link is dependent on damage sustained by various building materials due to the absorption of water as noted in Table 4. The establishment of a continuous relationship between flood duration and damage sustained by various building materials would be ideal in providing the most accurate estimation of damage due to a specific flooding event. Unfortunately there is little information available on this subject other than limited discrete information of material failure or non-failure in time intervals measured in days. For this study, the link is established through data provided from the work done by Aglan et al. (2004) in Field Testing of Energy-Efficient Flood-Damage-Resistant Residential Envelope Systems, which provides information on the failure or non-failure of various building materials after a 3 day flooding event, as well tests conducted by the Engineered Wood Association (APA), (APA Reports T92L-13, T93-25, R&D86L-43 and RR-132), which provide failure/non-failure information after an approximate 6 day wetting of plywood products.

Subsequent to the estimation of damage caused by an extreme event, it is necessary to determine if the damage sustained by the building falls within the performance objectives through the establishment of a link between the damage state of the building and those performance objectives. As previously mentioned, this study considers the damage state of a building caused by flood depth and duration and the performance objective of manageable financial losses. Therefore, setting aside those performance objectives which lie outside of the scope of this study, the link between building damage and the performance objectives will be that of the estimation of cost of repair or replacement of damaged building items due to absorption of water compared with the acceptable financial losses specified by the owner or occupants of the building. The designer may repeat the basic PBD process with various building designs, including damage mitigating design alternatives, until a solution is reached which best balances probable losses with construction costs.

# 4. Fragility Approach

As previously discussed, the PBD approach includes the following steps: (1) determination of performance objectives, (2) probabilistic quantification of the hazard, (3) linking the hazard characteristics with damage to the building, and (4) determination of the effectiveness of the design in meeting performance objectives. Step 4, the final step in the PBD approach, is the comparison between the calculated performance of the building from step 3, and the initial performance objectives prescribed in step 1. From this comparison the determination is made as to whether the quantitative results of step 3 sufficiently meet the performance objectives set forth in step 1 (which may be qualitative or quantitative). The quantitative results from step 3 can be considered the *damage state* of the building and since the obtainment of that damage state provides the basis for the determination of the efficacy of the building design in meeting the established performance objectives, the calculation of that damage state can be considered to be the main objective in each iteration of the PBD approach. Since flood events are uncertain in nature, it follows that obtaining a discreet value for the damage state of a building due to potential flooding is not rational; rather, an appropriate result would be the probability of reaching the damage state. A risk analysis can be conducted to obtain the probability that a damage state would be met through the following equation:

$$P\{D\} = \Sigma\, P\{D \mid EED = x\} * P\{EED = x\} \qquad (1)$$

where $P\{D\}$ is the probability of reaching a damage state (D), $P\{EED = x\}$ is the probability of occurrence of an extreme event demand (EED) such as specific depth or duration of flooding, and $P\{D \mid EED = x\}$ is the conditional probability of reaching a specific damage state conditioned on the occurrence of a specific extreme event demand, which is also know as the fragility (Rosowsky and Ellingwood 2002). Decoupling the damage level from the hazard occurrence is also advantageous in that, through the expression of the extreme event demand as a continuous function of x, it allows a fragility model to be generated which provides information on the probabilistic damage state of the building for various extreme event demands, but remains independent of the extreme event details associated with a specific geographical location. This allows a fragility model for a specific structure to be applicable to any location. In addition, for flooding, the probability of occurrence of the extreme event demand of flood depth can be re-coupled, once a location is decided upon, using 100 year and 500 year flood data to calculate return periods associated with the flood depths from the fragility model (see Figure 10, C). There is, however, a significant difficulty in performing risk analyses associated with extreme flooding events as compared to other hazards which is that, while other hazards can be quantified through one dominant extreme event demand such as spectral acceleration for seismic hazards and gust speed for wind hazards, flooding has a multiplicity of event demands each with a significant and varied effect on the damage state of a building. One could conceive of a three dimensional fragility curve, as shown in Figure 9, wherein building damage is related to two continuous variables such as flood depth and duration; however, graphic representations of building damage versus increasing numbers of independent extreme event demand variables becomes inordinately difficult.

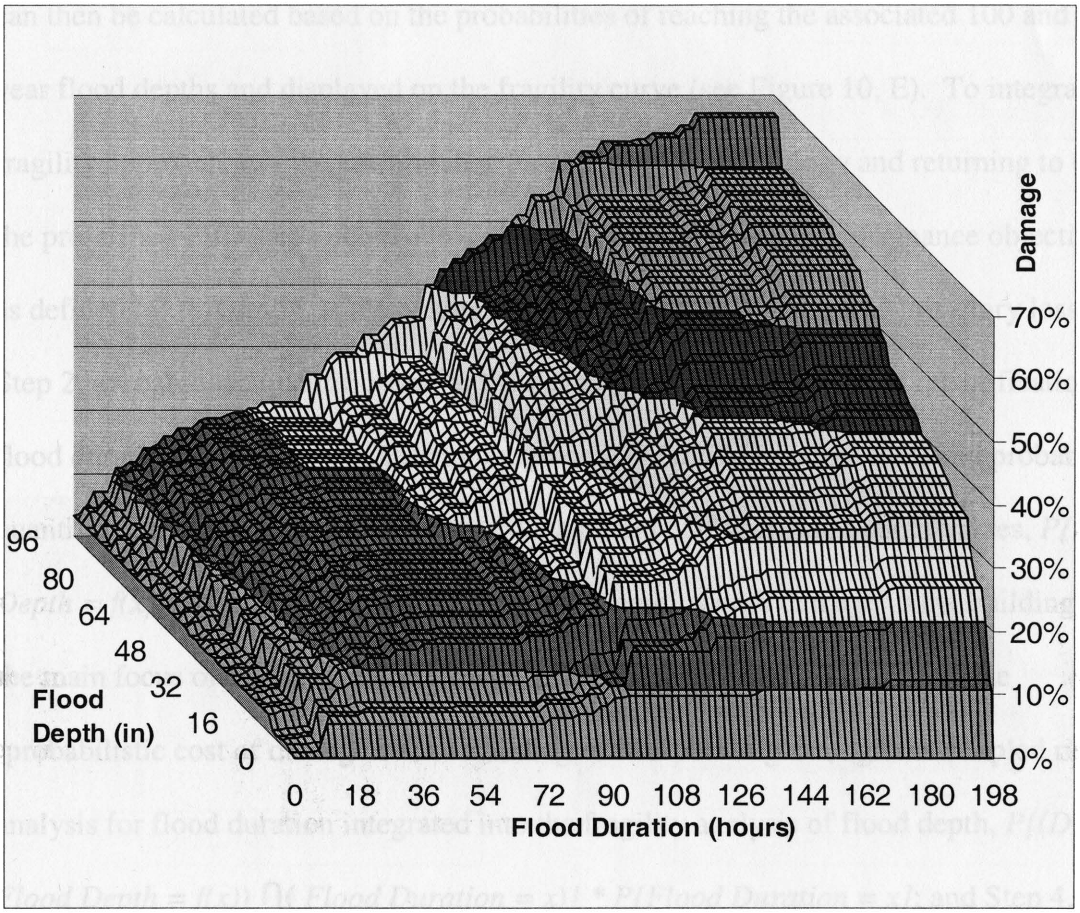


**Figure 9. Conceptual three dimensional fragility curve of damage due to flooding with respect to flood depth and flood duration**

Since flood depth is the predominantly studied and documented extreme event demand for flooding events, and since it has the greatest immediate effect on the damage state of a building, it follows that this should be the continuous variable to which we relate the building damage state. For the purposes of this study, to account for flood duration without undue complication of output, a combined methodology is proposed wherein flood depth is uncoupled from the risk analysis calculation and flood duration remains coupled thereby allowing the calculation of a fragility curve based on a specific probability flood duration and a continuous representation of flood depth (see Figure 10, D). As previously mentioned, the probabilities of reaching the various depths of flooding can then be calculated based on the probabilities of reaching the associated 100 and 500 year flood depths and displayed on the fragility curve (see Figure 10, E). To integrate the fragility approach into the performance based design methodology and returning to the to the prescribed PBD steps noted above, Step 1, determination of performance objectives, as defined for this study, is the qualitative requirement of manageable monetary loss; Step 2, probabilistic quantification of the hazard, involves probabilistic quantification of flood duration using best engineering judgment, *P{Flood Duration = x},* and probabilistic quantification of flood depth based on 100 year and 500 year flood depth values, *P{Flood Depth = f(x)}*; Step 3, linking the hazard characteristics with damage to the building, is the main focus of this study and includes the determination of the damage state (probabilistic cost of damage due to flooding) of the building through the coupled risk analysis for flood duration integrated into the fragility analysis of flood depth, *P{(D | Flood Depth = f(x))* ∩( *Flood Duration = x)} * P{Flood Duration = x}*; and Step 4, determination of the effectiveness of the design in meeting performance objectives, is provided for through the comparison between the building damage state, obtained from the fragility curve generated in step 3, and the performance objectives or in other words the comparison between the probabilistic cost of damage due to flooding and the client's definition of manageable monetary loss.

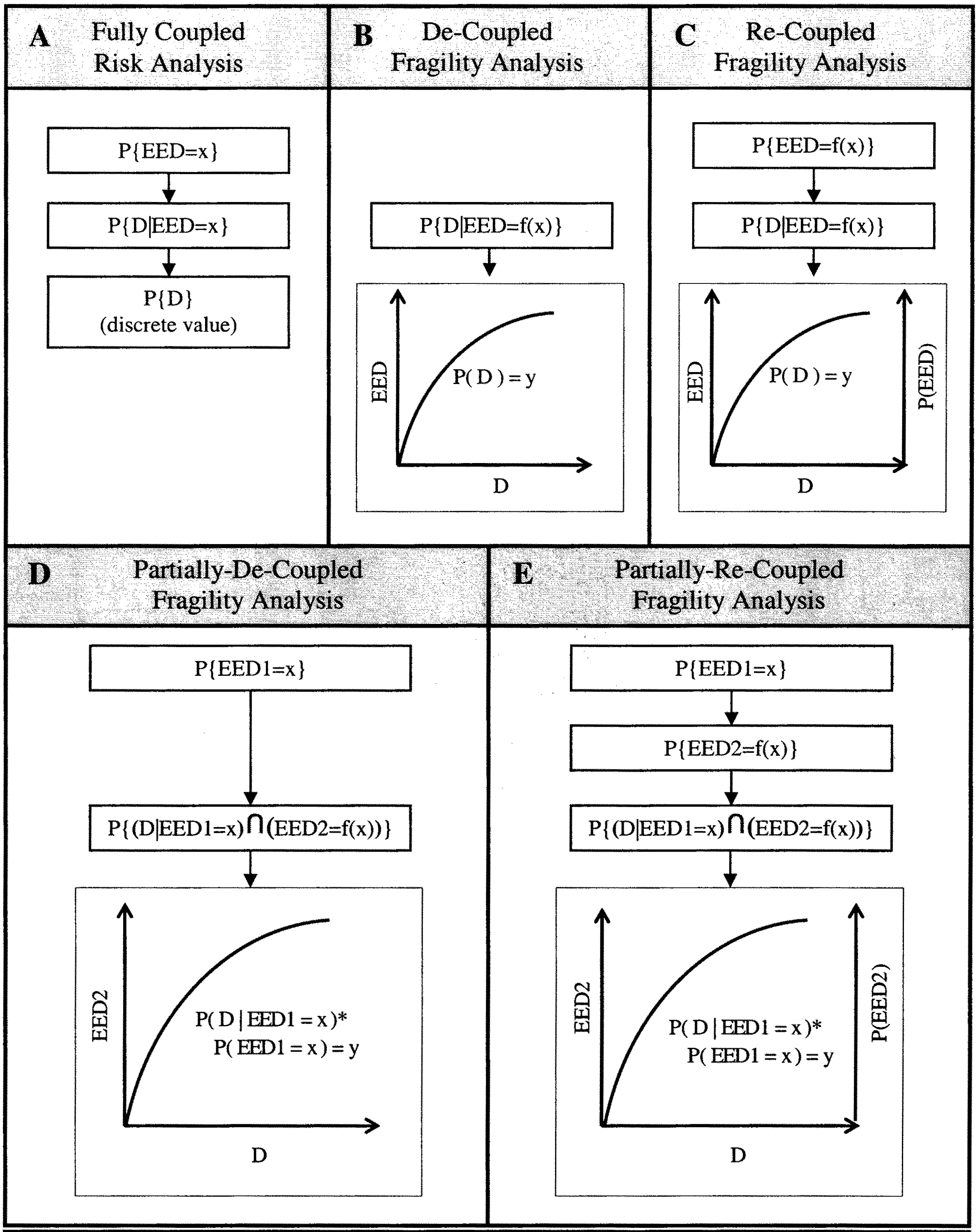


**Figure 10. Risk Analysis and Fragility Analysis Methodologies**

# 5. Procedure

## *5.1 Overview*

In order to accurately estimate the damage and subsequent cost of repair to a structure as a result of flooding, as well as to estimate the cost savings generated by applying one or more damage mitigation techniques, several key components must be in place: Firstly, it is necessary to quantify the characteristics of a flood event; secondly, one must have a knowledge of the structure including a building layout with building component dimensions and quantities; and finally, the relationship between the failure of the building components and the characteristics of a flood event, including the related costs of repair or replacement of those building components is needed. Due to the uncertain nature of flood events and construction repair costs as well as the extreme variability of building layouts and materials, a probabilistic solution is applied. The proposed process of calculation is shown in Figures 11 and 12 and discussed in detail in this chapter.

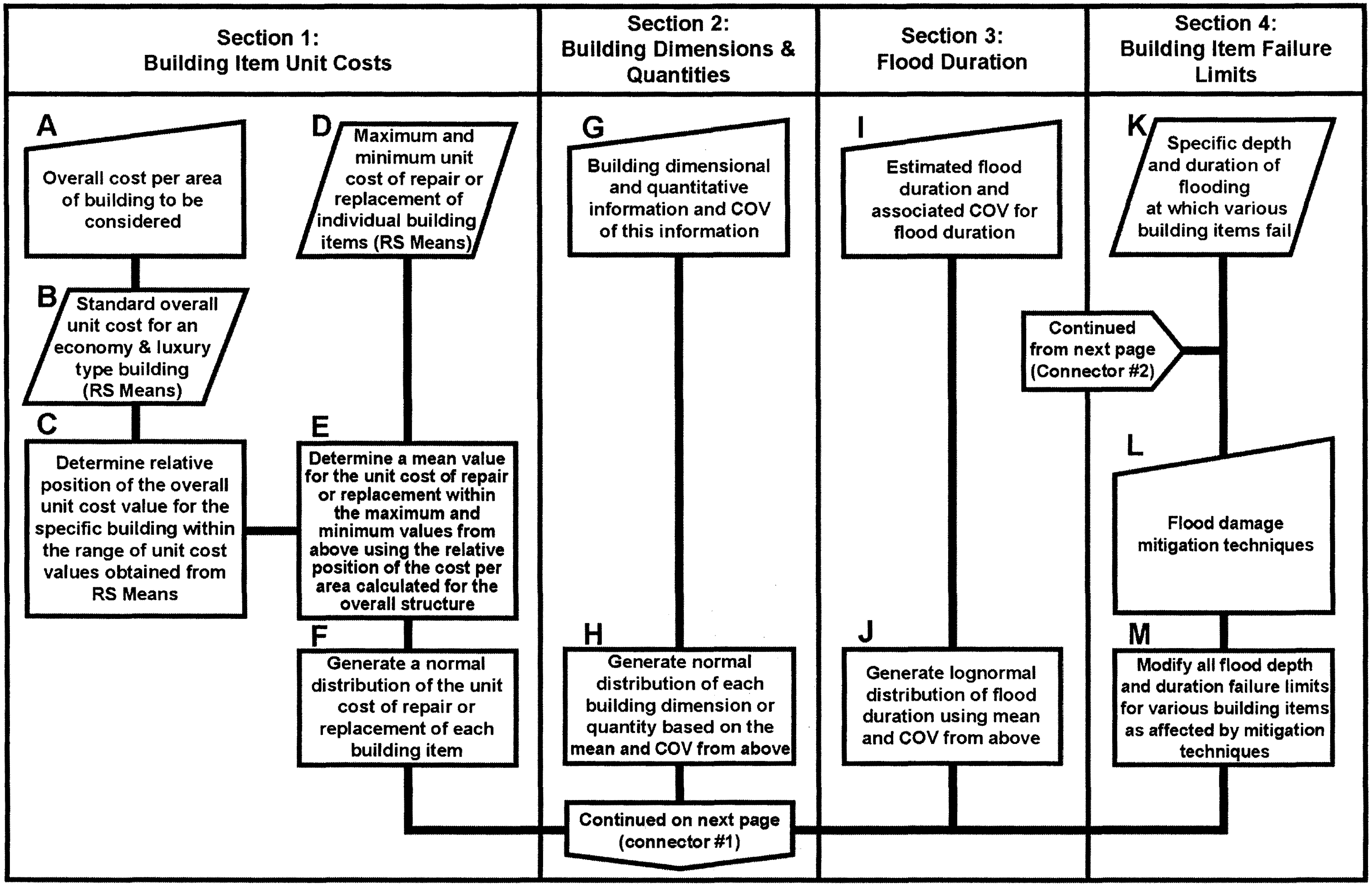


Figure 11. Flood cost damage estimation process flow chart (part 1)

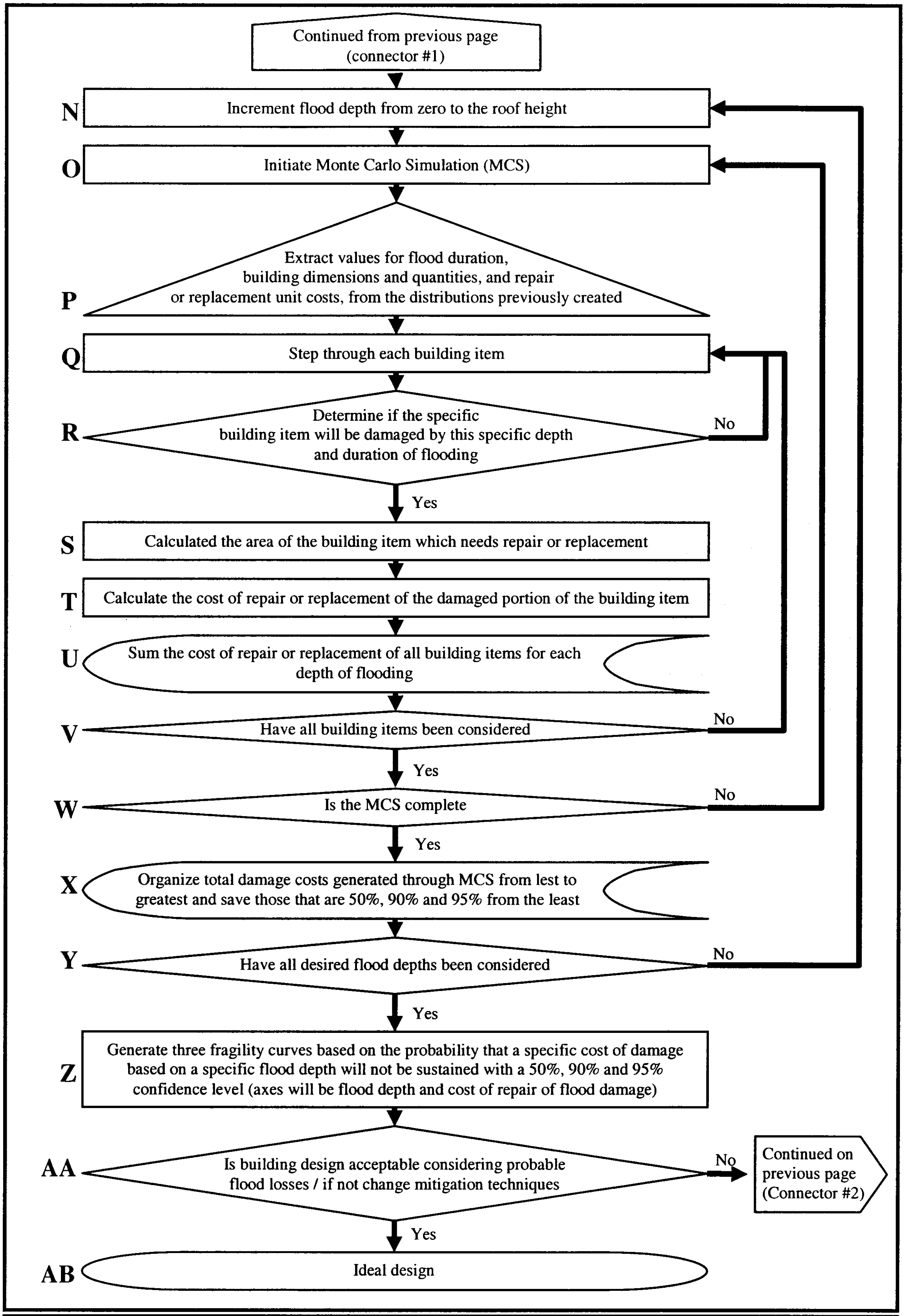


**Figure 12. Flood cost damage estimation process flow chart (part 2)**

## *5.2 Item Repair and Replacement Cost*
## *(See figure 11, section 1)*

To obtain a reasonable estimate of the costs associated with flood damage, specific and accurate estimates of repair and replacement costs of each building system are required. Of course, obtaining actual values of the cost of repair or replacement for specific items in a specific area based on experiential evidence, would be the most accurate cost estimating tool. For example, a general contracting company specializing in remodeling work and using a number of subcontractors, will easily obtain an accurate per area or per quantity cost estimate based on recent prior experience. However, in many cases this information will not be available for a particular area because design-level flooding is, fortunately, quite rare. Therefore it is necessary to estimate costs in some other way. Some of the most commonly available and widely accepted cost estimating resources are the RS Means estimating and cost data guides. For the purpose of estimating cost of repair and replacement type work the RS Means *Repair & Remodeling Cost Data (24th Annual Edition, 2003 used for this study)* guide will provide the most appropriate cost data. The guide includes the costs associated with demolition, labor, materials, equipment and overhead as well as adjustments for location within the United States. Also frequently included are maximum and minimum replacement costs for each building system. Since the cost of replacement of a specific building item would be variable, even for identical damage at the same location, based on different contractors' profit margins, individual material costs, employee costs, convenience of the job site to the contractors' locations and so forth, it is desirable to use probabilistic rather than deterministic cost estimates. It is desirable to choose a mean value for the cost of repair or replacement which falls approximately within the minimum and maximum values prescribed by the RS Means *Repair and Remodeling Cost Data ($24^{th}$ Edition, 2003)* guide. Further, it then becomes necessary to choose some criterion which will allow a relative cost within this range, or distribution. In order to produce a cost estimating methodology which will be applicable to a wide range of structures, it is important to select a criterion which will be valid and predictable across as many different structures as possible. While the pricing obtained from different contractors for the same job would be variable, it would not be predictable based on availability of work in the area, number of quotes obtained by the building owner, and many other circumstantial considerations. The variability in cost associated with quality of an item, both in terms of materials and workmanship, is significant and predictable. For example, the unit cost of cabinets constructed of particle board and associated installation cost would nearly always be exceeded by the unit cost of cabinets constructed of an exotic solid wood and associated installation costs. It can safely be assumed that, in nearly all cases, the material cost as well as the care required for installation, and thus cost of installation would be greater with higher quality materials. It can also be generally assumed that the overall cost per area of most homes will be indicative of the quality of material and workmanship contained therein. Therefore the relative placement of the cost per area value of a specific home within the national average minimum and maximum cost per area values of a similar standard home, obtained from RS Means *Square Foot Costs ($24^{th}$ Annual Edition, 2003)*, will provide a reasonable relative placement of the unit costs of specific building items within their respective cost ranges as obtained from RS Means *Repair & Remodeling Cost Data($24^{th}$ Annual Edition, 2003).*

This value is assumed herein to be the mean for the specific building item unit cost and a normal distribution can then be created around this mean using a reasonable coefficient of variation such as 0.2, or other.

However, the process by which the maximum and minimum unit costs for a certain type of building are extracted from RS Means *Square Foot Costs (24th Annual Edition, 2003)* proves to be more involved than simply a table lookup process and choosing two values. The unit cost of residential structures is variable based on the number of stories, the existence or non-existence of a basement, whether or not that basement is finished or unfinished, the overall area of the building, façade type, structural type, building footprints other than rectangular, and whether the building is considered to be economy, average, custom or luxury. In addition, the unit costs listed in the provided tables do not include many cost adders such as bathrooms, garages and various material upgrades, which are all listed separately. It should be noted that the most accurate estimation of the unit cost range would be obtained through a detailed analysis of the specific building of concern for economy and luxury type construction and a designer could follow these steps for each situation and design. However, it is also desirable to develop a streamlined approach to the process using a standard methodology to facilitate a more timely analysis such that a variety of design alternatives could be considered quickly, thus keeping the engineering and estimation costs associated with performance-based engineering for flood as low as possible.

In order to simplify the estimation process it is desirable to develop a function or a number of functions which will reasonably estimate the unit cost effects of various building types and features but will not require the consideration of all of those specific characteristics thus providing a unit cost value which will be valid for a wide range of building variations with limited input. The basic tables from the *Square Foot Costs* manual are organized as show in Table 5.

Identical tables exist for wings or ells which are connected to the basic rectilinear building footprint and which provided alternate unit costs for these sections of the building. Identical tables also exist for different numbers of stories as well as different construction types such as economy, average, custom and luxury.

**Table 5. Base cost per area of living area for a 1 story residential structure of economy construction**

| | Living Area | | | | |
|---|---|---|---|---|---|
| **Exterior Wall** | **600** | **800** | **1000** | **1200** | **1400** |
| Wood Siding - Wood Frame | 79.95 | 72.60 | 67.00 | 62.4 | 58.35 |
| Brick Veneer - Wood Frame | 87.00 | 78.95 | 72.75 | 67.55 | 63.05 |
| Stucco on Wood Frame | 78.15 | 71.00 | 65.55 | 61.10 | 57.15 |
| Painted Concrete Block | 81.50 | 74.00 | 68.25 | 63.55 | 59.35 |
| Finished Basement, Add | 20.90 | 19.65 | 18.75 | 17.95 | 17.30 |
| Unfinished Basement, Add | 9.60 | 8.60 | 7.90 | 7.30 | 6.75 |

In a list format, located beneath each of these tables are cost adders due to the bathrooms, garages, and material upgrades. Upon investigation of a number of these tables it was found that a row of unit cost data, such as is outlined in the zigzag box in Table 5, can be reasonably represented through a power function of building area versus building unit cost, as shown in Figure 13, for convenience. It was also discovered that reasonable additions could be made to unit costs such as the addition of bathrooms, garages, wings and various material upgrades, as might be expected for various building areas and construction qualities, and that these updated unit costs are also well represented with a power curve. Through the completion of this part of the process, if the construction quality, such as economy, the number of stories, basement information, and the façade and structural type are chosen, the previously generated power curve can be used to provide an estimate of unit cost data for a specific building area without specific data as to the shape of the building, bathrooms, garages and material upgrades.

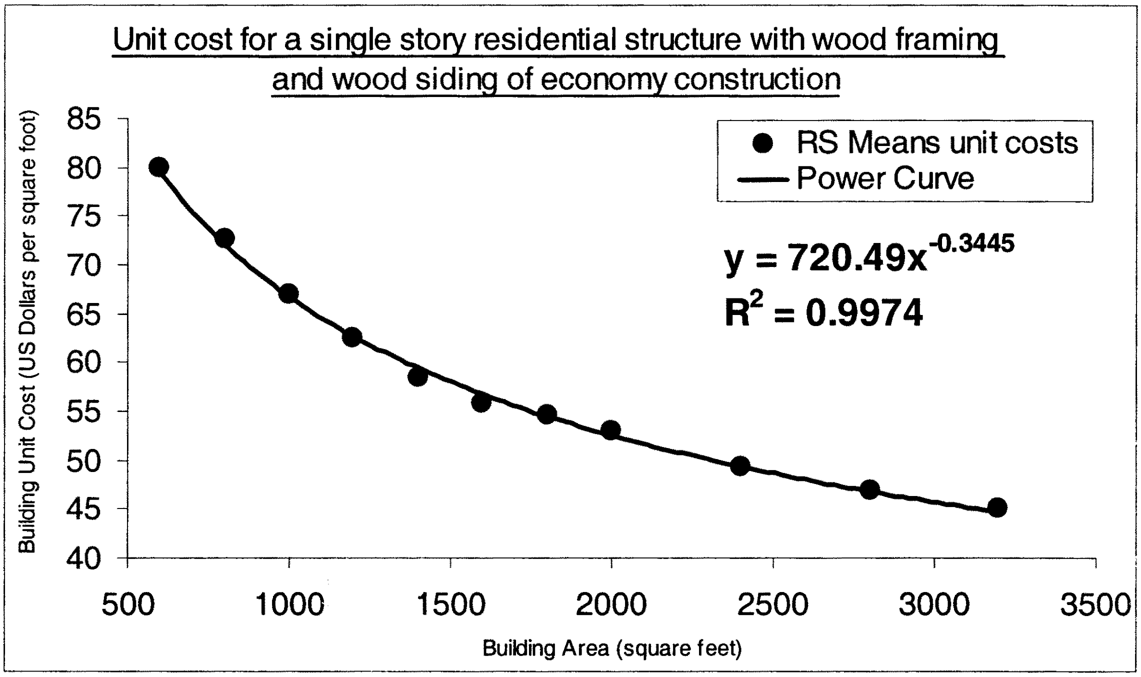


**Figure 13. Power curve fit to unit cost values obtained from RS Means *Square Foot Costs (24th Annual Edition, 2003)***

Upon further investigation, it was found that unit cost generated for a specific building area through the use of four power curves generated for the four respective construction qualities (economy, average, custom, luxury), while holding basement, number of stories, façade and structure constant, were approximately linearly related, two examples of which are shown in Figure 14. This relationship held true for a variety of building areas, number of stories and basement, façade and structural types; therefore the calculation of any unit cost data for the average and custom construction quality are not necessary as they can be linearly interpolated between the economy and luxury values. There seemed, however, no justifiable way to quantify unit cost variations due to number of stories, building area and basement type without specific knowledge of these characteristics. The only building features contained in the residential section of the *Square Foot Costs* manual not yet considered herein are the building façade and structure.

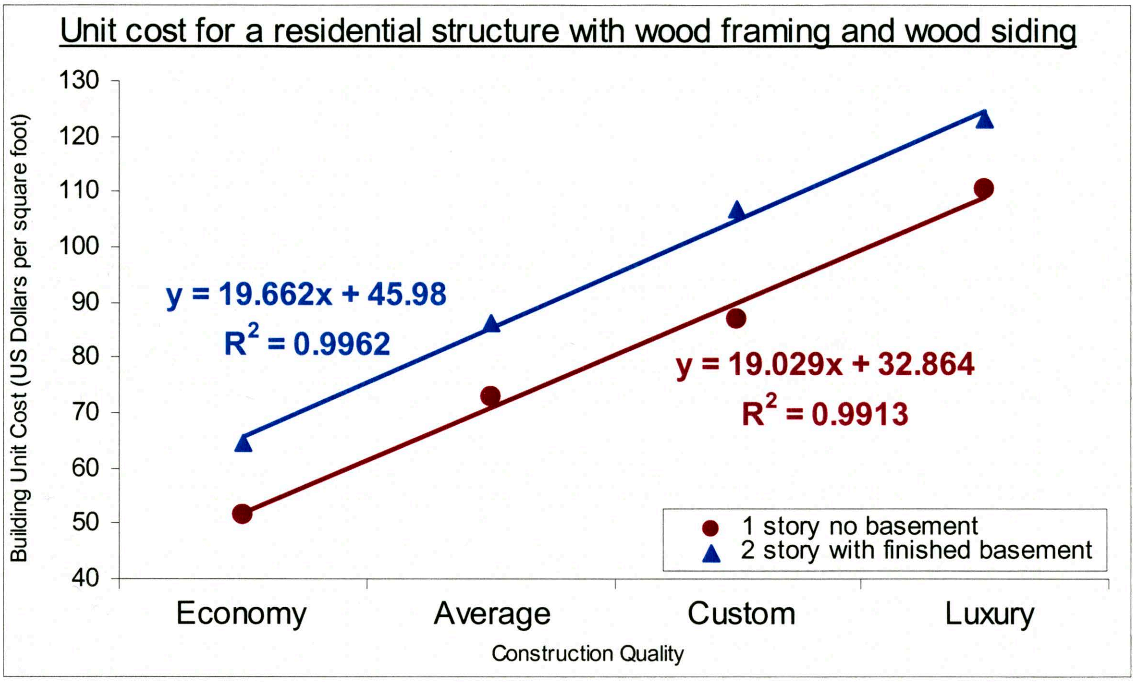


**Figure 14. Linear relationship between construction qualities**

Since the desired outcomes from this process are the maximum and minimum unit costs of a standard building and since the façade and structural cost variations are most often smaller relative to the number of stories, building area and basement type, these variations were taken into account by using unit cost values of the lease expensive façade and structural type for the economy construction and lower bound of the linear unit cost relationship and the unit cost values of the most expensive façade and structural type for the luxury and upper bound of the linear unit cost relationship. This is the last step needed to complete the simplified unit cost estimation methodology.

To put this process to use, power curves with inclusions as noted previously would be generated as an initial step and saved for future use. The various curves required include those corresponding to each basement type, each number of stories and for economy construction using the least expensive façade and structural type to luxury construction using the most expensive façade and structural type (see Table 6).

**Table 6. The 12 required power curves**

| **Economy** (using least expensive façade and structure) | | |
|---|---|---|
| No Basement | 1 story | 2 story |
| Unfinished Basement | 1 story | 2 story |
| Finished Basement | 1 story | 2 story |

| **Luxury** (using most expensive façade and structure) | | |
|---|---|---|
| No Basement | 1 story | 2 story |
| Unfinished Basement | 1 story | 2 story |
| Finished Basement | 1 story | 2 story |

Identification of the building type for the analysis based on combinations of basement type and number of stories which best matches the specific building of concern is performed and the power curves will provide the best unit cost estimates selected. Since the power curves relate overall building area with building unit cost, the maximum and minimum unit costs are calculated by entering the area of the building of concern into the equations of the selected power curves from the economy and luxury models, respectively.

As previously discussed, the relative placement of the actual unit cost of the building being analyzed within these maximum and minimum overall unit cost values is then determined. Then, the mean unit cost of repair or replacement of each individual building item is calculated using linear interpolation within the maximum and minimum repair or replacement values as prescribed in the *Repair & Remodeling Cost Data* guide around which a normal distribution is created.

## *5.3 Building Dimensions and Quantities*
## *(See figure 11, section 2)*

To obtain the most accurate estimate of the costs associated with damage due to a specific depth of flooding, a multitude of specific building dimensions and quantities would need to be tediously obtained and included in calculations; however, due to the uncertain nature of flood depth, duration, and return period, such a detailed analysis is not easily justified. The procurement of some basic building dimensional and quantitative data is sufficient, i.e. the specific type of which is selected based on ease of procurement, and relative effect on cost. The list is shown in table 7 and is meant to be complete without being exhaustive and outweighing the uncertainty associated with the analysis.

Since this flood damage estimation process should be useable for both existing buildings and for those still in the beginning design stages, some adjustment must be made for the certainty with which the building dimensions and quantities are known. It is therefore desirable to use a probabilistic method to produce these values for calculation purposes. This probabilistic method is also valuable considering the non-exhaustive nature of the building information as well as allowing the designer to estimate the building dimensional and quantitative information rather than requiring that he or she attempt exact measurements (when the final design may not yet even be known). Mean values for building dimensions and quantities are therefore obtained based on either specific knowledge of an existing structure or the general reasonable assumptions of a designer. Clearly it is desirable that there be different coefficients of variation which correspond to the varying degrees of accuracy with which the building information is known. Coefficients of variation of 0.3, 0.15, and 0.01 were used in this study to correspond with the level of confidence with which the designer knows these values.

**Table 7. Dimensional and quantitative information required**

| General information for each story | General information for entire building |
|---|---|
| Total floor area | Total floor area |
| Finished floor area | Value of home |
| Total floor area covered with carpet | Number of stories |
| Total floor area covered with tile | Any basement |
| Total floor area covered with decorative wood flooring | **Floor on which appliances are located** |
| Total floor area covered with vinyl | Furnace location |
| Total length of lower cabinets | Air conditioning compressor location |
| Total length of upper cabinets | Water heater location |
| Total length of baseboard trim | Washer and dryer location |
| Total length of trim not including baseboards | Range location |
| Total length of interior walls | Refrigerator location |
| Total length of exterior walls which are covered on the interior surface | Garbage disposal location |
| Total length of exterior walls which are covered on the exterior surface | Dishwasher location |
| Number of windows | Vented hood location |
| Number of interior doors | Electrical panel box location |
| Number of exterior doors | **Heights for each story** |
| Number of closet doors | Height from floor to ceiling |
| Number of garage doors | Height from floor of current story to floor of story above |
| Number of staircases | Height of electrical outlets |
| Number of electrical outlets | Height of electrical switches |
| Number of electrical switches | |
| Number of light fixtures | |

There are, however, some of these measurements which should remain discrete. Since the prescribed process increments flood depth rather than using a probabilistically chosen flood depth, any height measurement in the model are assumed correspondingly deterministic. In addition the number of stories and whether or not a specific building has a basement are items which should not be switched on and off through a probabilistic analysis but should be kept separate to be changed only intentionally by a designer to evaluate the benefits of any desired modifications. Lastly, since the total floor area of the home and the monetary value of the home are key in the calculation of the cost of repair or replacement of building items, but each of these values may not be well known by the designer at the time of the analysis, arguments for either a deterministic or probabilistic accounting of these values may be justified. However, for the purpose of this study, the building area is considered probabilistically because the variation of its distribution would likely correspond to the variation of the remainder of the building measurement distributions. The monetary value of the building is considered deterministically because it would not necessarily share the same correspondence. The remainder of the listed building information, as shown under the *general information needed for each story* section in Table 7, is considered probabilistically.

## *5.4 Flood Duration*

*(See figure 11, section 3)*

It is necessary to quantify the duration of flooding in order to accurately estimate the cost of building repairs; however, there is little available data for this quantification that is readily available. As a result of this dearth of data, the prescribed process leaves much of this to the judgment of the designer. A mean flood duration value is prescribed by the designer using his or her best engineering judgment based on the location, elevation and local topography and a lognormal distribution is formulated around this mean value, using a coefficient of variation of 0.2. The lognormal distribution is chosen to preclude the generation of any negative values of flood duration. As more accurate information on flood duration prediction becomes available, this distribution should be modified accordingly.

## *5.5 Building Item Failure Limits*
## *(See figure 11, section 4)*

### 5.5.1 Failure Limit Determination

The failure of a building item is described as the necessity that the item be repaired or replaced in order to return it to pre-flood conditions. For the current discussion, failure due to duration of flooding will be set aside as a separate issue to be covered after failure due to flood depth and, for the discussion of failure due to flood depth, all items will be considered to fail at a flood duration of zero hours; obviously all items do not actually fail instantaneously when touched by water but will be temporarily considered to do so for this section only for simplification of discussion. To obtain a reasonable estimate of the cost of flood damage it is necessary to accurately estimate the depth at which an item will be damaged and at which it will require either repair or replacement. There is a deficiency of data with respect to specific relative flood depths required to fail a building item; however, many building items have flood failure depths which are easy to calculate. Building item failure modes can be broken down categorically into three basic groups.

The first failure mode includes items for which the variability of damage is insignificant with respect to their vertical dimensions and for which the choice between repair and replacement is independent of flood depth such as carpeting, wood flooring, ceilings, electrical outlets and so forth. The failure flood depth for these items is taken as equal to their height above the designated zero flooding point and at this flood depth they are considered to be in need of total replacement.

The second failure mode includes items which have significant vertical dimensions and which fail below the flood level and remain in relatively good condition above the flood level and for which the choice between repair and replacement is independent of flood depth. It is important to note that a partial replacement is not equivalent to a repair, i.e. repair of drywall would be sanding and repainting rather than partial removal and replacement. This category includes items such as vertical drywall and exterior wood siding. Since capillary action will cause these items to fail at some distance above the flood level and since there is insufficient data as to this specific distance, the failure depth of these items is taken to be one foot (30 cm) above the depth of flooding and the items are considered to be in need of complete replacement below the failure depth and considered undamaged above the failure depth.

The third failure mode includes items for which the choice between repair and replacement is dependent on flood depth such as appliances. As flood depth increases additional components in the appliance may be damaged until a point at which the cost of repair is greater than the cost of replacement. Due to the immense variability in appliance design, components, component cost, component placement and ease of repair, it is not reasonable to expend undue effort to obtain specific repair costs and associated cost variability with depth. For calculations purposes, however, it is justifiable to choose a reasonable repair failure depth to be associated with a distribution of repair costs as well as to choose a reasonable replacement failure depth to be associated with a distribution of replacement costs.

The three failure modes listed herein provide a framework for the appropriate estimation of building item failures due to flood depth from which damage costs may be estimated, and is consistent with expectation of a reasonable degree of input producing reasonably accurate output. The building items and their respective failure modes are listed in Table 8.

**Table 8. Building items and associated failure modes due to flood depth**

| Building Item Flood Depth Failure Modes | | | |
|---|---|---|---|
| **Mode 1** | | **Mode 2** | **Mode 3** |
| Baseboard | Interior Doors | Wall Drywall | Air Conditioning |
| Carpet | Joists | Exterior Painting | Dishwasher |
| Ceiling Drywall | Light Fixtures | Framing | Furnace |
| Closet Doors | Lower Cabinets | Interior Painting | Garbage Disposal |
| Counters | Stairs | Siding | Range / Oven |
| Electrical Box | Subflooring | Vertical Insulation | Refrigerator |
| Electrical Outlets | Tile Flooring | | Vented Hood |
| Electrical Switches | Trim Board | | Washer and Dryer |
| Exterior Doors | Upper Cabinets | | Water Heater |
| Exterior Sheathing | Vinyl Flooring | | |
| Garage Door | Windows | | |
| Horizontal Insulation | Wood Flooring | | |

Continuing now to the duration of flooding required to fail a building item; there is some data available related to items which are either damaged or not damaged after specified periods of time but little was found concerning the specific time to failure of each building item. A study entitled "Field Testing of Energy-Efficient Flood-Damage-Resistant Residential Envelope Systems" (Aglan et al., 2004) provided some data, and testing done by the Engineered Wood Association (T92-L13, Moisture Effect on the Bending Stiffness of Wood-Based Structural-Use Panels, Borjen Yeh, 1992 / T93-25, Product Evaluation for Metropolitan Dade County, Florida, Thomas P. Cunningham Jr., 1993 / R&D86L-43, Dimensional Stability of Structural-Use Panels, Steven C. Zylkowski, 1986 / RR-132, Plywood in Hostile Environments, M.R. O'Halloran, 1975) along with performance standards for structural-use panels set forth by NIST (Voluntary Product Standard PS2-04, Performance Standard for Wood-Based Structural-Use Panels, December 2004) provides limited additional insight. Based on these references, there are four basic failure duration categories: (1) lack of removal and replacement of building item negatively impacts drying of building, (2) building item was failed when checked at three days flood duration, (3) building item was not failed when checked at three days flood duration and was not included in any studies of greater duration, (4) building item was not failed when checked after 83 hours of water spray (panels held at 30 degrees from vertical and sprayed with water on one side for the specified period of time), followed by a vacuum-pressure soaking (details not included in report). For the purposes of the current study the associated failure values are taken to be respectively: (1) building item failure duration is 0 hours, (2) building item failure duration is 36 hours (1.5 days), (3) building item failure duration is 144 hours (6 days), and (4) building item failure duration is 192 hours (8 days), which is only for wood items and the derivation of this duration will be described hereafter. The data associated with number 4 is somewhat inconclusive as the details of the vacuum-pressure soaking (VPS) are not provided in the paper and there is no specific understanding of the relationship between the spraying of the wood versus submersion. For the purposes of this study, based on the NIST PS2-04 section 7.19.3, the 83 hour spray test will be considered to be equivalent to 83 hours of submersion and the VPS will be considered to be equivalent to 72 hours submersion. Hence, the resultant sum of 155 hours or roughly 6.5 days will be considered the point at which the testing was done; the results of which were considered to be passing. Therefore, similar to the other derivations of flood duration, the wood products will be assumed to fail 1.5 days after the 6.5 day testing period or at 8 days (192 hours). A final category of failure durations was added for items not included in the study and for which damage is not dependent on flood duration which corresponds to a building item failure duration of 0 hours (see Table 9 for complete list).

The combination of building item failure limits for flood duration and flood depth provide a framework by which to begin to estimate the damage caused by a flood with specific characteristics and whereby, if a flood is probabilistically quantified, the probable damage due to flooding may be obtained.

**Table 9. Flood duration point of failure of various building items**

| Building Item Flood Duration Failure Limit | |
|---|---|
| **0 hours** | **36 hours** |
| *removal required for overall drying of building* | Baseboards |
| Carpet | Trim Board |
| Drywall (interior of exterior walls) | Doors (closet) |
| Painting (interior of exterior walls) | Doors (exterior) |
| Insulation | Doors (interior) |
| *Items not adequately covered in the studies* | Painting (exterior) |
| Electrical Box | Painting (interior of interior walls) |
| Light Fixtures | Cabinets |
| Electrical Outlets | Counters |
| Electrical Switches | Vinyl Flooring |
| Air Conditioning Compressor | Wood Flooring |
| Dishwasher | |
| Furnace | |
| Garbage Disposal | |
| Range / Oven | |
| Refrigerator | |
| Vented Hood | |
| Washer and Dryer | |
| Water Heater | |
| **144 hours** | **192 hours** |
| Drywall (interior of interior walls) | Exterior Sheathing |
| Drywall (ceiling) | Garage Door |
| Framing | Joists |
| Siding | Stairs |
| Tile Flooring | Subflooring |
| Windows | |

### 5.5.2 Failure Limit Modification / Flood Damage Mitigation Techniques

One of the primary purposes in the creating a procedure for estimation of probable flood damage to a building is to allow designers to explore options by which the probable flood damage may be reduced. There are a variety of flood damage mitigation techniques which have been proposed by many organizations and individuals. These mitigation techniques most frequently have to do with variation in building or site construction which would reduce the probability that waters from a specific flood would contact any or all building items. These objectives may be obtained either through raising the entire structure, raising a specific building item within that structure, re-ordering building design such that building items of greater flood resistance or lesser replacement costs are at lower elevations and building items of lesser flood resistance or greater replacement costs are at higher elevations, or through constructing the building so as to prevent flood waters from entering the structure even when partially submerged. Another basic flood damage mitigation technique is to change specific construction materials to those with greater flood damage resistance. Each of these flood damage mitigation techniques can be accounted for in the prescribed process through modification of the building item failure limits as show in Table 10. The process of probable flood damage calculation, as outlined herein, can be repeated with various damage mitigation techniques in place, or in other words with various modifications to building item flood failure limits, to allow evaluation of their efficacy.

**Table 10. Categorical relation between flood damage mitigation techniques and building item failure limits**

| Flood Damage Mitigation Techniques | Modifications to Building Item Failure Limits |
|---|---|
| Site modifications (i.e. raising the entire structure) | Increase failure depth limit of all building items |
| Building item modification (i.e. raising the electrical outlets) | Increase failure depth limit of a single building item |
| Re-ordering building design (i.e. exchanging an upstairs bedroom with a downstairs kitchen ) | Increase failure depth limits of some building items and decrease failure depth limits of others |
| Prevention of water entrance (i.e. dry flood proofing) | Increase failure depth limit of all building items which are below dry flood proofing level to equal that level |
| Construction material modification (i.e. replacing batt insulation with spray foam) | Increase failure duration limit of a single building item |

## *5.6. Damage Cost Calculation*

*(See figure 12)*

The basic process of calculating the cost of flood damage involves the knowledge of: (1) the characteristics of a specific flood event (flood duration and depth), (2) the construction details of the building being analyzed, (3) the failure limits of building items, and (4) repair or replacement costs of damaged building items. It then requires ascertainment of damage caused to specific building items by that flood event, evaluation of the cost of repair or replacement of the various building items, and a summation of these costs to generate a total monetary loss (see Figure 15). If flooding events were always perfectly predictable in time and other characteristics, a simple deterministic evaluation as that noted above would be sufficient; however, the uncertain nature of all aspects of a flooding event make a deterministic evaluation improper and necessarily call for a probabilistic approach. The basic flood damage cost calculation noted above can be modified so as to be probabilistic by using flood characteristics, building construction details, and building item repair or replacement costs which are probabilistic in nature.

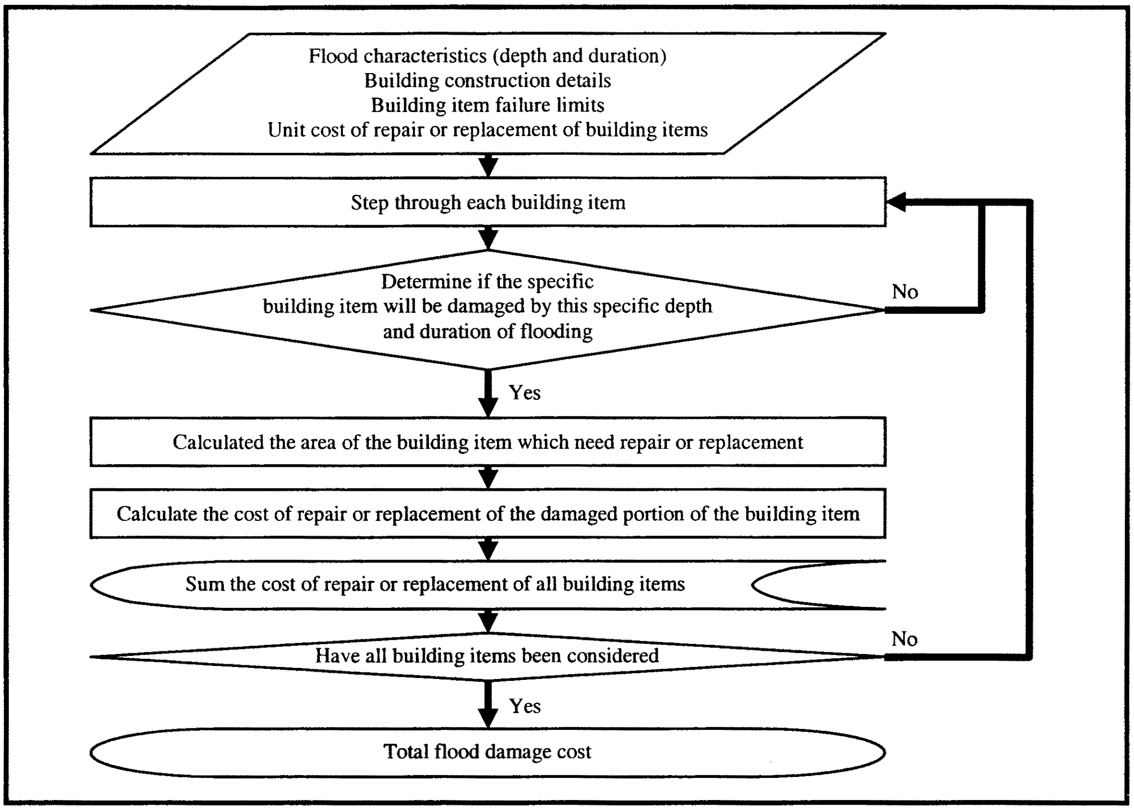


**Figure 15. Deterministic calculation of the cost of flood damage due to specific flooding characteristics**

Costs associated with flood damage are then generated using a Monte Carlo type simulation (see Figure 12). One item of note from the process outlined in Figure 12 is that flood depths are incremented and are outside the Monte Carlo simulation (MCS) rather than using a cumulative distribution function to estimate these values within the MCS. The reason for this change is to allow the results of the flood damage cost evaluation to be applied to a number of locations without recalculation. The results of the prescribed process will yield a monetary loss value for each depth of flooding and each of three probabilities of exceedance including 50%, 10% and 5%. Table 11 shows an example of this information and Figure 16 shows a plot of this data. Once such a plot is obtained as in Figure 16, one can calculate the return periods associated with each depth at various potential construction locations (this process will be discussed at the end of this section). Once such a plot is obtained as in Figure 16, one can calculate the return periods associated with each depth at various potential construction locations (this process will be discussed at the end of this section).

**Table 11. Flood damage data for a single story residential home with no basement**

| | | Damage | | | | Damage | |
|---|---|---|---|---|---|---|---|
| Depth | PE=50% | PE=10% | PE=5% | Depth | PE=50% | PE=10% | PE=5% |
| 0 | $0 | $0 | $0 | 50 | $60,117 | $63,577 | $64,622 |
| 2 | $13,360 | $14,996 | $15,565 | 52 | $63,910 | $67,085 | $67,862 |
| 4 | $24,110 | $26,504 | $27,061 | 54 | $64,543 | $67,951 | $69,184 |
| 6 | $30,089 | $32,618 | $33,476 | 56 | $64,829 | $68,228 | $69,279 |
| 8 | $30,476 | $33,213 | $34,164 | 58 | $64,902 | $68,424 | $69,545 |
| 10 | $34,165 | $36,461 | $37,183 | 60 | $67,427 | $71,197 | $71,923 |
| 12 | $41,242 | $43,986 | $44,875 | 62 | $67,598 | $71,223 | $72,275 |
| 14 | $41,464 | $44,194 | $44,928 | 64 | $68,474 | $72,074 | $73,067 |
| 16 | $42,318 | $45,258 | $45,972 | 66 | $68,435 | $72,090 | $73,057 |
| 18 | $42,421 | $45,114 | $46,108 | 68 | $68,788 | $72,581 | $73,298 |
| 20 | $44,305 | $47,137 | $47,924 | 70 | $69,206 | $72,985 | $73,910 |
| 22 | $44,842 | $47,657 | $48,534 | 72 | $70,361 | $74,370 | $75,368 |
| 24 | $46,920 | $49,575 | $50,424 | 74 | $70,644 | $74,178 | $75,501 |
| 26 | $47,025 | $50,146 | $50,917 | 76 | $71,006 | $74,963 | $76,290 |
| 28 | $47,642 | $50,451 | $51,146 | 78 | $71,201 | $74,954 | $75,941 |
| 30 | $48,001 | $50,799 | $51,506 | 80 | $71,136 | $75,004 | $75,878 |
| 32 | $48,242 | $51,243 | $52,210 | 82 | $71,148 | $74,942 | $75,947 |
| 34 | $50,856 | $53,960 | $54,785 | 84 | $71,741 | $75,265 | $76,300 |
| 36 | $51,289 | $54,165 | $55,040 | 86 | $71,683 | $75,081 | $76,317 |
| 38 | $51,723 | $54,820 | $55,643 | 88 | $71,598 | $75,519 | $76,681 |
| 40 | $54,033 | $57,435 | $58,192 | 90 | $71,880 | $76,001 | $76,980 |
| 42 | $54,558 | $57,693 | $58,256 | 92 | $71,979 | $76,119 | $76,986 |
| 44 | $54,936 | $57,952 | $58,780 | 94 | $72,430 | $76,371 | $77,760 |
| 46 | $55,210 | $58,200 | $58,992 | 96 | $81,847 | $86,028 | $87,013 |
| 48 | $59,508 | $62,998 | $63,770 | 98 | $81,860 | $85,944 | $87,228 |

Hence, for each incremental flood depth, an entire Monte Carlo simulation will be executed. Continuing, the first step inside the MCS (Figure 12, P) is the extraction of values from the previously computed distributions of flood duration, building dimensions and quantities, and repair or replacement unit costs (Figure 11, F,H,J). Once these values are derived, it is necessary to step through each building item (Figure 12, Q) and compare the building dimensional information with the flooding characteristics (depth and duration) to determine if flood waters will come in contact with a specific building item; followed by the comparison of building item failure limits with these flooding characteristics to determine whether or not there will be damage to the specific building item (Figure 12, R).

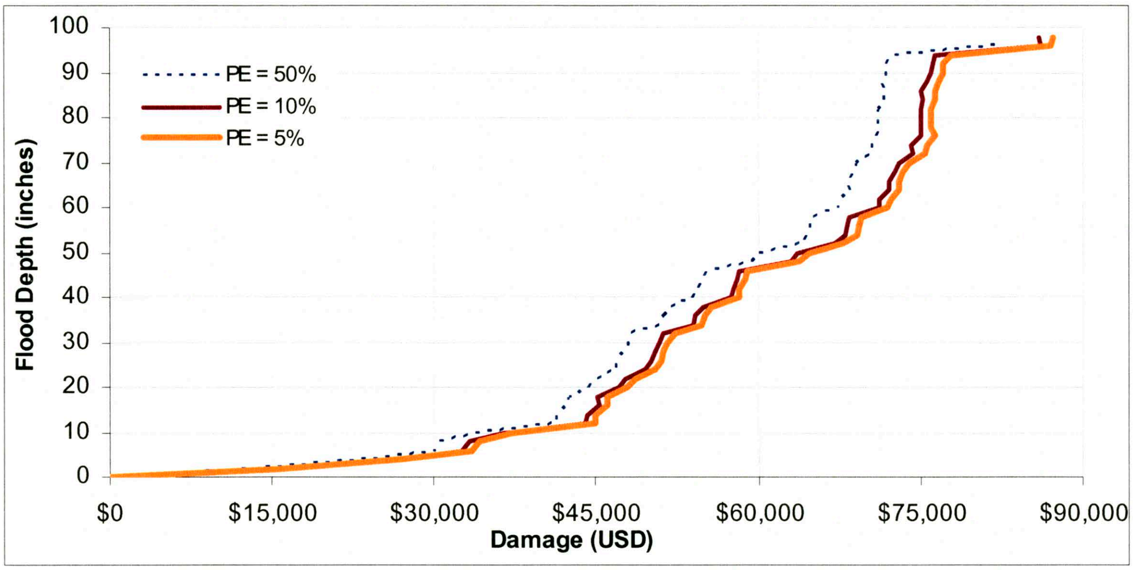


**Figure 16. Fragility curve for a single story home with no basement**

If the building item is found to sustain damage, the building dimensional information and flood characteristics are used to determine the specific area of damage or quantity if items damaged (Figure 12, S), the unit cost is multiplied by the area or quantity of items damaged to calculate the cost of repair or replacement of the damaged building item (Figure 12, T) and finally the cost of damage of each building item is summed with the previous (Figure 12, U) until each building item has been considered (Figure 12, V). This process is repeated, each time extracting new values of flood duration, building dimensions and quantities and repair or replacement unit costs, until the MCS is complete; 500 trials were found to be sufficient and will be used for the purposes of this study. After the completion of the MCS for each depth there will be 500 flood damage cost values which are rank ordered from smallest to largest. Once these data are organized, the 500$^{th}$, 900$^{th}$ and 950$^{th}$ values which respectively represent 50%, 90% and 95% confidence levels of non-exceedance, or 50%, 10% and 5% probabilities of exceedance, for that specific depth of flooding (Figure 12, X) are plotted. A fragility curve is then generated through the repetition of this process for each flood depth and the subsequent graphical representation of flood depth versus cost of flood damage for each of the aforementioned percentile (exceedance) levels (See Figure 12, Y,Z and Figure 16).

There are three basic modifications which can be made to the fragility curves previously generated to aid in the decision making process; two of these are non-essential and one is essential. The first non-essential change involves displaying the flood damage costs as annualized values rather than absolute values which is done simply by dividing the absolute costs by the expected period of ownership of the building and it is useful in demonstrating the effects of a longer or shorter exposure to a particular risk. The second non-essential change is to non-dimensionalize the flood damage costs by dividing either the absolute cost or the annualized cost by the total construction cost of the building, hence providing a flood damage cost per construction cost value which can be displayed as a percentage loss. This is useful in that, assuming a relatively consistent increase in all construction costs over time, it eliminates the inaccuracies associated with the time value of money; for example an estimated annual loss of $2000 over a 30 years ownership may be accurate if the building were to flood this year but completely incorrect if the building were to flood 25 years from now, however, an annual loss of 3% of the building cost would always be accurate if considered to be 3% of the current cost of construction of such a building in whatever year the flooding occurs. The final and essential modification to be made to the fragility curves is the addition of the associated probabilities of occurrence to the flood depths. Figure 17 shows a fragility curve with all of these modifications.

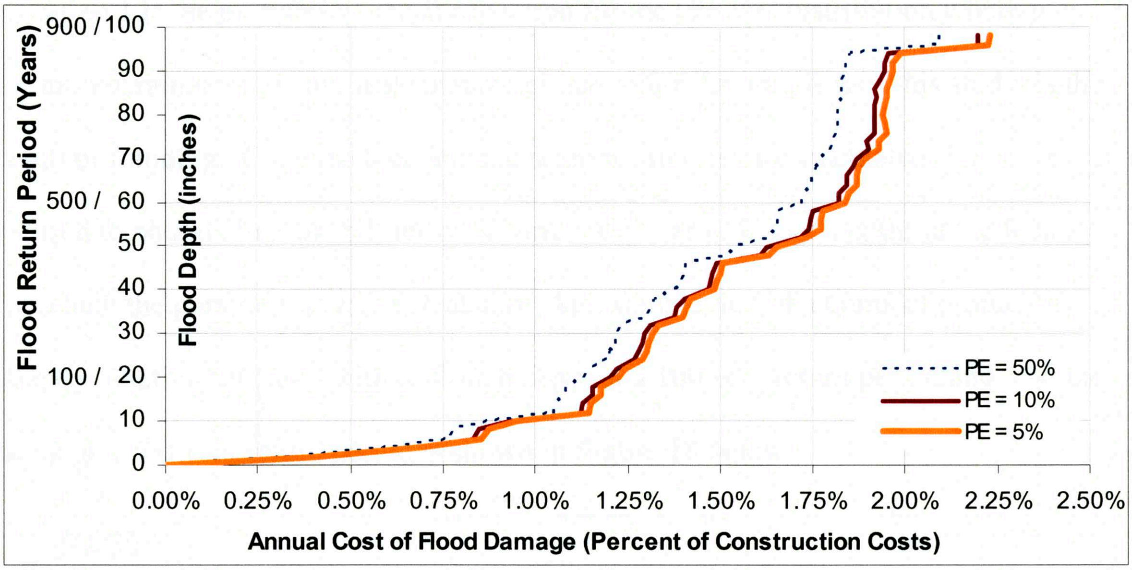


**Figure 17. Fragility curve for a single story home with no basement and with a 30 year ownership**

Adding the associated return period values to the flood depths is significantly more complex than the previous two modifications. The most widely available information on flood return periods is provided through the Federal Emergency Management Agency (FEMA) flood maps. These flood maps provide extents of flooding for 100 year and 500 flood events, which correspond to annual probabilities of 0.01 and 0.002 respectively. Using the maps of these flood extents along with a topographic map of the area, one can obtain the depth of flooding associated with these events at a specific location. A two parameter distribution can then be obtained using these two probabilities, associated flood depths, and an equation of a probability density function to solve for the distribution parameters; and although widely disputed, it has been suggested that a Gumbel distribution will provide reasonable estimations of flooding events and it is therefore used in this study (see Equation 1).

$$P(x) = [\exp(-(x-\mu)/\square)*\exp(-\exp(-(x-\mu)/\ \square))]/\ \square \qquad \underline{(1)}$$

Equation 1 is the probability density function for the Gumbel distribution where $\mu$ is the location parameter, □is the scale parameter and x, for the purposes of this study, is the depth of flooding. Once the location and scale parameters are calculated, Equation 1 can be used to obtain the probabilities of occurrence of various flood depths at the location for which the parameters were calculated. An example plot of a Gumbel probability density function for flood with a 20 inch depth at a 100 year return period and a 50 inch depth at a 500 year return period is shown in Figure 18 below.

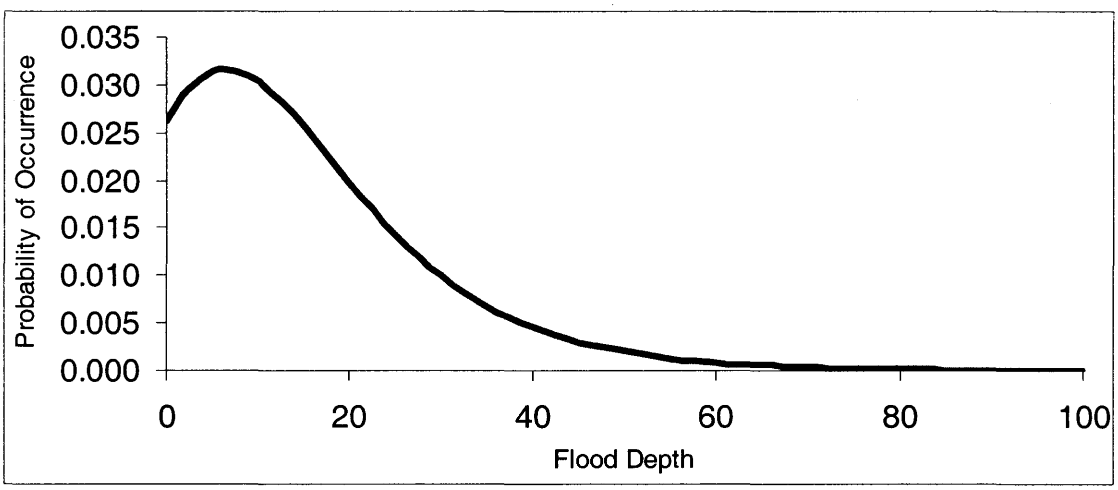


**Figure 18. Gumbel PDF for a 20 inch depth 100 year flood and 50 inch depth 500 year flood event**

These probabilities can then be displayed on the fragility curve plots either in probability form or in the form of return periods. This is essential since flood depth was incremented rather than included in the Monte Carlo Simulation and therefore the designer cannot make any rational decisions on the financial benefit of various designs unless he or she can compare the flood damage costs to their associated probabilities of occurrence rather than only to a depth of flooding.

After the desired modifications are made to these fragility curves, other design options may be considered and the entire process repeated to generate additional sets of fragility curves which can be compared with the previous sets and the potential flood damage cost reductions can be compared with one another to determine the optimum design solution (Figure 12, AA,AB).

# 6. Illustrative Examples

## *6.1 Overview*

Recall that the purpose of this study is to develop a process, using a performance based design approach, to provide information concerning potential monetary losses due to damage sustained by a building caused by a flooding extreme event. This will allow current or potential property owners to make informed cost-benefit decisions concerning the implementation of flood damage mitigation techniques for the purpose of the reduction of flood damage costs. This is accomplished through the calculation of the damage caused to all building systems when subjected to incremental flooding from zero to the top floor ceiling height. A specific duration of flooding is assigned, and the calculation of the cost of repair or replacement of each damaged building item is determined and summed. The generation of fragility curves representing a 50%, 10% and 5% probability of exceedance and which relate flood depth to overall monetary losses provide a visual representation of this information. Flood damage mitigation techniques are then added to the building model, the process is repeated, and the flood damage results are plotted to provide quantitative insight into the benefits associated with the implementation of these mitigation techniques. The analyst then has the data necessary to perform a cost-benefit analysis of building design changes which have the potential to reduce flood damages. This information can then be conveyed to the owner or occupant.

Four home designs have been selected as a representative sample of typical residential construction. The designs selected include a single story home without a basement, a single story home with an unfinished basement, a single story home with a finished basement and a two story home without a basement. The homes contain a variety of interior finishes and the dimensional quantities of each building item have been calculated using the mean values obtained from the plans and each of three coefficient of variations (COV's) namely, 0.01, 0.15 and 0.30. There are three overall building unit values used in the calculations: \$60, \$100 and \$160 per square foot (0.093 $m^2$); these precise values have been used with the single story home without a basement, however, the values were adjusted to provide the same relative placement within the range of the prescribed RS Means Economy and Luxury unit costs values for the three other home designs. There were six different flood damage mitigation techniques considered including: (1) raising the entire house 24 inches (61 cm), (2) raising electrical switches and outlets to 60 inches (152 cm) above the floor of each level and raising the electrical panel box to 72 inches (183 cm) above the lowest floor level, (3) raising the furnace, air conditioning, water heater and washer and dryer 18 inches (46 cm) above their original locations, (4) changing the wall insulation to a foam type insulation which is impervious to water damage, (5) changing the siding to vinyl, and (6), raising the ceiling height of each level by 18 inches (46 cm); as well as 4 different combinations of these mitigation techniques. Finally the flood depth was incremented as noted above and the houses were subjected to 3 different durations of flooding including 24 hours, 96 hours and 168 hours. All of the trials performed are listed in the Figure 19.

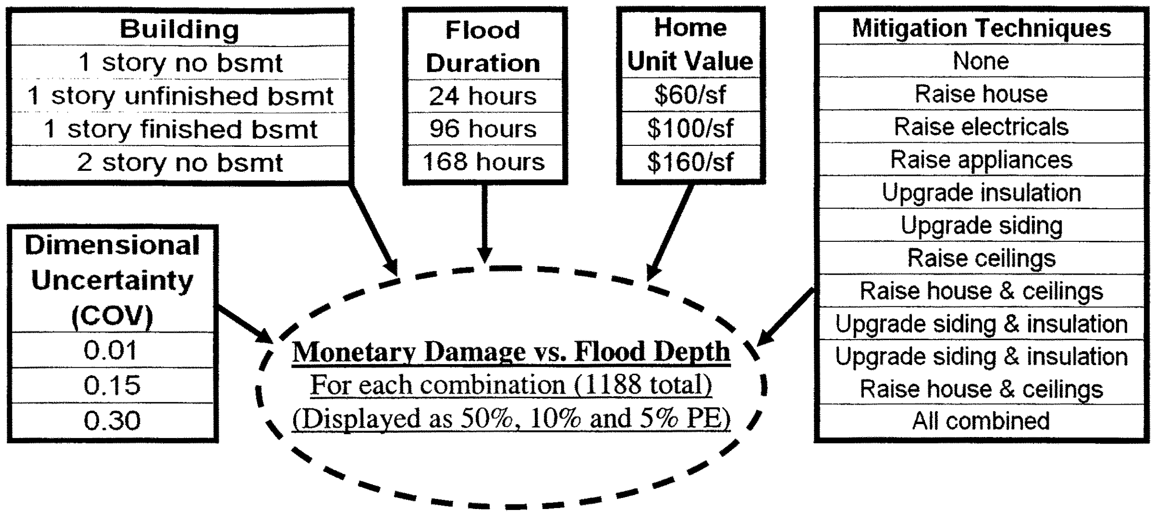


**Figure 19. Summary of trials for illustrative examples**

## *6.2 Adjusted Home Unit Cost Values*

It was determined to use three overall unit cost values for this study which were $60, $100 and $160 per square foot and which were selected to correspond to the single story home with no basement as shown in Figure 27. Using the values extracted from the RS Means *Square Foot Costs (24$^{th}$ Annual Edition, 2003)* manual for the unit costs of an economy and luxury single story home with no basement at 1304 square feet (121 square meters), the relative placements of $60, $100 and $160 unit costs were calculated within that range. Through linear interpolation, these relative placement values were then used to calculate the associated unit cost values for the single story home with an unfinished and finished basement as well as for the 2 story home using the RS Means economy and luxury unit cost values associated with these types of homes, see Figure 20. Table 12 shows the results of those calculations and the actual unit cost values used in each trial.

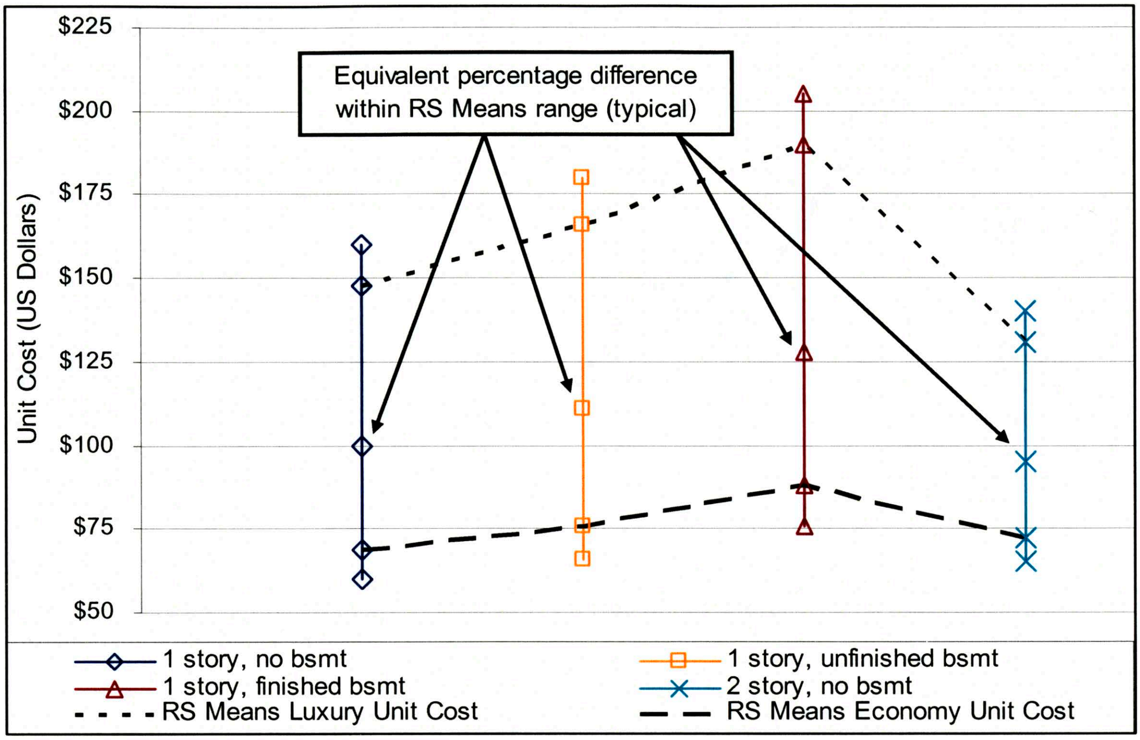


**Figure 20. Example of linear interpolation used to calculate various unit cost values**

**Table 12. Adjusted unit cost values**

| House | 1 Story | 1 Story | 1 Story | 2 Story |
|---|---|---|---|---|
| Basement | None | Unfinished | Finished | None |
| RS Means Economy Unit Cost | $69 | $76 | $88 | $72 |
| RS Means Luxury Unit Cost | $148 | $166 | $190 | $131 |
| Adjusted $60 Unit Cost | $60 | $66 | $76 | $65 |
| Adjusted $100 Unit Cost | $100 | $111 | $128 | $95 |
| Adjusted $160 Unit Cost | $160 | $180 | $205 | $140 |

## *6.3 General Findings*

Variations in the uncertainties of building dimensional values have little effect when considered with damage values associated with a 50% probability of exceedance; when considered with damage values associated with a 5% probability of exceedance, a greater value of the COV increases the variability of the damage, resulting in increased values for flood damage as can be seen in Figures 21 and 22.

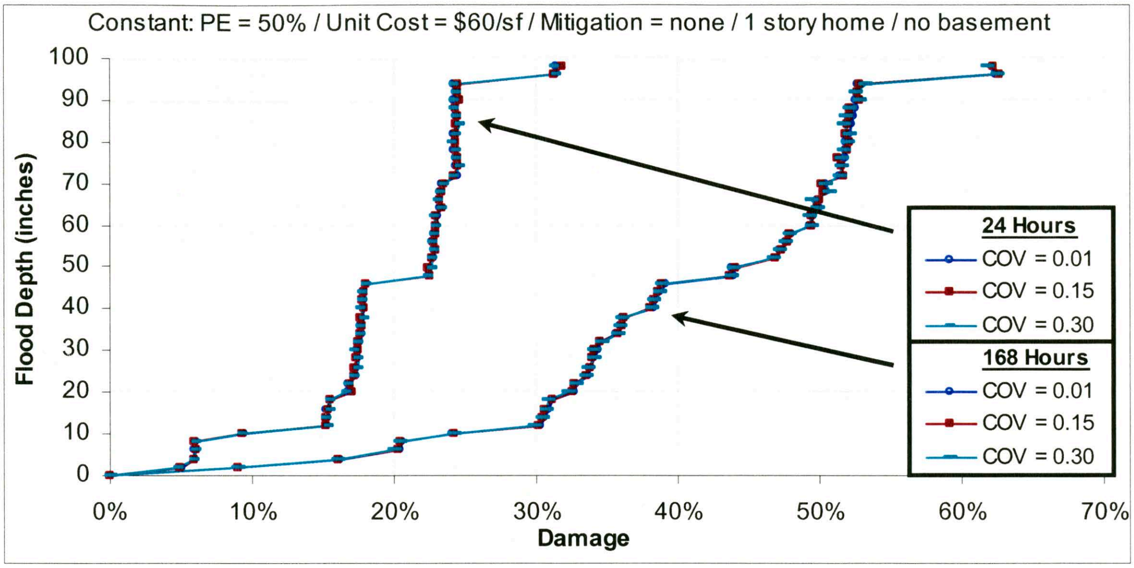


**Figure 21. Changes in flood damage results with varying building dimensional uncertainties at a probability of exceedance of 50%**

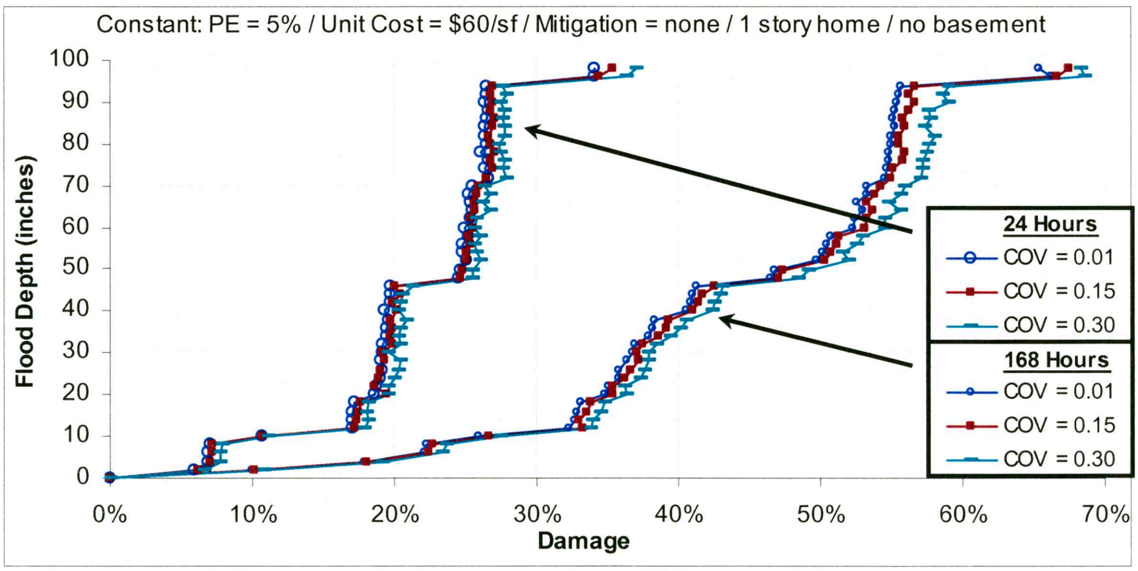


**Figure 22. Changes in flood damage results with varying building dimensional uncertainties at a probability of exceedance of 5%**

As expected, damage values increase with higher probabilities of exceedance and the gap between the damage values which are associated with different probabilities of exceedance increases as the damage values increase as is show in figures 23 and 24.

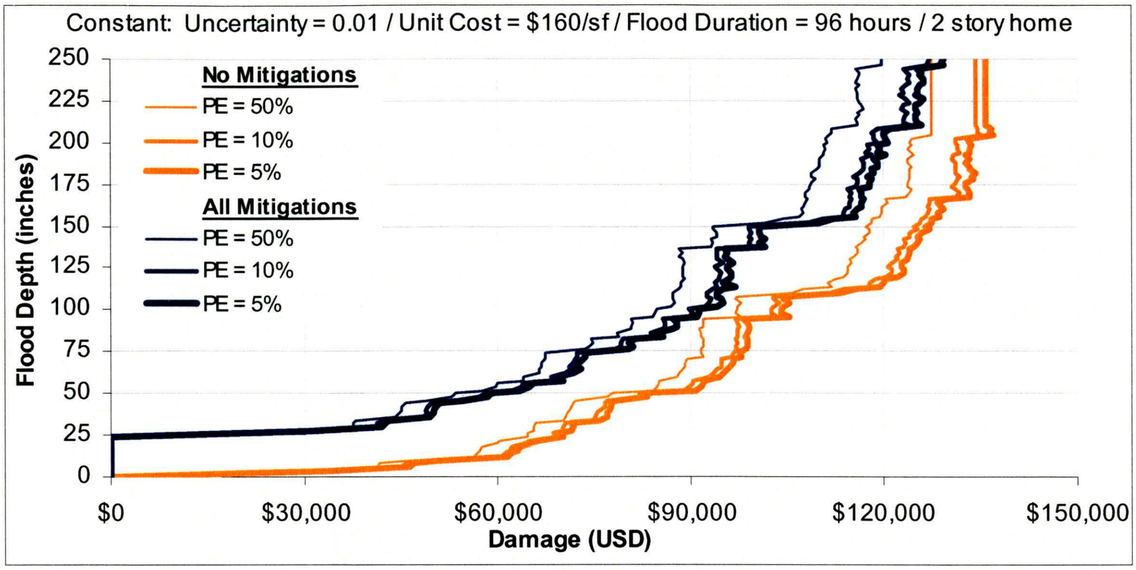


**Figure 23. Changes in flood damage results with varying probabilities of exceedance expressed in terms of U.S. dollars**

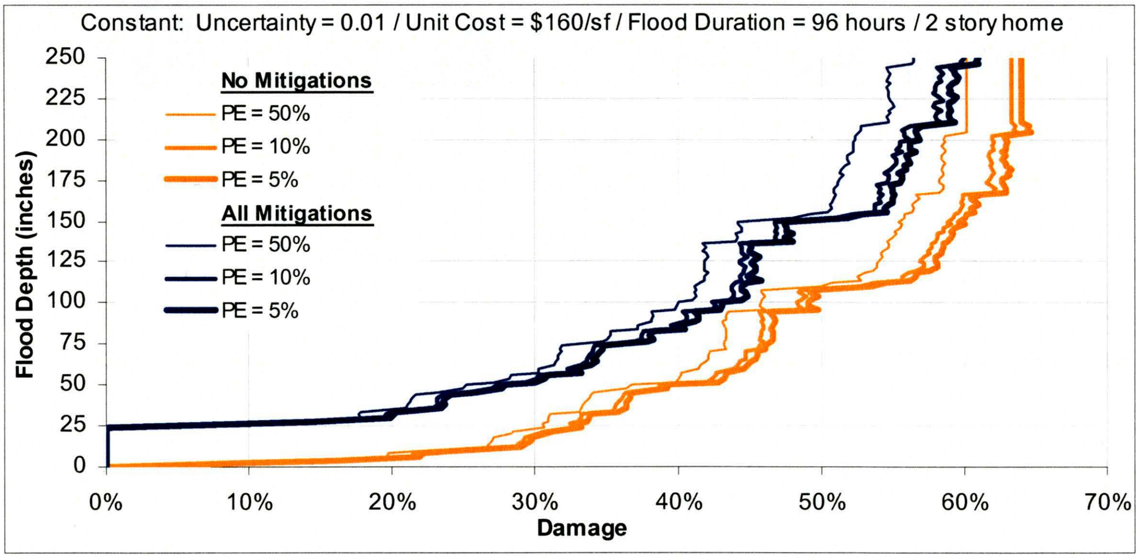


**Figure 24. Changes in flood damage results with varying probabilities of exceedance expressed in terms of a percentage of the total home cost**

Figure 25 provides an example of the breakdown of the different building items which contribute to the damage as a result of the flooding. This example is for a flood depth of 58 inches (147 cm) for the single story home with no basement, with a unit cost of $100 per square foot, a flood duration of 168 hours and a dimensional uncertainty COV value of 0.01. This example considers each damaged building item as a percentage of the total damage at this flood depth. From this plot, the most costly items to replace for this home would be the cabinets, carpet, drywall, siding and interior painting.

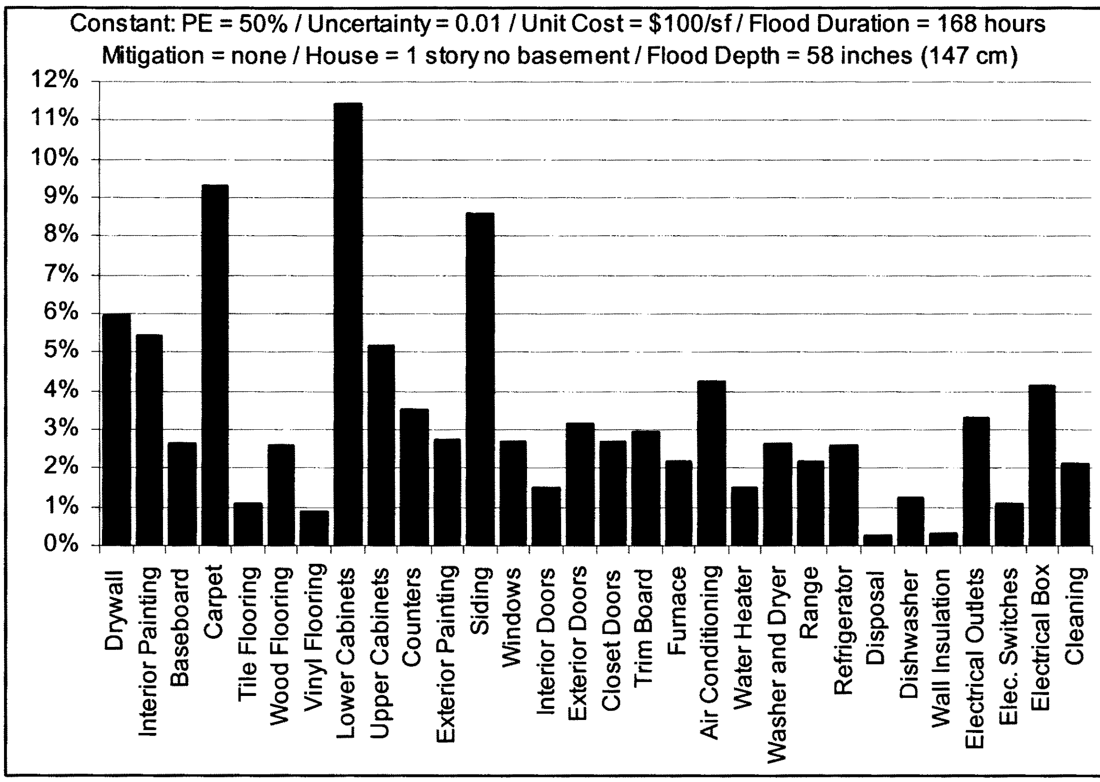


**Figure 25. Contributions of various building items to total damage at a 58 inch (147 cm) flood depth**

Figure 26 is a detailed view of the fragility curve for the single story home with no basement with a unit cost of $100 per square foot, a flood duration of 168 hours and a dimensional uncertainty COV value of 0.01. On the fragility, particular points at which different building items influence the fragility curve are shown.

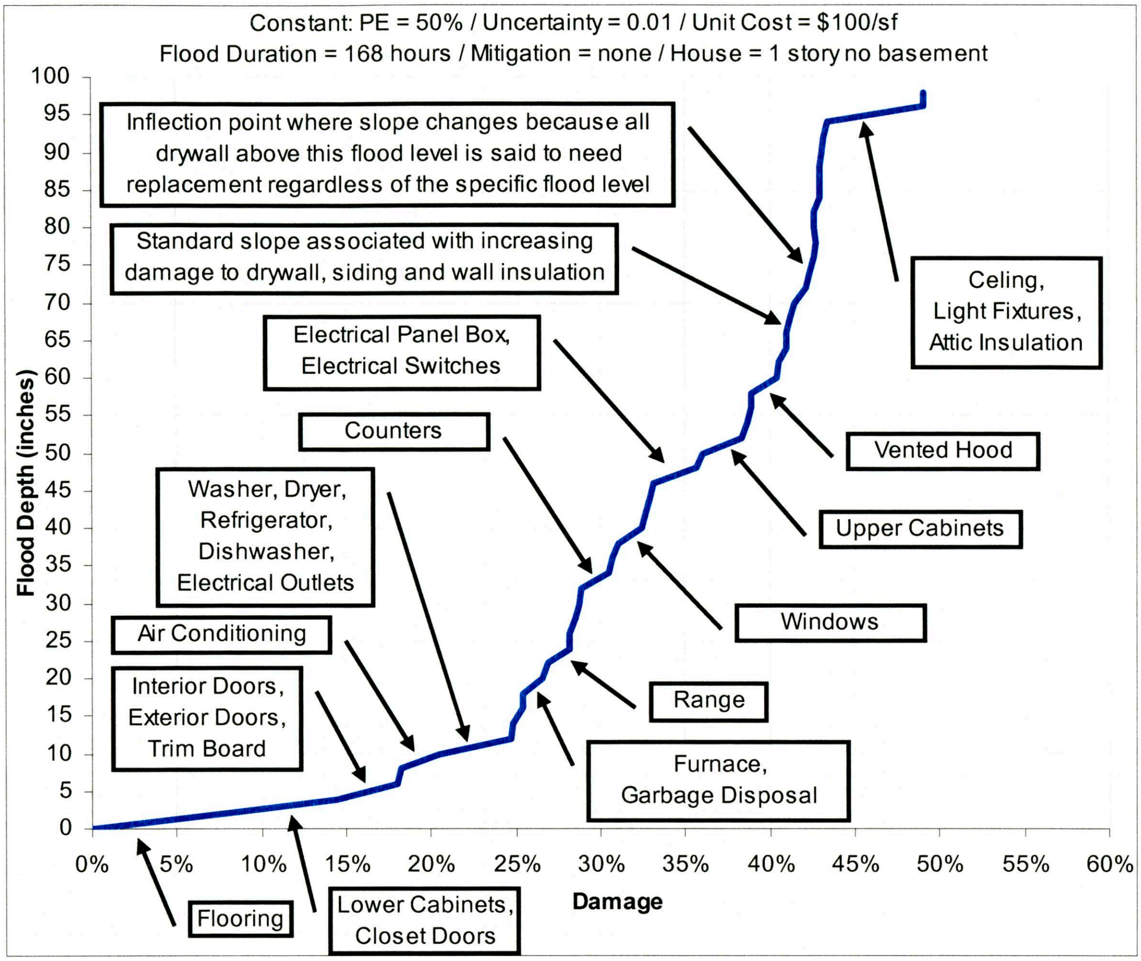


**Figure 26. Components of the fragility curve**

## *6.4 Single story home with no basement*

The following example involves the flood damage sustained by a single story residential home with no basement representing flooding from floor level to ceiling level. The basic house plan is show in figure 27. All of the building dimensional information used to calculate the flood damage to the single story home with no basement are shown in Table 13.

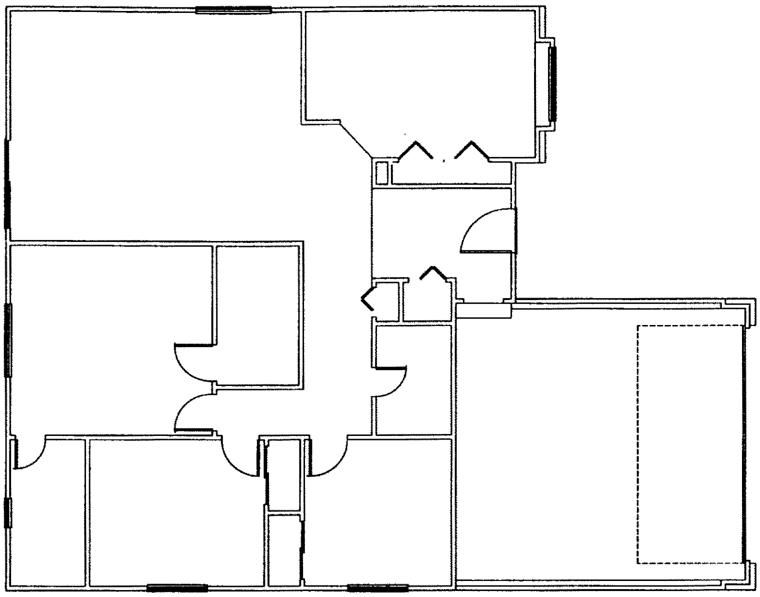

**Figure 27. Basic plan for the single story residential home with no basement**

**Table 13. Building dimensional information for the single story residential home with no basement**

| General information for story #1 | | General information for entire bldg | |
|---|---|---|---|
| Total floor area | 1304 sf | Total floor area | 1304 sf |
| Finished floor area | 1304 sf | Value of home | Varied |
| Total floor area covered with carpet | 992 sf | Number of stories | 1 |
| Total floor area covered with tile | 72 sf | Any basement | No |
| Total floor area covered with decorative wood flooring | 144 sf | **Location of appliances** | |
| Total floor area covered with vinyl | 96 sf | Location of furnace | Floor 1 |
| Total length of lower cabinets | 33 ft | Location of air conditioning compressor | Floor 1 |
| Total length of upper cabinets | 18 ft | Location of water heater | Floor 1 |
| Total length of baseboard trim | 420 ft | Location of washer and dryer | Floor 1 |
| Total length of trim not including baseboards | 336 ft | Location of oven | Floor 1 |
| Total length of interior walls | 137 ft | Location of refrigerator | Floor 1 |
| Total length of exterior walls which are covered on the interior surface | 146 ft | Location of garbage disposal | Floor 1 |
| Total length of exterior walls which are covered on the exterior surface | 164ft | Location of dishwasher | Floor 1 |
| Number of windows | 7 | Location of vented hood | Floor 1 |
| Number of interior doors | 4 | Location of electrical panel box | Floor 1 |
| Number of exterior doors | 2 | **Height of items** | |
| Number of closet doors | 8 | Height from floor to ceiling | 96 in |
| Number of garage doors | 1 | Height from floor below to floor above | NA |
| Number of staircases | 0 | Height of electrical outlets above floor | 12 in |
| Number of electrical outlets | 52 | Height of electrical switches above floor | 48 in |
| Number of electrical switches | 16 | | |
| Number of light fixtures | 21 | | |

Figures 28 through 31 show the damage sustained by the single story residential home subjected to a variety of flood durations as well as a variety of overall unit cost values for the home. As expected, the greatest damage sustained by the home occurs with the combination of greatest flood duration and greatest unit cost of the home and the least damage is sustained by the home with the combination of shortest flood duration and least unit cost of the home. A comparison between Figures 28 and 30 or 29 and 31 reveals that the damage values expressed as a percentage of the total value of the home tend to be grouped in terms of the three durations of flooding. In addition, the greater unit cost value of a home tends toward the greater percentage damage to the home showing that the division of the damage values by the total value of the homes removes much of the variability due to unit cost differences. However, the type of items which have a tendency to be most readily damaged by flooding (interior finishes), are a higher percentage of the total value of the home for a luxury type home than for an economy type home, i.e. the framing and structural portion are similar but the interior quality is not.

The comparison between the flood damage values associated with a 50% and 5% probability of exceedance shows that there is no change in the relative placements of the fragility curves but there is an overall decrease in damage values associated with the curves for the 50% probabilities of exceedance than with those associated with the 5% probabilities of exceedance. This is as expected.

Figures 32 through 37 show the results of implementation of the various mitigation techniques covered in this study. The mitigation techniques have been split into three groups for graphical clarity and each group has been plotted at a 50% probability of exceedance as well as a 5% probability of exceedance.

In figures 32 and 33 the flood damage mitigation techniques related to modifications to siding and/or insulation only, are minimally effective at small flood depths and increasingly effective with greater flood depths. This is as expected since these items do not require total replacement upon any contact with flood waters but rather require only a partial replacement which is related to the quantity which comes into contact with the flood waters. Hence when flood depth increases a greater amount of damage is sustained by these items and thus a greater savings is realized based on using flood performance alternatives.

In figure 34 and 35 the fragility curve associated with raising the house follows the same pattern as the curve associated with no mitigation technique except that its path is 24 inches (61 cm) above that of the curve associated with no mitigation technique. This is expected since raising the house would have no effect on the failure durations of the building items and affect the failure depth only by the depth to which the house is raised.

In figures 34 and 35 the fragility curves associated with raising the ceiling and that of raising both the ceiling and the house result in the only cases where the damage due to flooding up to the ceiling level actually exceeds that of the house when no mitigation technique was used. This is rational since the increase in ceiling height requires additional construction materials such as drywall, framing, insulation, siding and painting in order to increase the wall height and the damage to all of these additional materials is accounted for in the total damage to the home. Thus, the mitigation technique results in a savings for equivalent flood depths but would result in a greater loss resulting from a greater cost of re-construction due to a complete submersion of the home. However, when raising the ceiling height is combined with modifications to the insulation and siding, as show in figures 32 and 33, the additional wall height becomes more flood resistant and hence the total damage becomes less than that of the home without any mitigation techniques in place.

In figures 36 and 37 the fragility curves associated with raising electricals and raising appliances are shown. These are unique from the previously considered mitigation techniques in that they offer savings only for a narrow range of flooding after which their fragility curves re-combine with the curve associated with no mitigation technique. Looking more closely at the fragility curve associated with raising the electricals compared with that of no mitigation technique, as expected the curves separate at about 12 inches (30 cm) which is the original height of the electrical outlets and the curves rejoin at about 72 inches (183 cm) which is the height to which the electrical panel box was raised. Similarly, comparing the fragility curve associated with raising the appliances to that of no mitigation technique the curves separate at about 4 inches, which was the first failure depth which was associated with the water heater, and rejoin at about 38 inches, which is the failure depth of the furnace of 20 inches (51 cm) plus the height to which it was raised by the mitigation technique, 18 inches (46 cm).

Again the changes in the fragility curves associated with a 5% probability of exceedance as compared with a 50% probability of exceedance show no change in relative placement of the curves but only of an overall decrease in damage values for the 50% PE compared with the 5% PE.

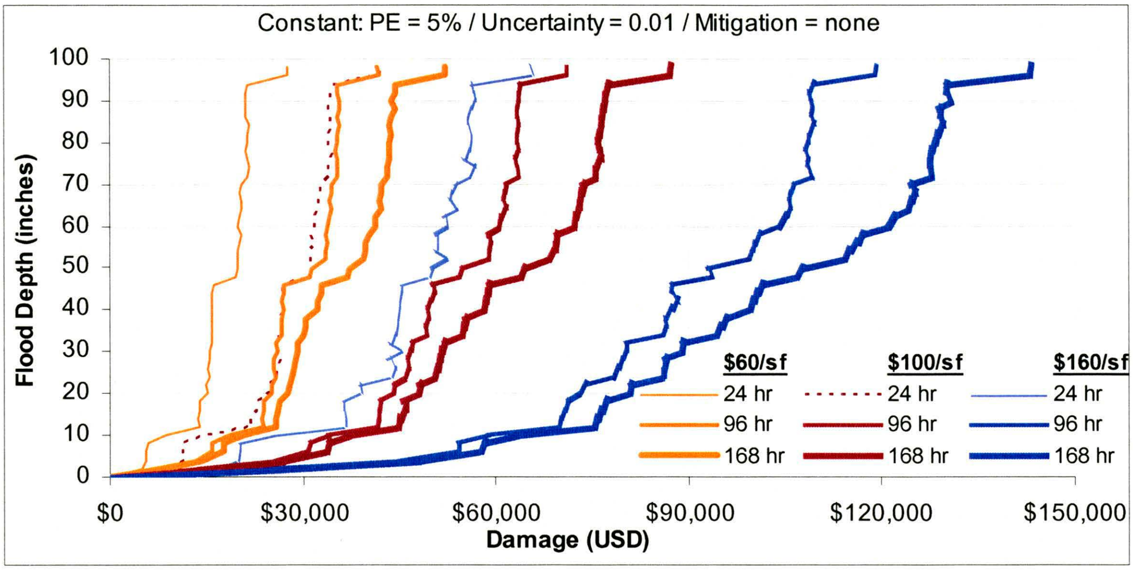


**Figure 28. Flood damage values associated with variations in building unit cost and flood duration expressed in terms of U.S. dollars and at a 5% probability of exceedance**

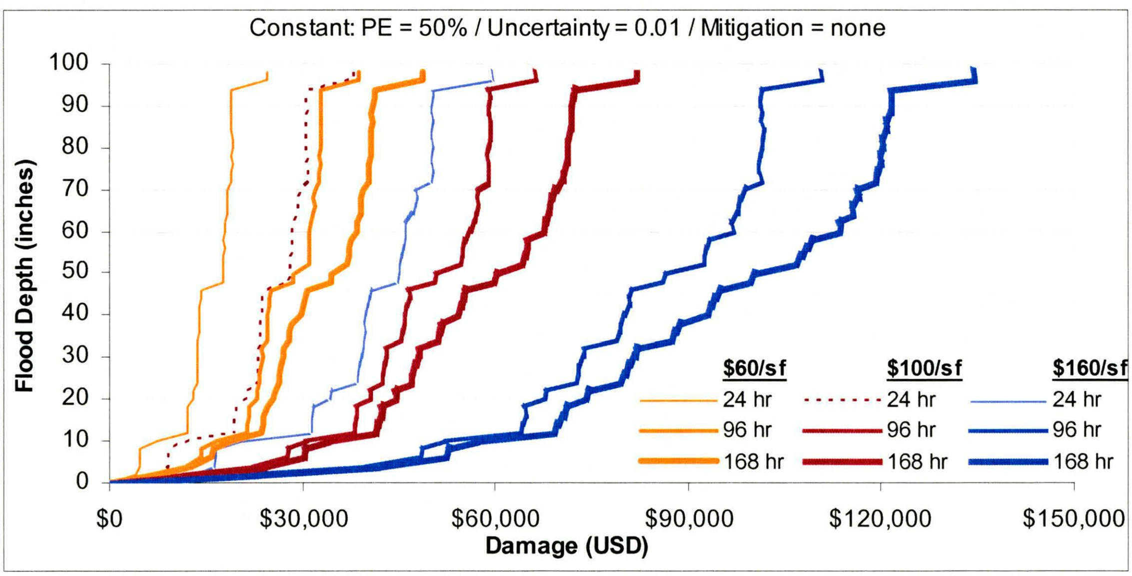


**Figure 29. Flood damage values associated with variations in building unit cost and flood duration expressed in terms of U.S. dollars and at a 50% probability of exceedance**

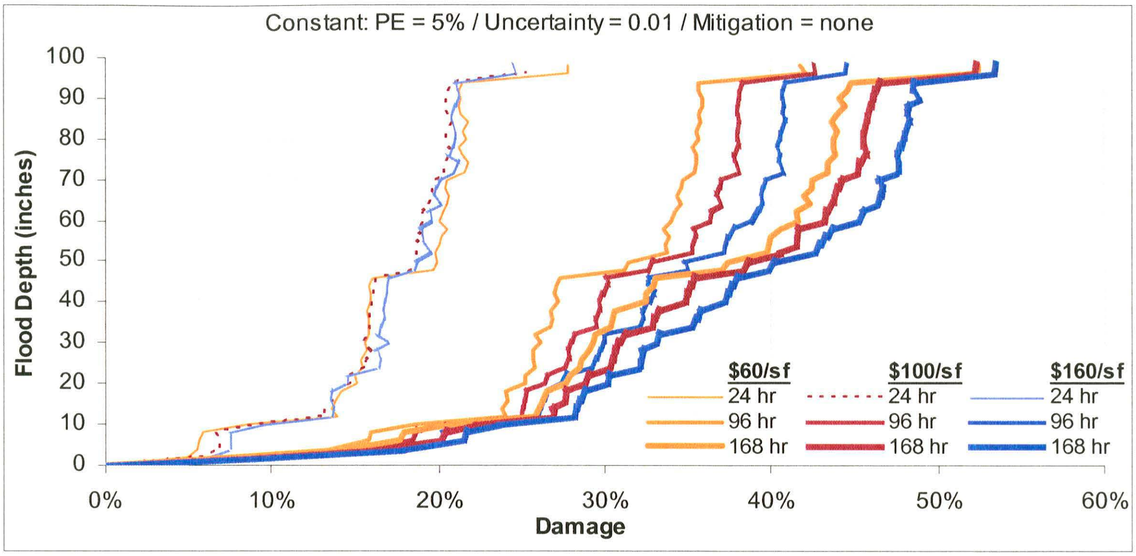


**Figure 30. Flood damage values associated with variations in building unit cost and flood duration expressed in terms of a percent of the total home cost and at a 5% probability of exceedance**

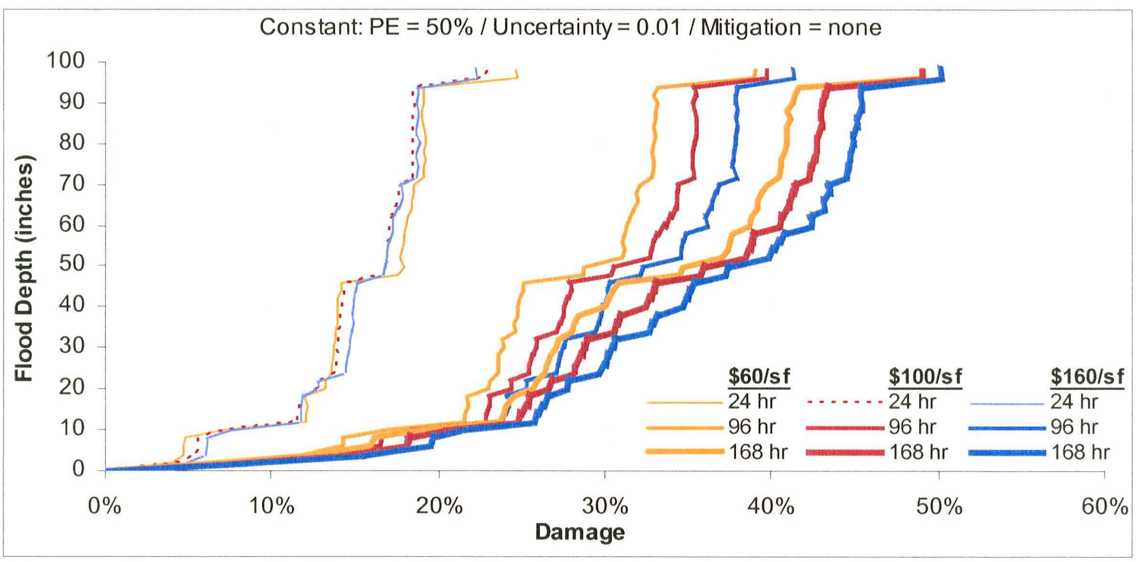


**Figure 31. Flood damage values associated with variations in building unit cost and flood duration expressed in terms of a percent of the total home cost and at a 50% probability of exceedance**

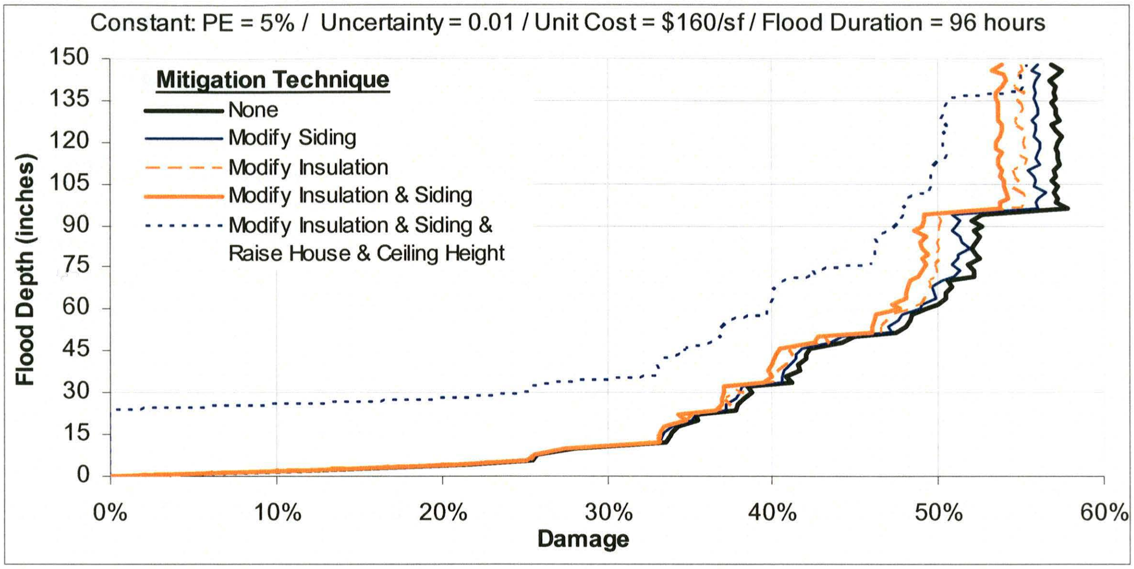


**Figure 32. Flood damage with various mitigation techniques in terms of a 5% probability of exceedance**

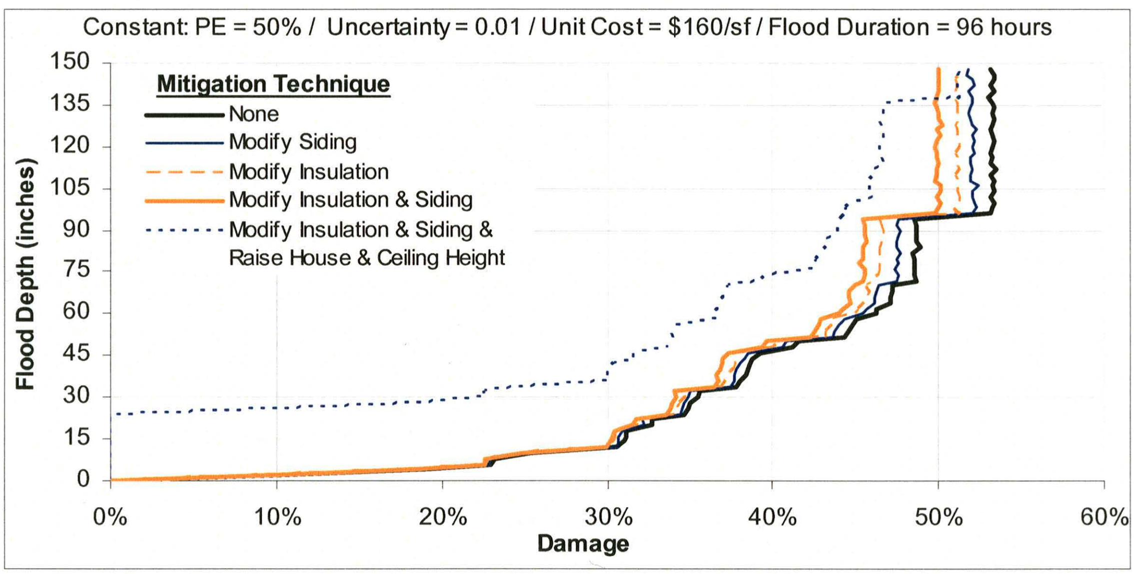


**Figure 33. Flood damage with various mitigation techniques in terms of a 50% probability of exceedance**

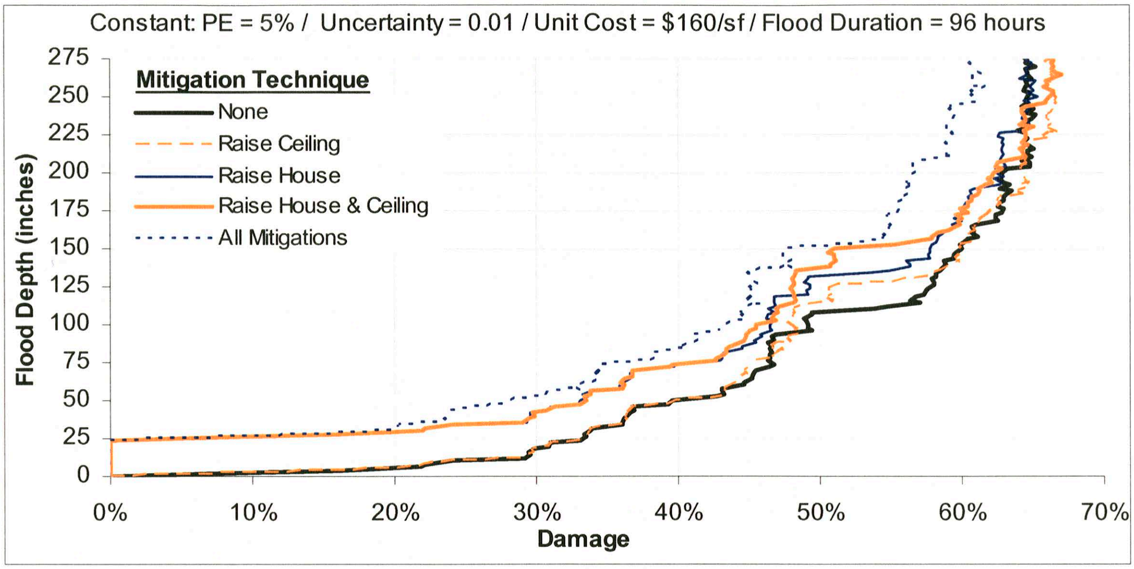


**Figure 34. Flood damage with various mitigation techniques in terms of a 5% probability of exceedance**

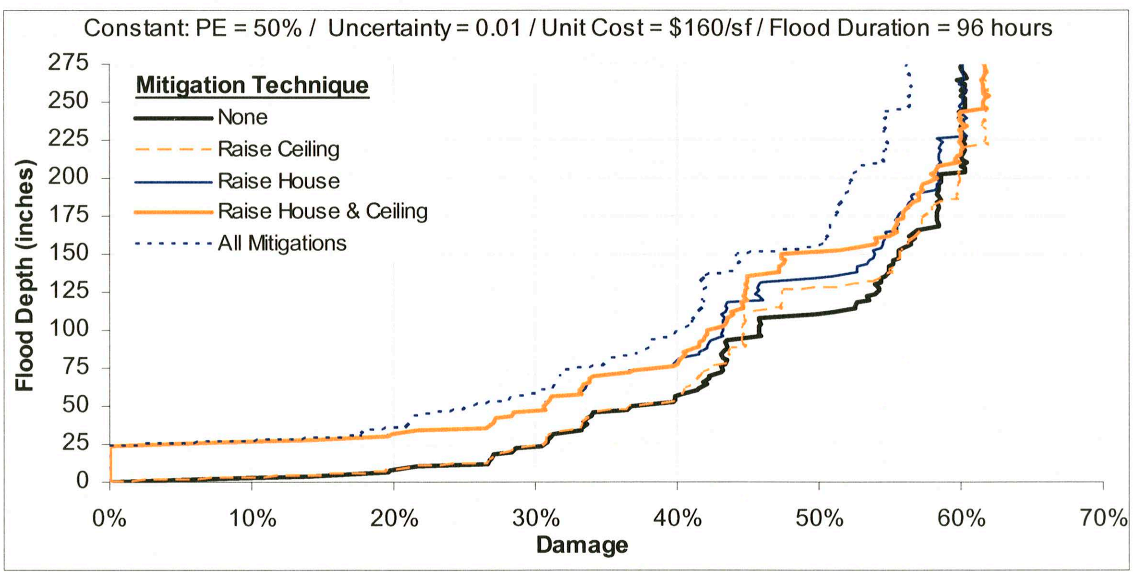


**Figure 35. Flood damage with various mitigation techniques in terms of a 50% probability of exceedance**

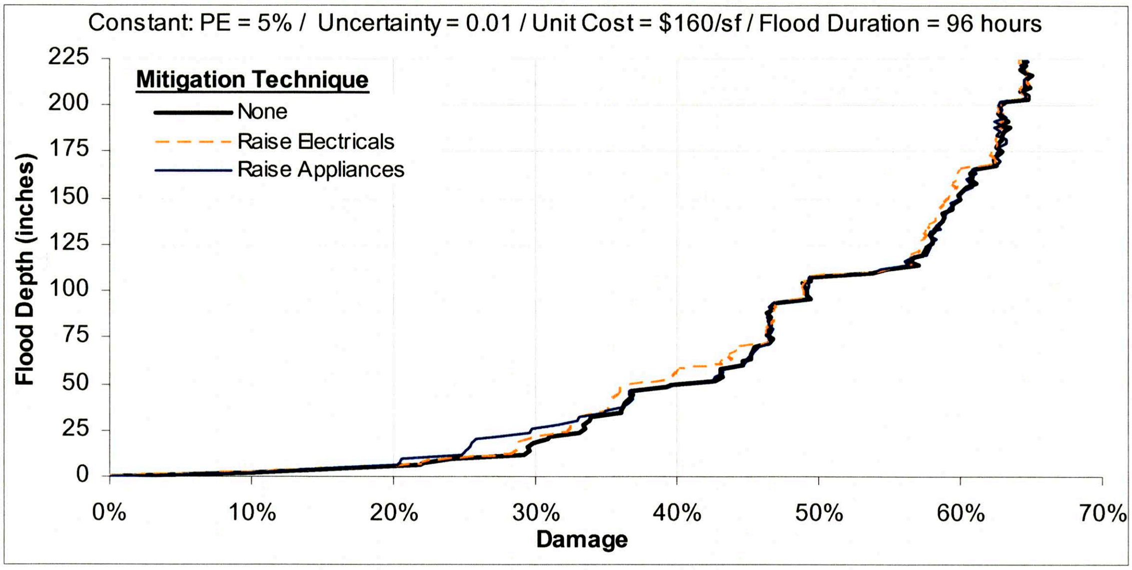


**Figure 36. Flood damage with various mitigation techniques in terms of a 5% probability of exceedance**

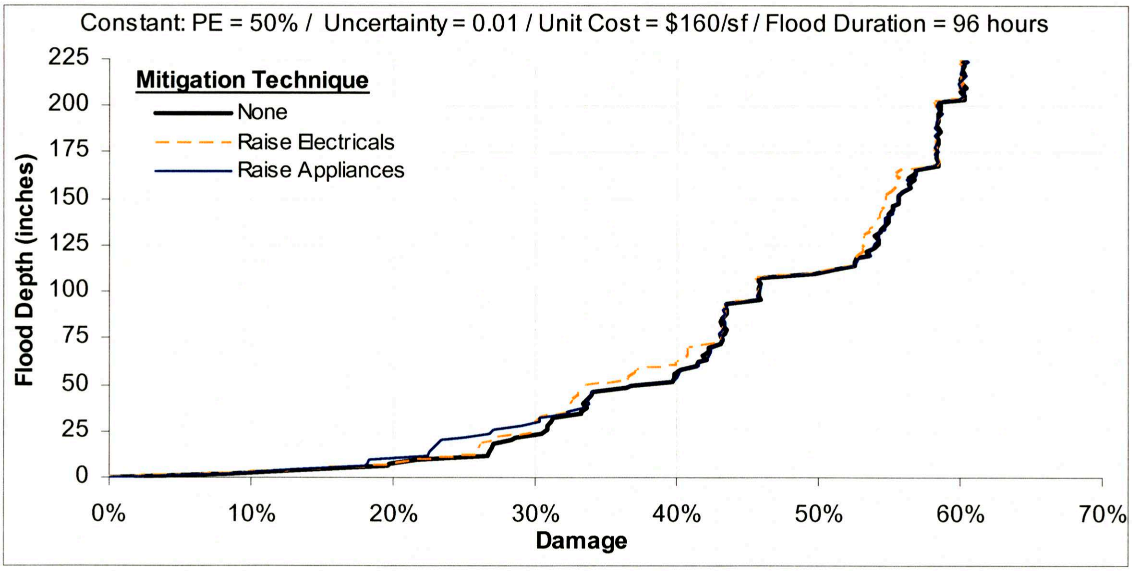


**Figure 37. Flood damage with various mitigation techniques in terms of a 50% probability of exceedance**

## *6.5 Single story home with an unfinished basement*

The following illustrative example involves the flood damage sustained by a single story residential home with an unfinished basement representing flooding from the floor level in the basement to the ceiling level of the first floor. The basic house plan is show in figure 38 and is the same as for the single story with no basement previously considered with the exception of the addition of the basement and the reduction of the mater bedroom closet to make room for the staircase. All of the building dimensional information used to calculate the flood damage to the single story home with an unfinished basement is contained in Table 14.

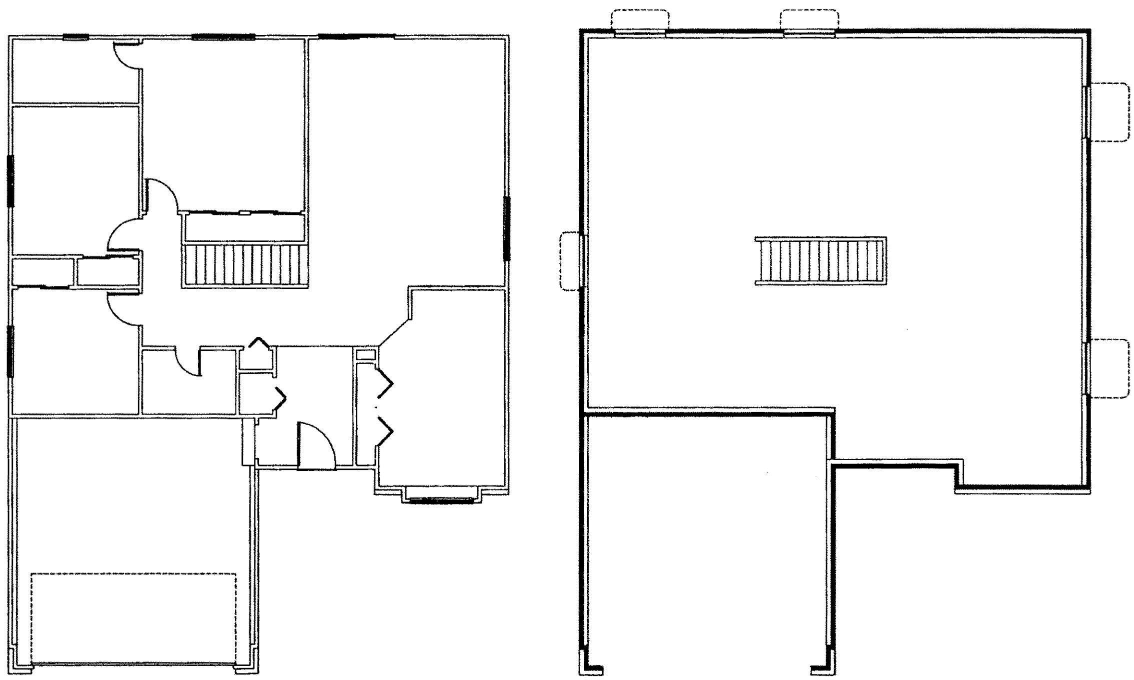

**Figure 38. Basic plan for the single story residential home with an unfinished basement**

Figures 39 through 42 show the damage sustained by the single story residential home with an unfinished basement when subjected to a variety of flood durations as well as a variety of overall unit cost values for the home. Similar to the previous example and as expected, the greatest damage sustained by the home occurs with the greatest flood duration and the greatest unit cost value of the home and the least damage sustained by the home occurs with the shortest flood duration and least unit cost value of the home.

**Table 14. Building dimensional information for the single story residential home with an unfinished basement**

| General information for story #1 | | General information for basement | |
|---|---|---|---|
| Total floor area | 1304 sf | Total floor area | 1304 sf |
| Finished floor area | 1304 sf | Finished floor area | 0 sf |
| Total floor area covered with carpet | 992 sf | Total floor area covered with carpet | 0 sf |
| Total floor area covered with tile | 72 sf | Total floor area covered with tile | 0 sf |
| Total floor area covered with decorative wood flooring | 144 sf | Total floor area covered with decorative wood flooring | 0 sf |
| Total floor area covered with vinyl | 96 sf | Total floor area covered with vinyl | 0 sf |
| Total length of lower cabinets | 33 ft | Total length of lower cabinets | 0 ft |
| Total length of upper cabinets | 18 ft | Total length of upper cabinets | 0 sft |
| Total length of baseboard trim | 420 ft | Total length of baseboard trim | 0 ft |
| Total length of trim not including baseboards | 336 ft | Total length of trim not including baseboards | 0 ft |
| Total length of interior walls | 137 ft | Total length of interior walls | 0 ft |
| Total length of exterior walls which are covered on the interior surface | 146 ft | Total length of exterior walls which are covered on the interior surface | 0 ft |
| Total length of exterior walls which are covered on the exterior surface | 164ft | Total length of exterior walls which are covered on the exterior surface | 0 ft |
| Number of windows | 7 | Number of windows | 5 |
| Number of interior doors | 4 | Number of interior doors | 0 |
| Number of exterior doors | 2 | Number of exterior doors | 0 |
| Number of closet doors | 8 | Number of closet doors | 0 |
| Number of garage doors | 1 | Number of garage doors | 0 |
| Number of staircases | 0 | Number of staircases | 1 |
| Number of electrical outlets | 52 | Number of electrical outlets | 12 |
| Number of electrical switches | 16 | Number of electrical switches | 3 |
| Number of light fixtures | 21 | Number of light fixtures | 3 |
| **General information for entire bldg** | | **Location of appliances** | |
| Total floor area | 1304 sf | Location of furnace | Bsmt |
| Value of home | Varied | Location of air conditioning compressor | Floor 1 |
| Number of stories | 1 | Location of water heater | Bsmt |
| Any basement | Yes | Location of washer and dryer | Floor 1 |
| **Height of items** | | Location of oven | Floor 1 |
| Height from floor to ceiling | 96 in | Location of refrigerator | Floor 1 |
| Height from floor below to floor above | 108 in | Location of garbage disposal | Floor 1 |
| Height of electrical outlets above floor | 12 in | Location of dishwasher | Floor 1 |
| Height of electrical switches above floor | 48 in | Location of vented hood | Floor 1 |

Again as in the previous example, comparing Figures 39 and 41 or 40 and 42, there is a tendency for grouping of damage values associated with the durations of flooding when it is presented as a percentage of the total value of the home. This further underscores the fact that the division of the damage values by the total home value removes much of the effect of the unit cost of the home but that the finishes of a luxury type home tend to be a greater percentage of the total value of the home than for an economy type home. Interestingly, however, the basement portion of the curves (between 0 and 108 inches / 0 and 274 cm), are grouped by home value rather than by duration. This is unique to the unfinished basement example and is a result of the fact that the only items damaged in the unfinished basement are appliances, such as the furnace and water heater. The electrical panel box as well as the aforementioned appliances tend to be more similarly priced for an economy and a luxury home than other building items and therefore their replacement in an economy type home would be a significantly higher percentage of the total cost of the home than their replacement in a luxury type home.

The comparison between the curves associated with a 50% versus 5% probability of exceedance follow the same pattern previously noted wherein relative curve placement is unaffected and damage values at 50% PE are lower than those at 5% PE.

Figures 43 through 48 show the results of implementation of the various mitigation techniques covered in this study as they relate to a single story home with an unfinished basement. Their mitigation techniques have again been split into three groups and each group has been plotted at a 50% PE as well as a 5% PE.

As in the previous example, figures 43 and 44 show that the flood damage mitigation techniques having to do with modifications to siding and/or insulation only, are minimally effective at small flood depths and increasingly effective with greater flood depths. However, there is no savings associated with this type of mitigation technique until ground level is reached since there is assumed to be no siding or wall insulation in the standard unfinished basement used in this study.

In Figure 45 and 46 the fragility curve associated with raising the house only, follows the fragility curve for no mitigation technique except that it is separated from the other by the height to which the house was raised; this was expected and is the same as was observed in the example of the single story house with no basement.

In Figures 45 and 46 the fragility curves associated with raising the ceiling and that of raising both the ceiling and the house again result in the only cases where the damage due to flooding to ceiling level actually exceeds that of the house when no mitigation technique was used. This pattern follows that of the single story home with no basement with the exception that the curve for raising the ceiling of the home with no basement is only effective for a very narrow range of flooding, but the range in this example is much broader. Specifically, for the previous case it helps only between the height of the ceiling and the point at which the cost of repair or replacement of the added wall height reach that of the replacement of the ceiling items and attic insulation. For this example the savings due to raising the ceiling height of the basement is realized for flooding from the original basement ceiling height until just below the new ceiling height of the first floor.

We see, similar to the previous example and as shown in Figures 43 and 44, that as the additional wall height becomes more flood resistant through modified siding and insulation the total damage becomes less than that of the home without any mitigation techniques in place despite the added wall height.

In figures 47 and 48 the fragility curves associated with raising electricals and raising appliances are shown and these curves behave similarly to those shown in the previous example with the exception that there are two locations on each curve for which savings are realized. These two locations are, of course, the duplicate instances of raising outlets and switches in the basement and on the first floor and then the raising of the furnace and water heater in the basement as well as raising of the washer and dryer on the first floor.

Again we see the changes in the fragility curves associated with a 5% probability of exceedance as compared with a 50% probability of exceedance show no change in relative placement of the curves but only of an overall decrease in damage values for the 50% PE compared with the 5% PE.

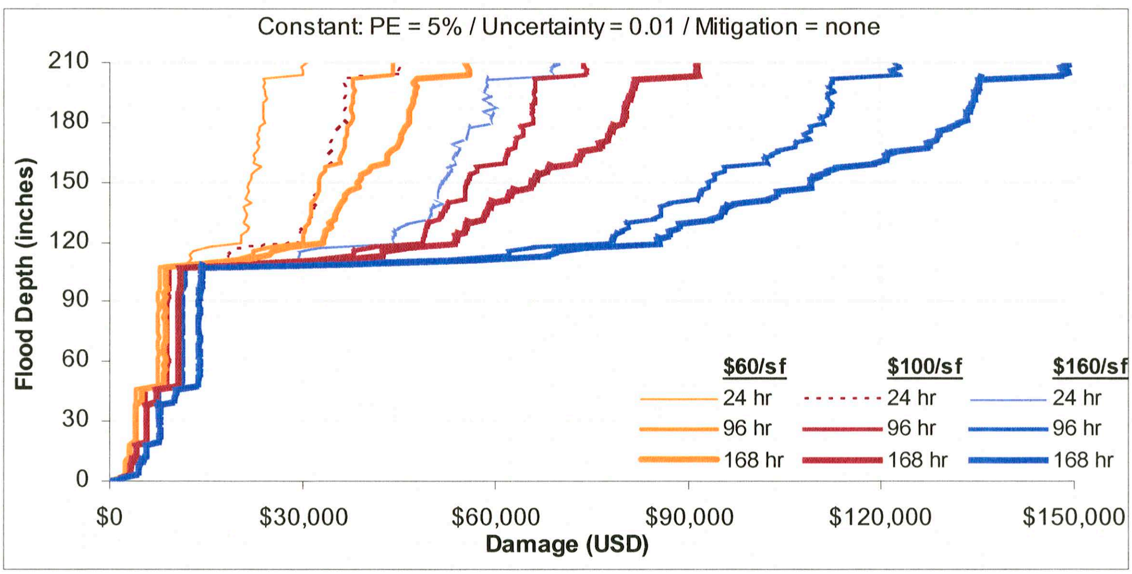


**Figure 39. Flood damage values associated with variations in building unit cost and flood duration expressed in terms of U.S. dollars and at a 5% probability of exceedance**

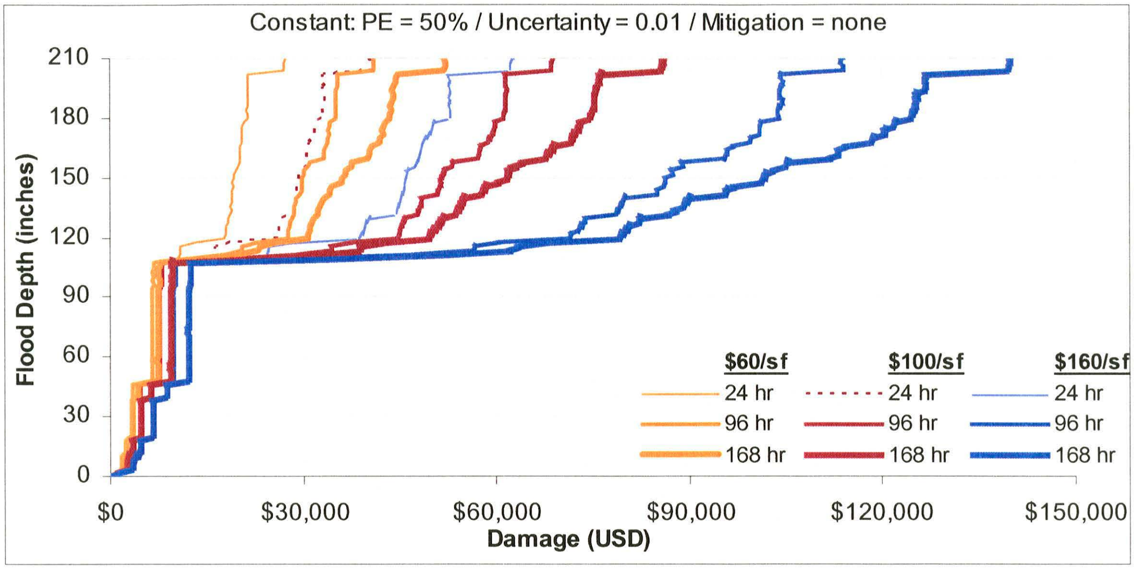


**Figure 40. Flood damage values associated with variations in building unit cost and flood duration expressed in terms of U.S. dollars and at a 50% probability of exceedance**

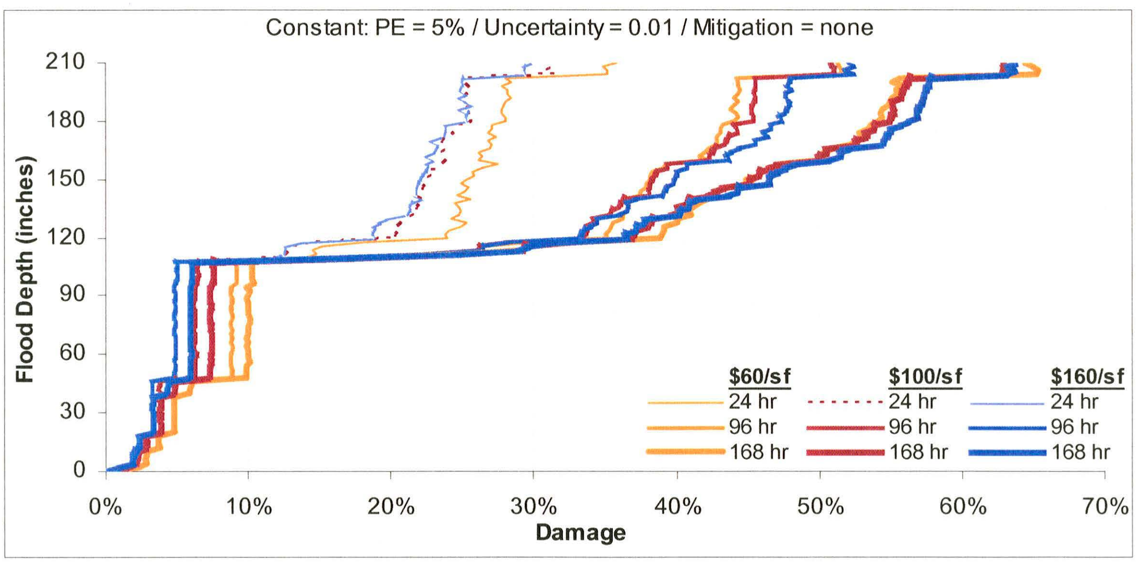


**Figure 41. Flood damage values associated with variations in building unit cost and flood duration expressed in terms of a percent of the total home cost and at a 5% probability of exceedance**

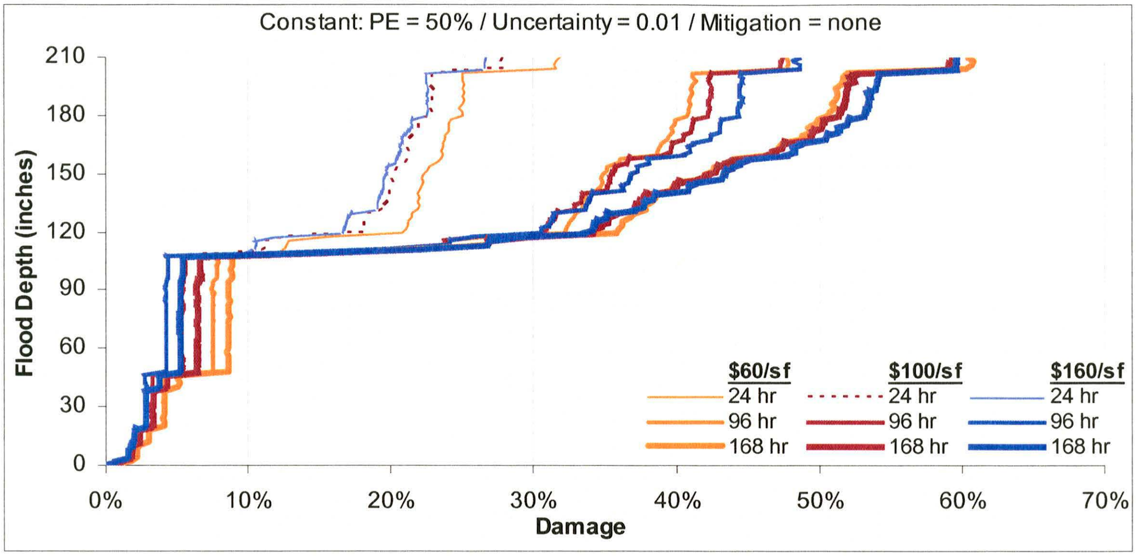


**Figure 42. Flood damage values associated with variations in building unit cost and flood duration expressed in terms of a percent of the total home cost and at a 50% probability of exceedance**

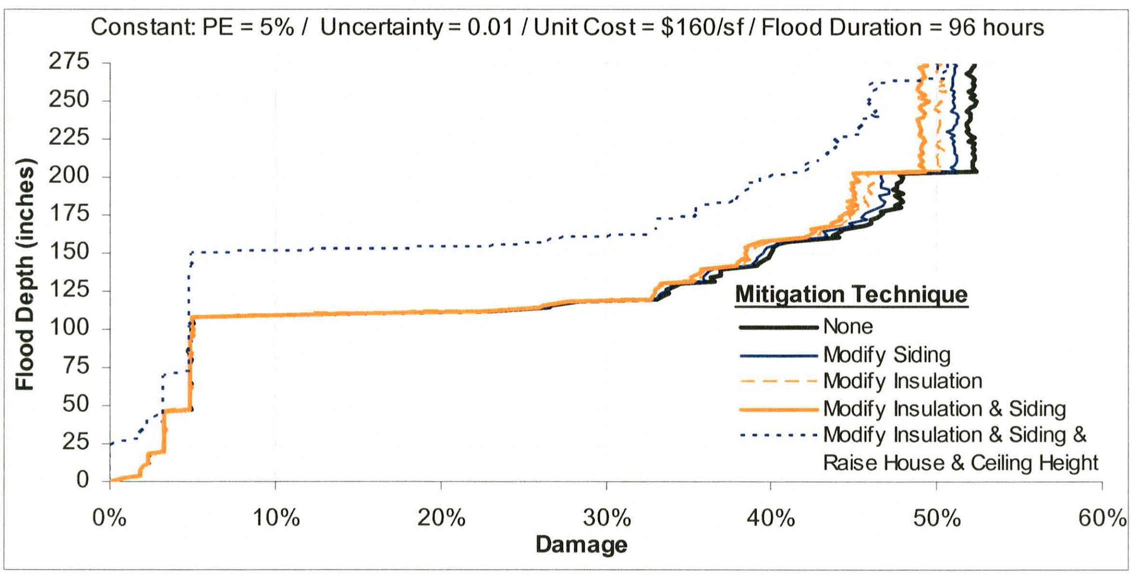


**Figure 43. Flood damage with various mitigation techniques in terms of a 5% probability of exceedance**

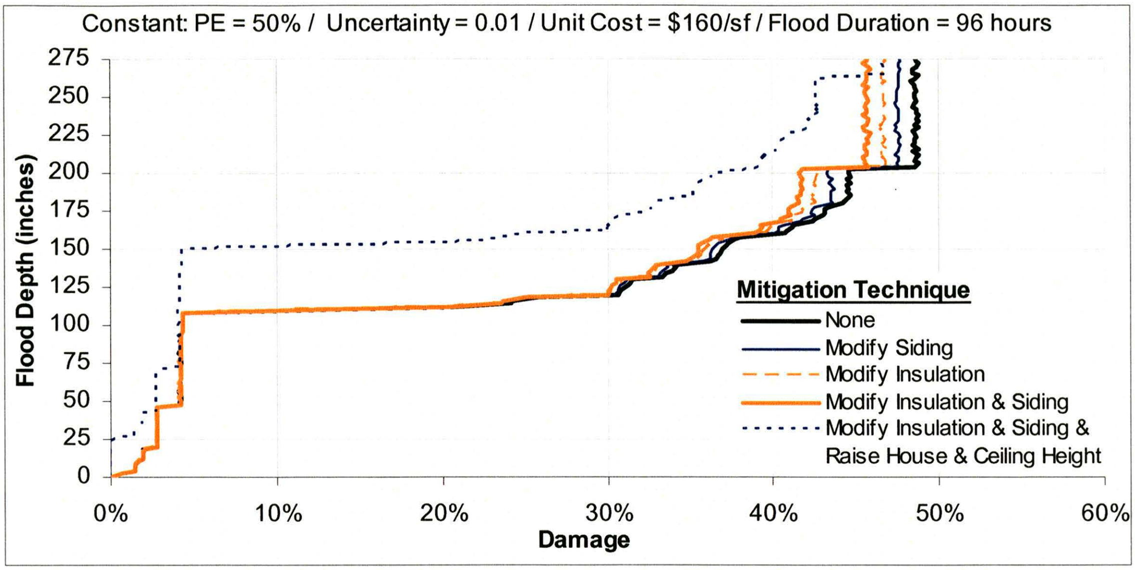


**Figure 44. Flood damage with various mitigation techniques in terms of a 50% probability of exceedance**

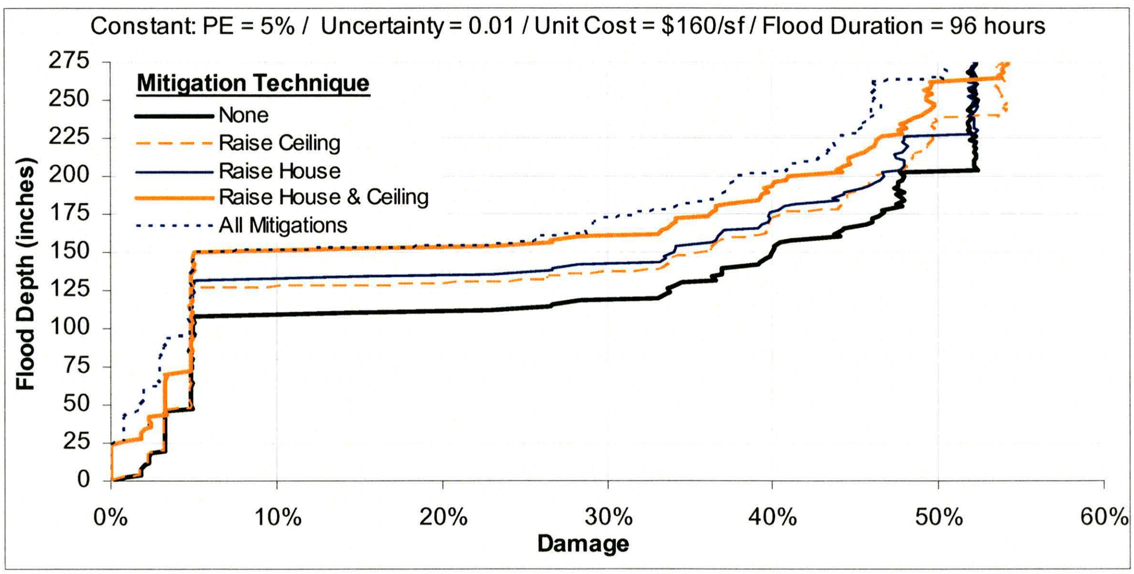


**Figure 45. Flood damage with various mitigation techniques in terms of a 5% probability of exceedance**

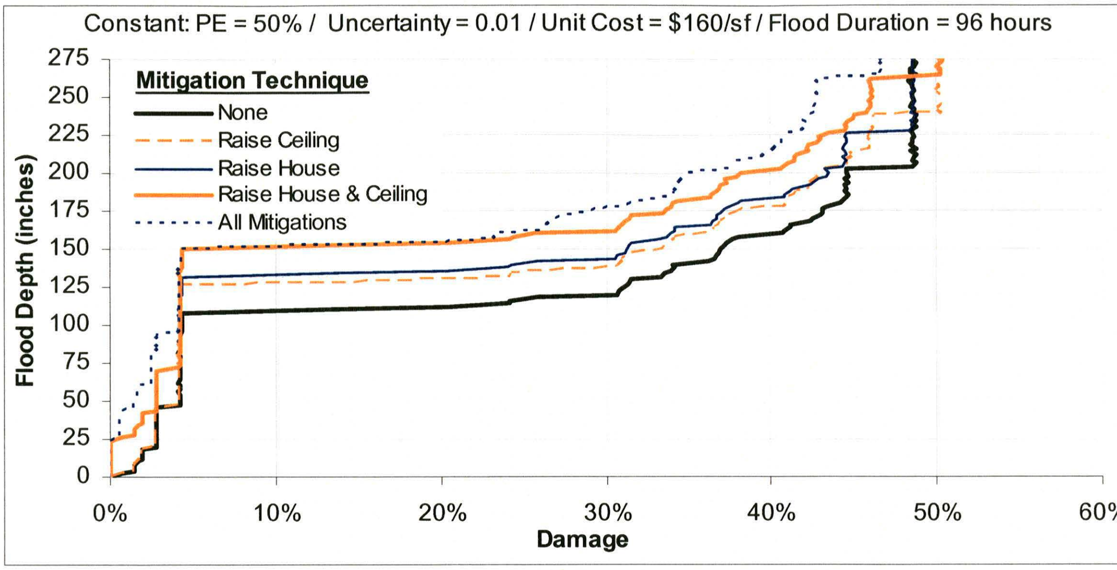


**Figure 46. Flood damage with various mitigation techniques in terms of a 50% probability of exceedance**

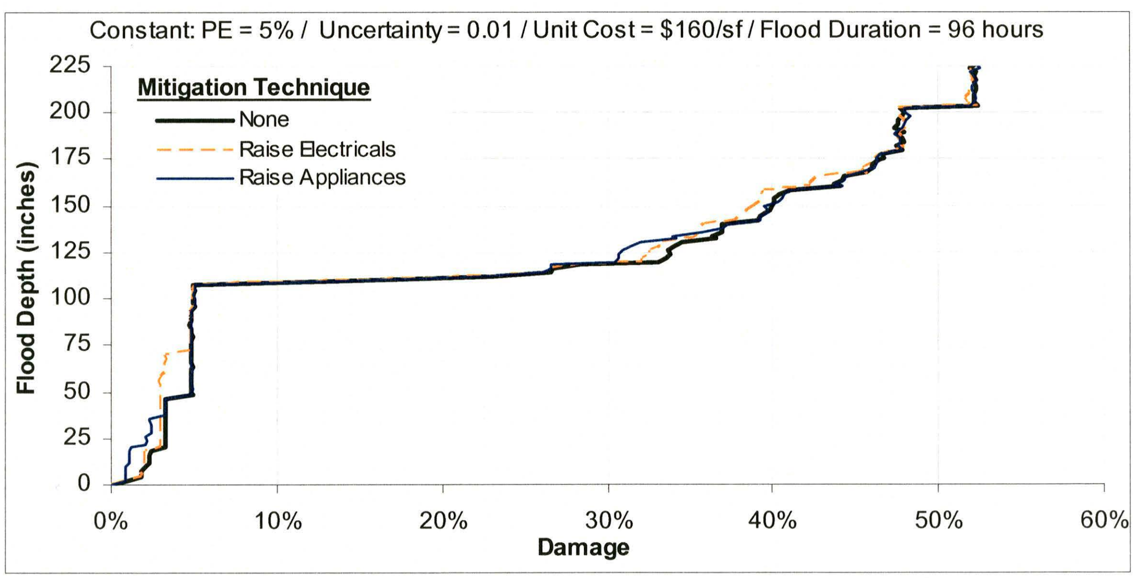


**Figure 47. Flood damage with various mitigation techniques in terms of a 5% probability of exceedance**

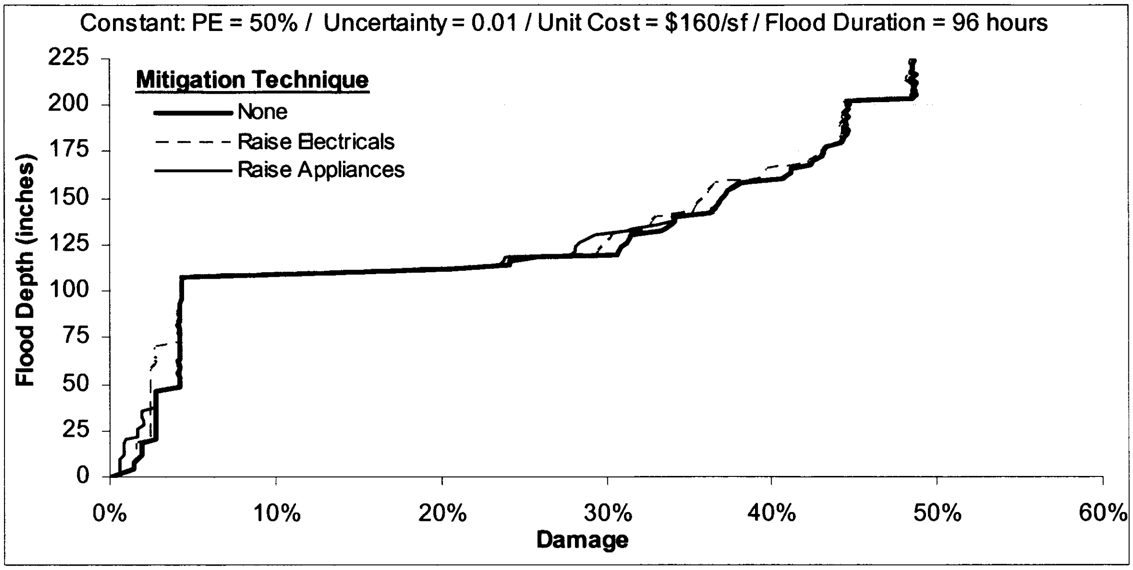


**Figure 48. Flood damage with various mitigation techniques in terms of a 50% probability of exceedance**

## *6.6 Single story home with a finished basement*

The following example involves the flood damage sustained by a single story residential home with a finished basement representing flooding from the floor level in the basement to the ceiling level of the first floor. The basic house plan is shown in figure 49 and is the same as for the single story with an unfinished basement previously considered with the exception of the addition of basement walls and interior finishes. All of the building dimensional information used to calculate the flood damage to the single story home with a finished basement is contained in Table 15.

Figures 50 through 53 show the damage sustained by the single story residential home with a finished basement when subjected to a variety of flood durations as well as a variety of overall unit cost values for the home. Similar to the previous examples and as expected, the greatest damage sustained by the home occurs with the greatest flood duration and the greatest unit cost value of the home and the least damage sustained by the home occurs with the shortest flood duration and least unit cost value of the home.

Again as in the previous examples, comparing Figures 50 and 52 or 51 and 53, there is a tendency for grouping of damage values associated with the durations of flooding when it is presented as a percentage of the total value of the home.

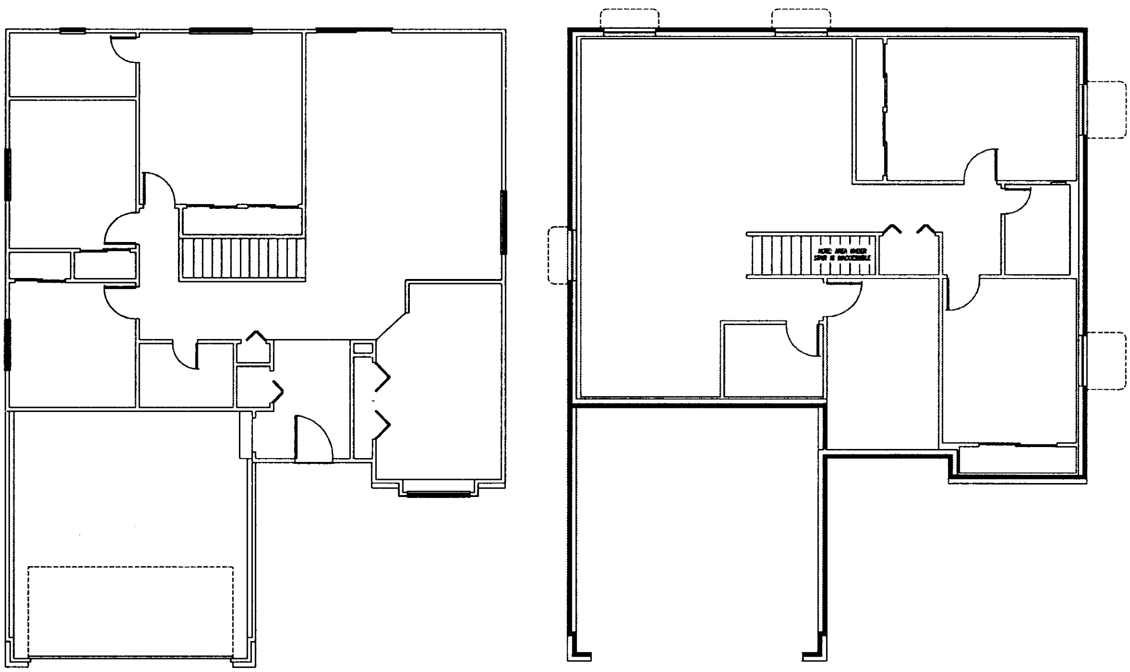

**Figure 49. Basic plan for the single story residential home with an unfinished basement**

The damage values in the basement, however, now follow more closely this grouping pattern rather than the grouping by unit cost values as was observed in the unfinished basement example. This is because there are now finishes in the basement such as cabinets, flooring and wall finishes with individual unit cost values which more similarly increase with increasing overall home unit cost values such as would be found in a luxury home. There is another difference to note related to the fragility curves in the basement. While the overall grouping of flood duration exists, the curves associated with the lower overall unit costs tend to have a higher percentage damage that those of the higher overall unit costs.

**Table 15. Building dimensional information for the single story residential home with an unfinished basement**

| **General information for story #1** | | **General information for basement** | |
|---|---|---|---|
| Total floor area | 1304 sf | Total floor area | 1304 sf |
| Finished floor area | 1304 sf | Finished floor area | 1120 sf |
| Total floor area covered with carpet | 992 sf | Total floor area covered with carpet | 1018 sf |
| Total floor area covered with tile | 72 sf | Total floor area covered with tile | 0 sf |
| Total floor area covered with decorative wood flooring | 144 sf | Total floor area covered with decorative wood flooring | 0 sf |
| Total floor area covered with vinyl | 96 sf | Total floor area covered with vinyl | 102 sf |
| Total length of lower cabinets | 33 ft | Total length of lower cabinets | 3 ft |
| Total length of upper cabinets | 18 ft | Total length of upper cabinets | 0 ft |
| Total length of baseboard trim | 420 ft | Total length of baseboard trim | 357 ft |
| Total length of trim not including baseboards | 336 ft | Total length of trim not including baseboards | 240 ft |
| Total length of interior walls | 137 ft | Total length of interior walls | 110 ft |
| Total length of exterior walls which are covered on the interior surface | 146 ft | Total length of exterior walls which are covered on the interior surface | 137 ft |
| Total length of exterior walls which are covered on the exterior surface | 164ft | Total length of exterior walls which are covered on the exterior surface | 0 ft |
| Number of windows | 7 | Number of windows | 5 |
| Number of interior doors | 4 | Number of interior doors | 5 |
| Number of exterior doors | 2 | Number of exterior doors | 0 |
| Number of closet doors | 8 | Number of closet doors | 5 |
| Number of garage doors | 1 | Number of garage doors | 0 |
| Number of staircases | 0 | Number of staircases | 1 |
| Number of electrical outlets | 52 | Number of electrical outlets | 44 |
| Number of electrical switches | 16 | Number of electrical switches | 14 |
| Number of light fixtures | 21 | Number of light fixtures | 19 |
| **General information for entire bldg** | | **Location of appliances** | |
| Total floor area | 1304 sf | Location of furnace | Bsmt |
| Value of home | Varied | Location of air conditioning compressor | Floor 1 |
| Number of stories | 1 | Location of water heater | Bsmt |
| Any basement | Yes | Location of washer and dryer | Bsmt |
| **Height of items** | | Location of oven | Floor 1 |
| Height from floor to ceiling | 96 in | Location of refrigerator | Floor 1 |
| Height from floor below to floor above | 108 in | Location of garbage disposal | Floor 1 |
| Height of electrical outlets above floor | 12 in | Location of dishwasher | Floor 1 |
| Height of electrical switches above floor | 48 in | Location of vented hood | Floor 1 |

This is because, even though there are now finishes which will increase with the increasing overall unit cost of the home, the specific finishes which are in place in the basement either do not vary as much as the finishes which are found on the first floor, or they do not exist in such quantities or at all in the basement; for example there is typically no tile or wood flooring in the basement, there are fewer cabinets and there is no exterior siding.

The comparison between the curves associated with a 50% versus 5% probability of exceedance follow the same pattern previously noted wherein relative curve placement is unaffected and damage values at 50% PE are lower than those at 5% PE.

Figures 54 through 59 show the results of implementation of the various mitigation techniques covered in this study as they relate to a single story home with a finished basement. There mitigation techniques have again been split into 3 groups and each group has been plotted at a 50% PE as well as a 5% PE.

As in the previous examples, figures 54 and 55 show that the flood damage mitigation techniques related to modifications to siding and/or insulation only, are minimally effective at small flood depths and increasingly effective with greater flood depths. Again, as in the unfinished basement example, there is no savings associated with modifying siding until ground level is reached. However, there is savings associated with upgrading insulation with the finished basement example making the savings associated with changing insulation type even more beneficial than in the unfinished basement example.

Again, in Figure 56 and 57 the fragility curve associated with raising the house only, follows the fragility curve for no mitigation technique except that it is separated from the other by the height to which the house was raised; as was expected.

In Figures 56 and 57, the fragility curves associated with raising the ceiling and that of raising both the ceiling and the house follow the pattern of the single story home with an unfinished basement with one exception. The difference between the overall damage value of the curves associated with the raised ceiling and that of the curve with no mitigation in place is slightly greater for the finished basement because of the damage sustained by the added drywall and painting of the increased basement wall height compared with the unfinished basement where these finishes did not exist.

As show in Figures 54 and 55, we see that, similar to the previous examples, when the additional wall height becomes more flood resistant through modified siding and insulation, the total damage to the house upon submersion becomes less than that of the home without any mitigation techniques in place, despite the added wall height.

In figures 58 and 59 the fragility curves associated with raising electricals and raising appliances are shown. These curves behave identically to those shown in the unfinished basement example except that the savings for raising appliances is slightly higher at the basement level of flooding and slightly lower at the first floor level of flooding for this example than it is for the unfinished basement example. This is because the washer and dryer are located on the first floor in the unfinished basement example and in the basement on the finished basement example.

Again the changes in the fragility curves associated with a 5% probability of exceedance as compared with a 50% probability of exceedance show no change in relative placement of the curves but only of an overall decrease in damage values for the 50% PE compared with the 5% PE.

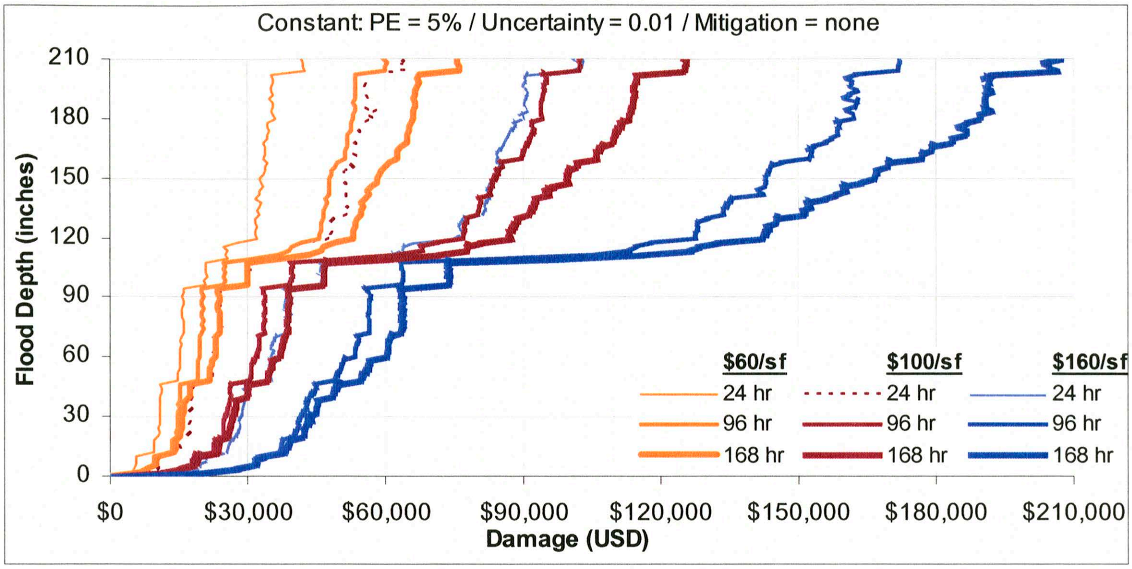


**Figure 50. Flood damage values associated with variations in building unit cost and flood duration expressed in terms of U.S. dollars and at a 5% probability of exceedance**

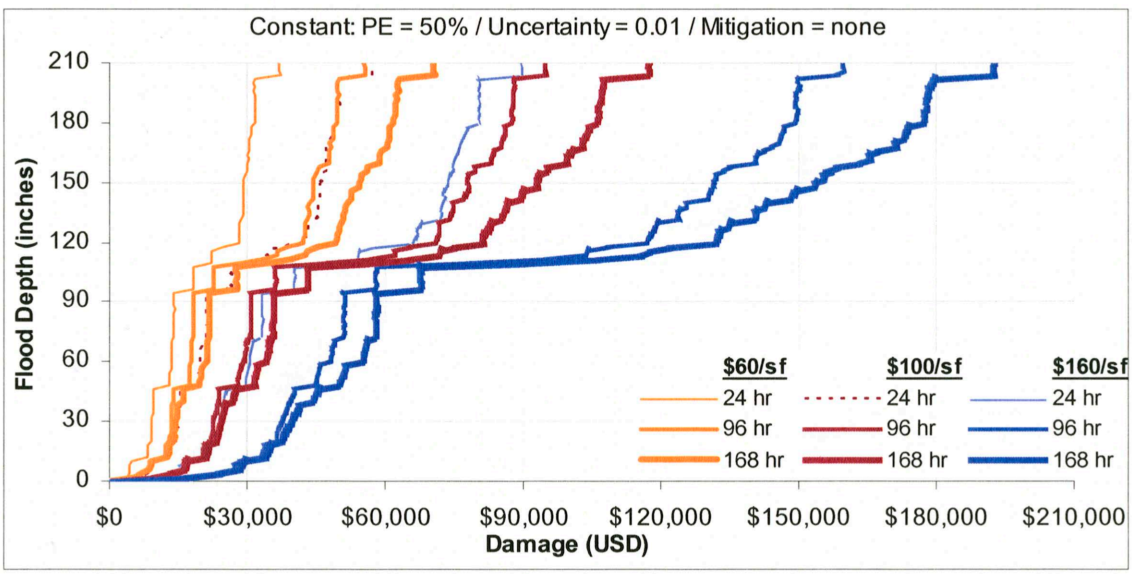


**Figure 51. Flood damage values associated with variations in building unit cost and flood duration expressed in terms of U.S. dollars and at a 50% probability of exceedance**

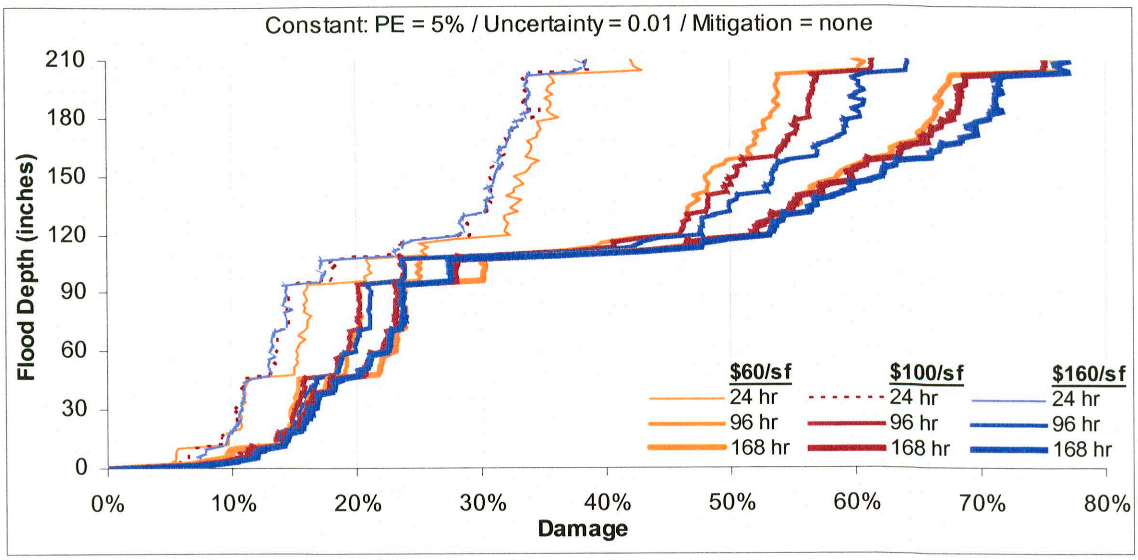


**Figure 52. Flood damage values associated with variations in building unit cost and flood duration expressed in terms of a percent of the total home cost and at a 5% probability of exceedance**

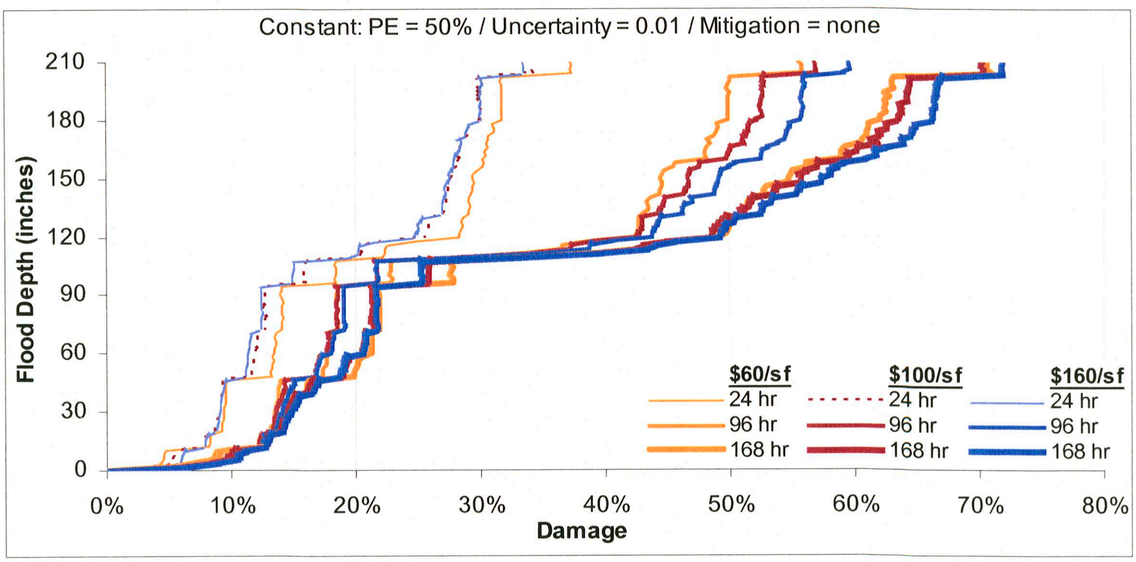


**Figure 53. Damage values associated with variations in building unit cost and flood duration expressed in terms of a percent of the total home cost and at a 50% probability of exceedance**

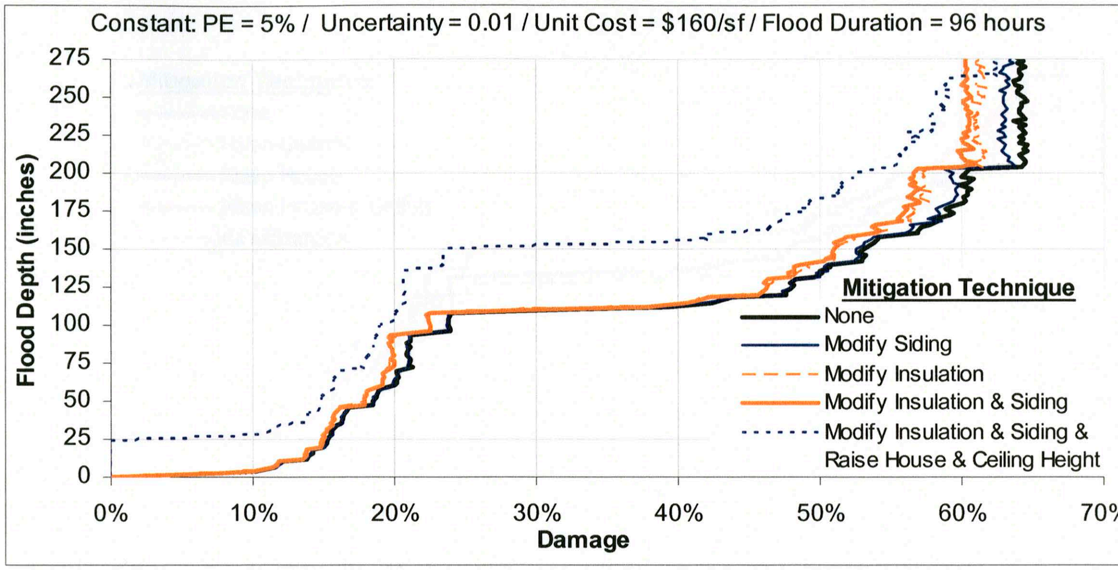


**Figure 54. Flood damage with various mitigation techniques in terms of a 5% probability of exceedance**

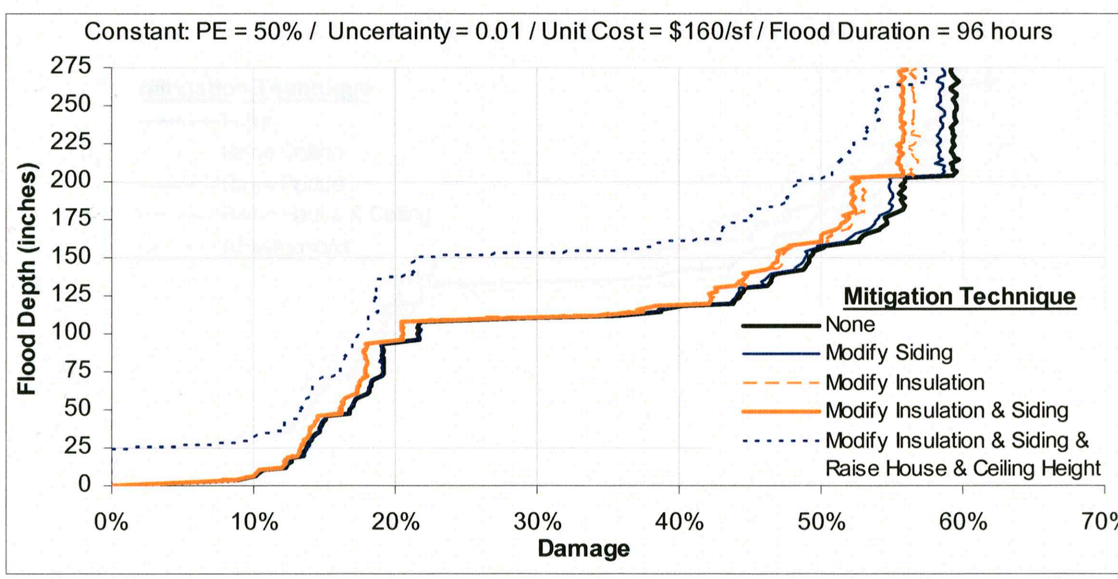


**Figure 55. Flood damage with various mitigation techniques in terms of a 50% probability of exceedance**

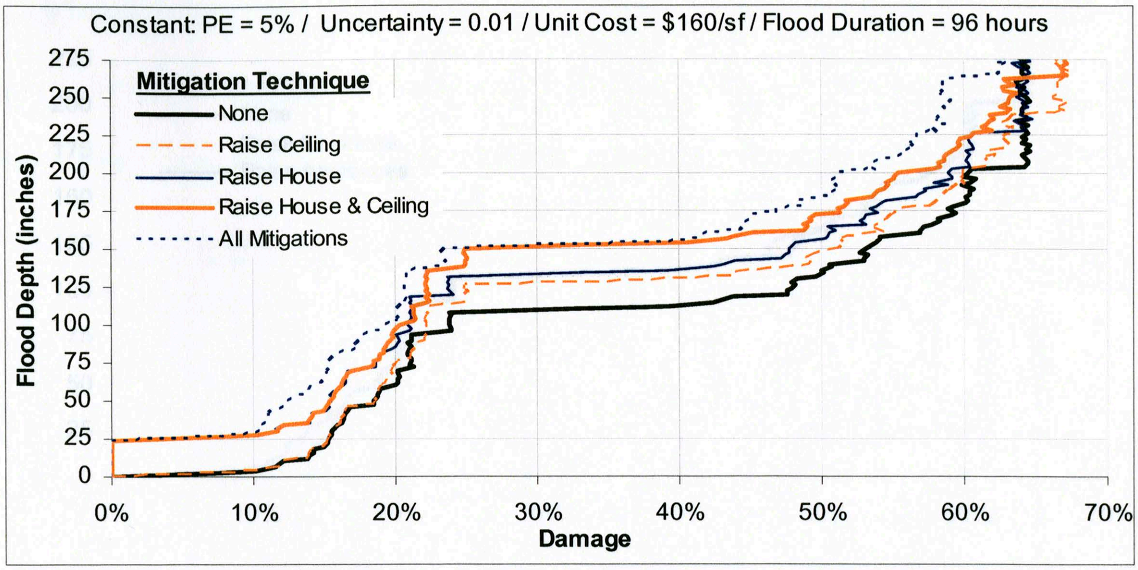


**Figure 56. Flood damage with various mitigation techniques in terms of a 5% probability of exceedance**

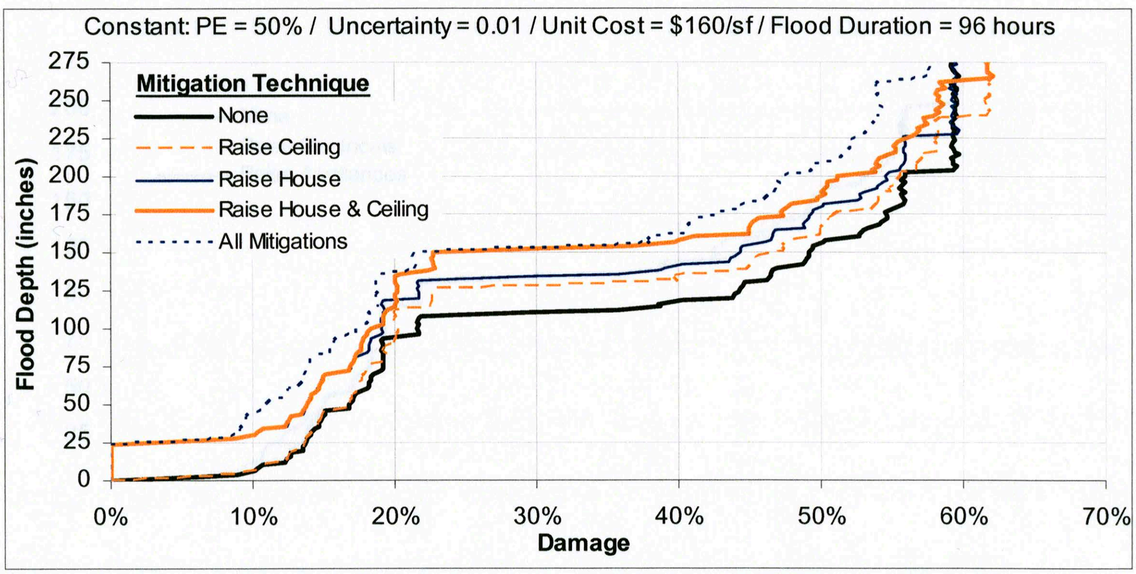


**Figure 57. Flood damage with various mitigation techniques in terms of a 50% probability of exceedance**

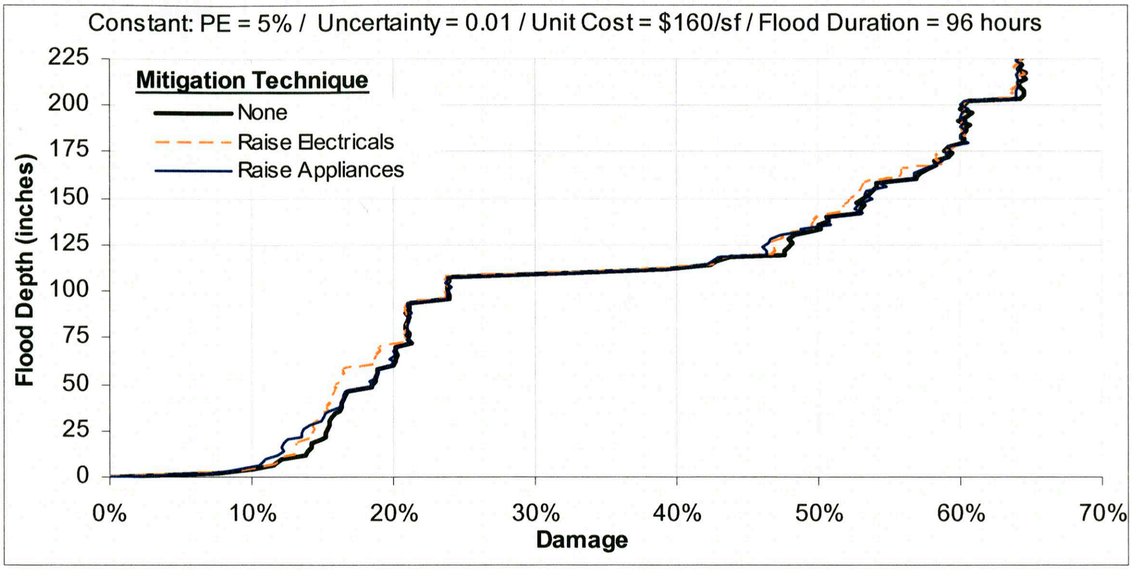


**Figure 58. Flood damage with various mitigation techniques in terms of a 5% probability of exceedance**

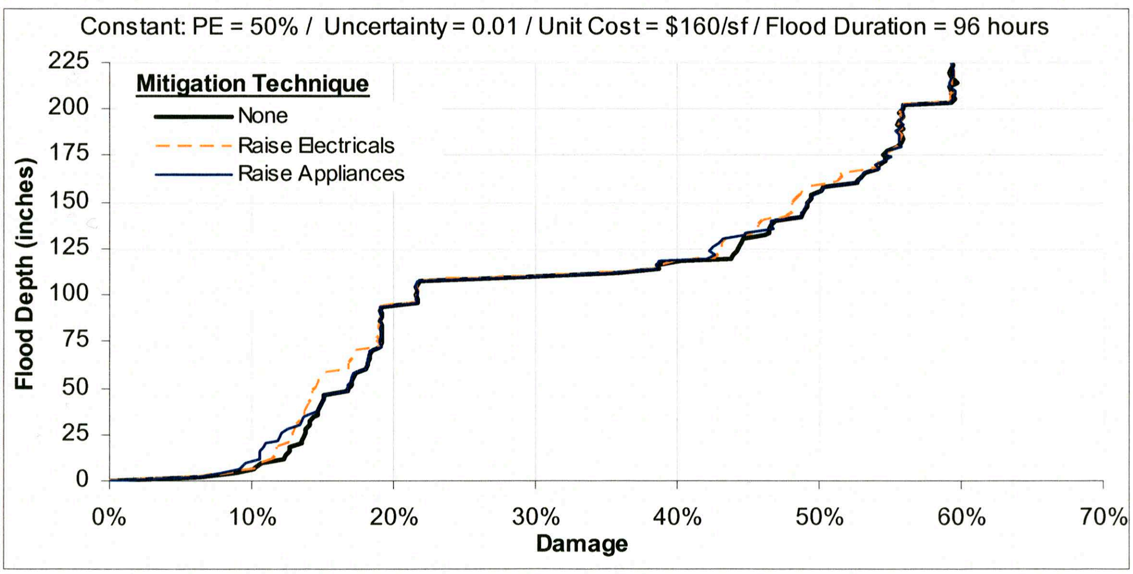


**Figure 59. Flood damage with various mitigation techniques in terms of a 50% probability of exceedance**

## *6.7 Two story home with no basement*

The following example focuses on the flood damage sustained by a two story residential home with no basement representing flooding from the floor level of the first floor to the ceiling level of the second floor. The basic house plan is show in figure 60 and differs from any plan yet considered. All of the building dimensional information used to calculate the flood damage to the two story home is presented in Table 16.

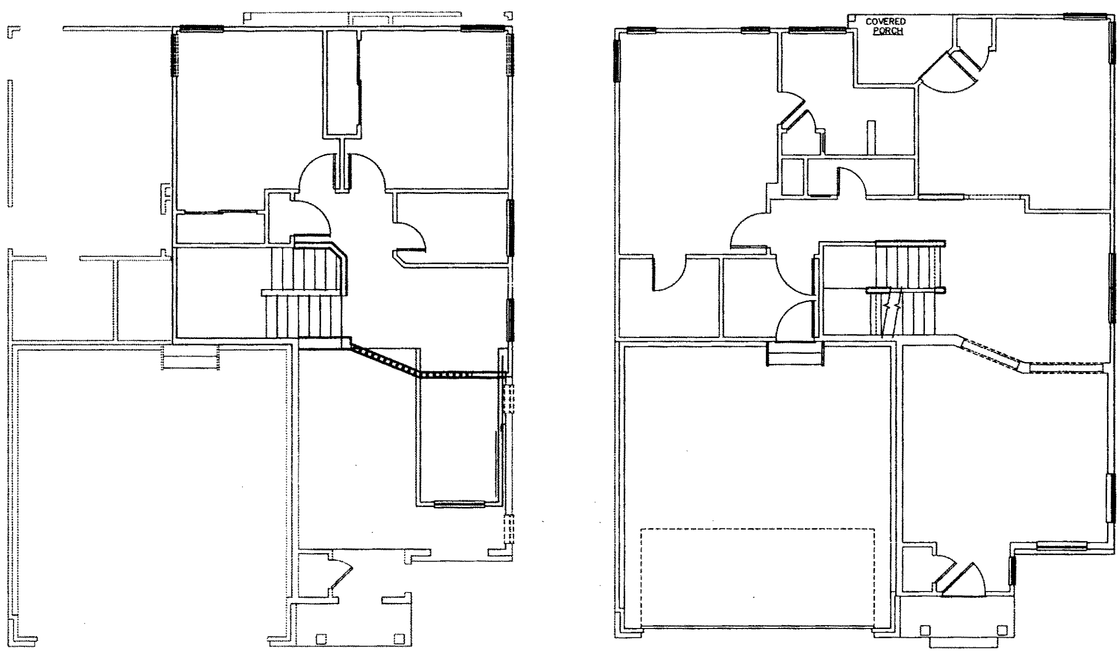


**Figure 60. Basic plan for the two story residential home with no basement**

Figures 61 through 64 show the damage sustained by the single story residential home with a finished basement when subjected to a variety of flood durations as well as a variety of overall unit cost values for the home. Similar to the previous examples and as expected, the greatest damage sustained by the home occurs with the combination of greatest flood duration and the greatest unit cost value of the home. Similarly, the least damage sustained by the home occurs with the combination of the shortest flood duration and least unit cost value of the home.

Again as in the previous examples, comparing Figures 61 and 63 or 62 and 64, shows that there is a tendency for grouping of damage values associated with the durations of flooding when it is presented as a percentage of the total value of the home.

**Table 16. Building dimensional information for the two story residential home with no basement**

| **General information for story #1** | | **General information for story #2** | |
|---|---|---|---|
| Total floor area | 1040 sf | Total floor area | 474 sf |
| Finished floor area | 1040 sf | Finished floor area | 474 sf |
| Total floor area covered with carpet | 838 sf | Total floor area covered with carpet | 436 sf |
| Total floor area covered with tile | 38 sf | Total floor area covered with tile | 0 sf |
| Total floor area covered with decorative wood flooring | 164 sf | Total floor area covered with decorative wood flooring | 0 sf |
| Total floor area covered with vinyl | 0 sf | Total floor area covered with vinyl | 38 sf |
| Total length of lower cabinets | 27 ft | Total length of lower cabinets | 3 ft |
| Total length of upper cabinets | 19 ft | Total length of upper cabinets | 0 ft |
| Total length of baseboard trim | 328 ft | Total length of baseboard trim | 246 ft |
| Total length of trim not including baseboards | 316 ft | Total length of trim not including baseboards | 210 ft |
| Total length of interior walls | 125 ft | Total length of interior walls | 66 ft |
| Total length of exterior walls which are covered on the interior surface | 115 ft | Total length of exterior walls which are covered on the interior surface | 114 ft |
| Total length of exterior walls which are covered on the exterior surface | 142 ft | Total length of exterior walls which are covered on the exterior surface | 114 ft |
| Number of windows | 10 | Number of windows | 7 |
| Number of interior doors | 8 | Number of interior doors | 4 |
| Number of exterior doors | 3 | Number of exterior doors | 0 |
| Number of closet doors | 0 | Number of closet doors | 2 |
| Number of garage doors | 1 | Number of garage doors | 0 |
| Number of staircases | 1 | Number of staircases | 0 |
| Number of electrical outlets | 41 | Number of electrical outlets | 31 |
| Number of electrical switches | 30 | Number of electrical switches | 8 |
| Number of light fixtures | 14 | Number of light fixtures | 8 |
| **General information for entire bldg** | | **Location of appliances** | |
| Total floor area | 1514 sf | Location of furnace | Floor 1 |
| Value of home | Varied | Location of air conditioning compressor | Floor 1 |
| Number of stories | 2 | Location of water heater | Floor 1 |
| Any basement | Yes | Location of washer and dryer | Floor 1 |
| **Height of items** | | Location of oven | Floor 1 |
| Height from floor to ceiling | 96 in | Location of refrigerator | Floor 1 |
| Height from floor below to floor above | 108 in | Location of garbage disposal | Floor 1 |
| Height of electrical outlets above floor | 12 in | Location of dishwasher | Floor 1 |
| Height of electrical switches above floor | 48 in | Location of vented hood | Floor 1 |

In this example, however, there is a wider spread between the fragility curves associated with the various overall unit cost values within the duration groupings than in the previous examples. The progression of relative costs damaged items on first floor as compared to a finished basement, follows the same progression that was noted previously in moving from an unfinished basement to a finished basement, such that there is an increasing quantity of building items with unit costs which are more highly variable between an economy type home and a luxury type home. For this two story home the main addition is the siding and exterior painting included on both levels rather than just the first floor level.

The comparison between the curves associated with a 50% versus 5% probability of exceedance follow the same pattern previously noted wherein relative curve placement is unaffected and damage values at 50% PE are lower than those at 5% PE.

Figures 65 through 70 show the results of implementation of the various mitigation techniques covered in this study for the two story home with no basement. Their mitigation techniques have again been split into three groups and each group has been plotted at a 50% PE as well as a 5% PE.

As in the previous examples, figures 65 and 66 show that the flood damage mitigation techniques related to modifications of the siding and/or insulation only, are minimally effective at small flood depths and increasingly effective with greater flood depths; however, here the savings for modifying siding are greater than previously seen since there is siding on two stories rather than only one.

Again, in Figure 67 and 68 the fragility curve associated with raising the house only, follows the fragility curve when no mitigation technique is used except that it is separated from the other by the height to which the house was raised.

In Figures 67 and 68, the fragility curves associated with raising the ceiling and that of raising both the ceiling and the house follow the pattern of those for the single story home with a finished basement except that the cost associated with the replacement of the added wall height causes the curves to join together again at the point where the water level reaches the height of the raised second story electrical outlets. At this point the same quantity of walls are damaged and all items on the second story floor have been damaged, thus the damage between the two home designs is equivalent at that depth.

By inspection of Figures 65 and 66, one can observe (similar to the previous examples) when the additional wall height becomes more flood resistant through modified siding and insulation, the total damage to the house upon submersion becomes less than that of the home without any mitigation techniques in place despite the added wall height.

In figures 69 and 70 the fragility curves associated with raising electricals and raising appliances are shown. These curves behave similarly to those shown in the unfinished and finished basement examples with the exception that the appliances are all located on the first floor and therefore there is only one location on the graph showing savings due to raising appliances.

Again the changes in the fragility curves associated with a 5% probability of exceedance as compared with a 50% probability of exceedance show no change in relative placement of the curves but only an overall decrease in damage values for the 50% PE compared with the 5% PE.

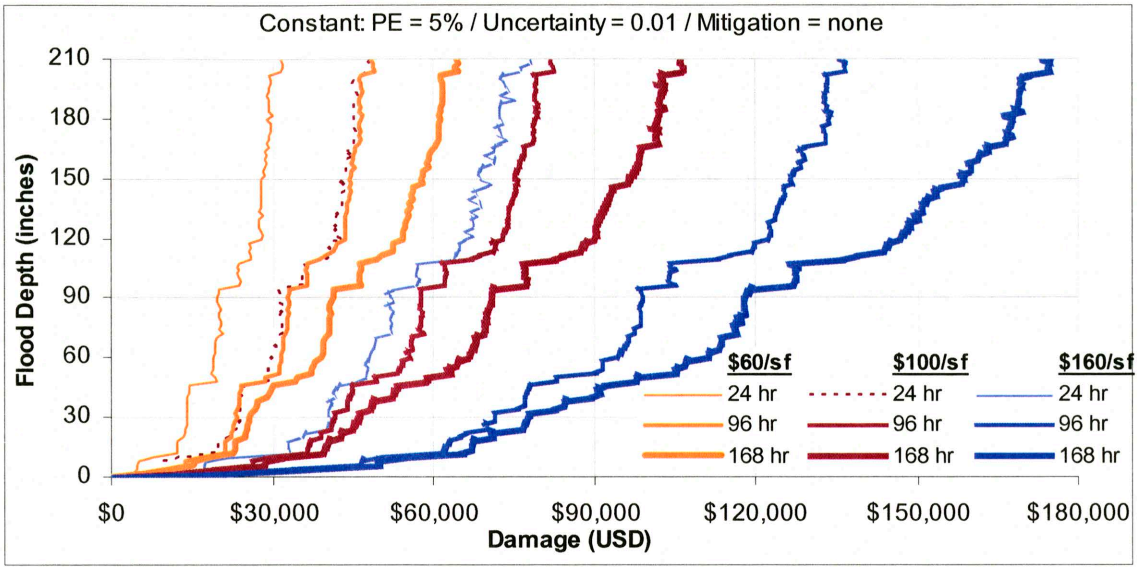


**Figure 61. Flood damage values associated with variations in building unit cost and flood duration expressed in terms of U.S. dollars and at a 5% probability of exceedance**

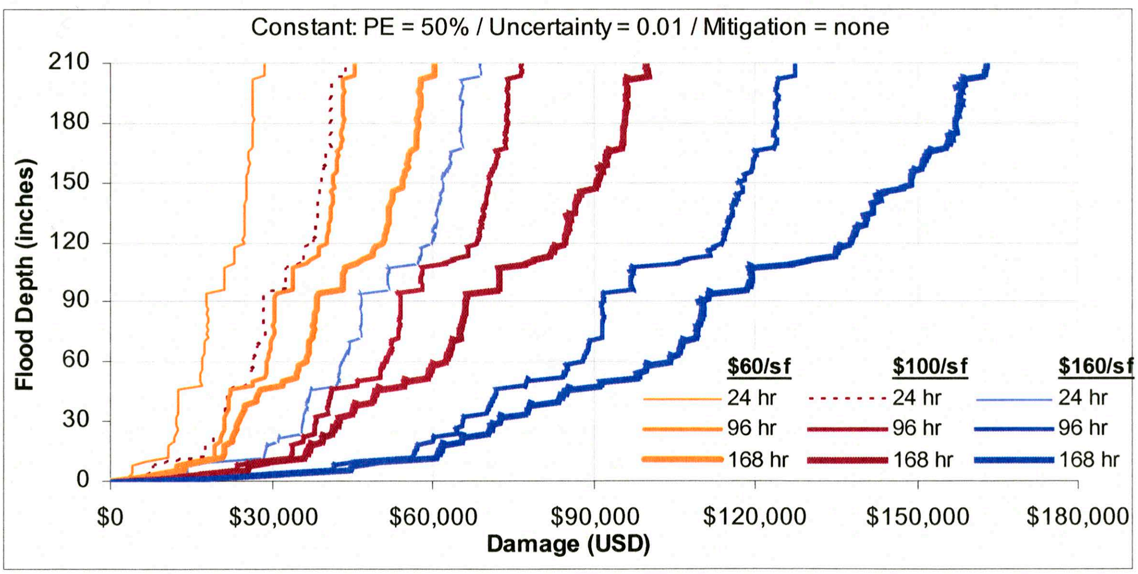


**Figure 62. Flood damage values associated with variations in building unit cost and flood duration expressed in terms of U.S. dollars and at a 50% probability of exceedance**

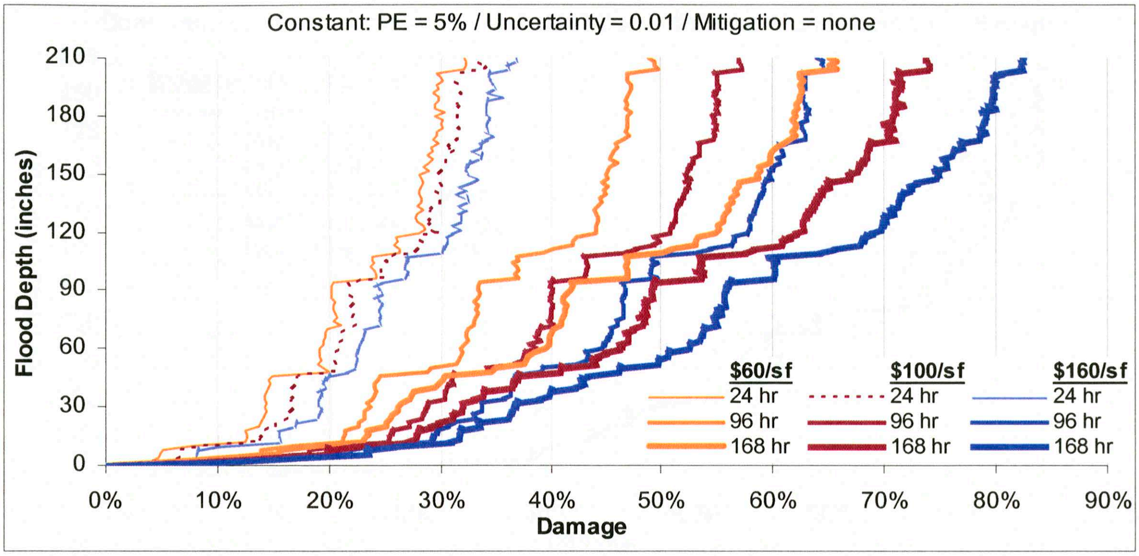


**Figure 63. Flood damage values associated with variations in building unit cost and flood duration expressed in terms of a percent of the total home cost and at a 5% probability of exceedance**

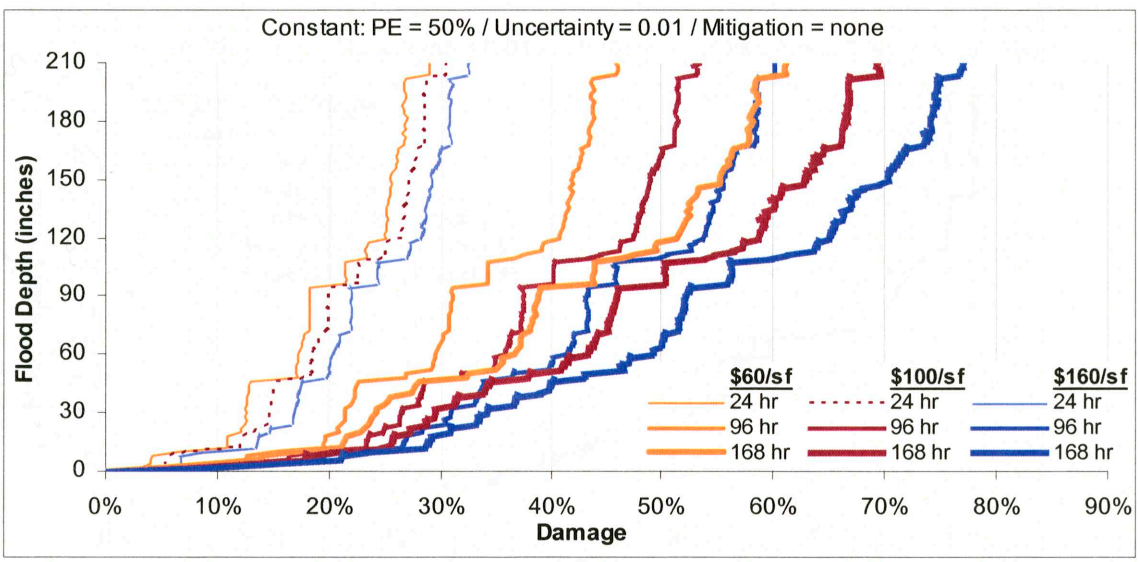


**Figure 64. Flood damage values associated with variations in building unit cost and flood duration expressed in terms of a percent of the total home cost and at a 50% probability of exceedance**

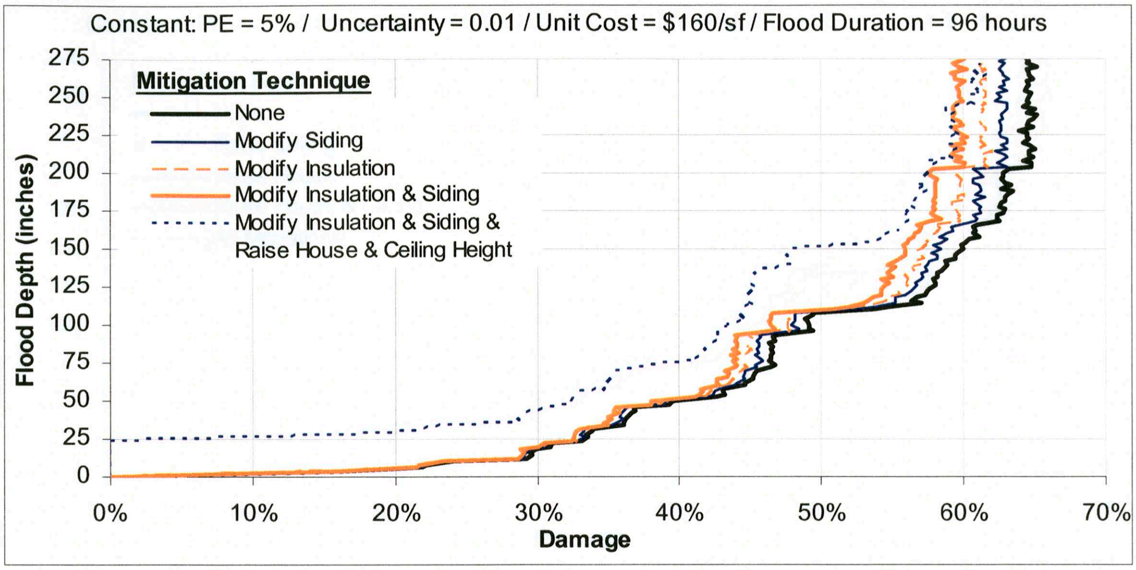


**Figure 65. Flood damage with various mitigation techniques in terms of a 5% probability of exceedance**

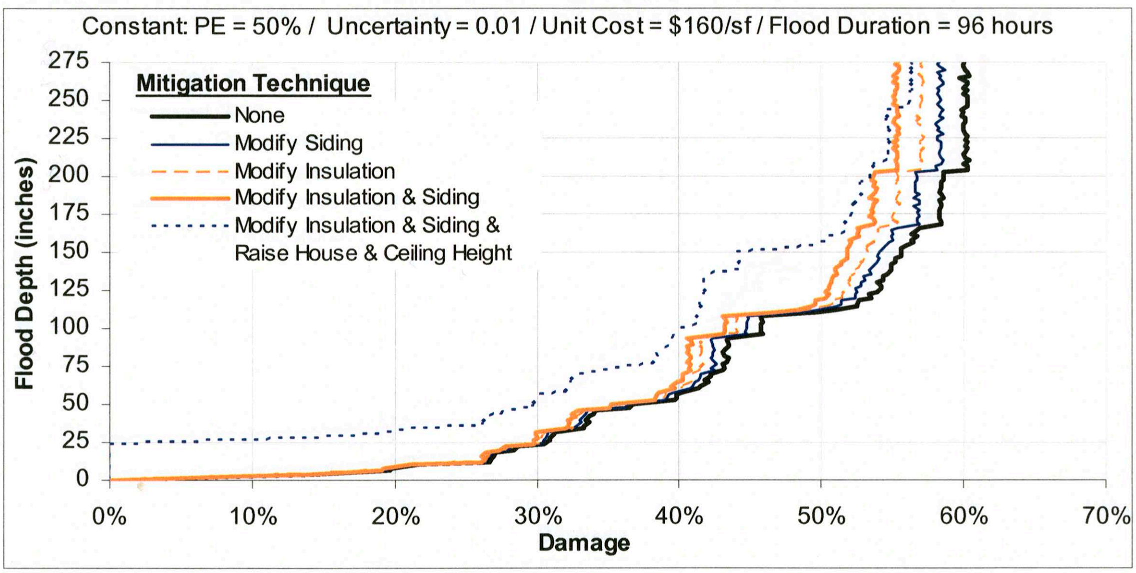


**Figure 66. Flood damage with various mitigation techniques in terms of a 50% probability of exceedance**

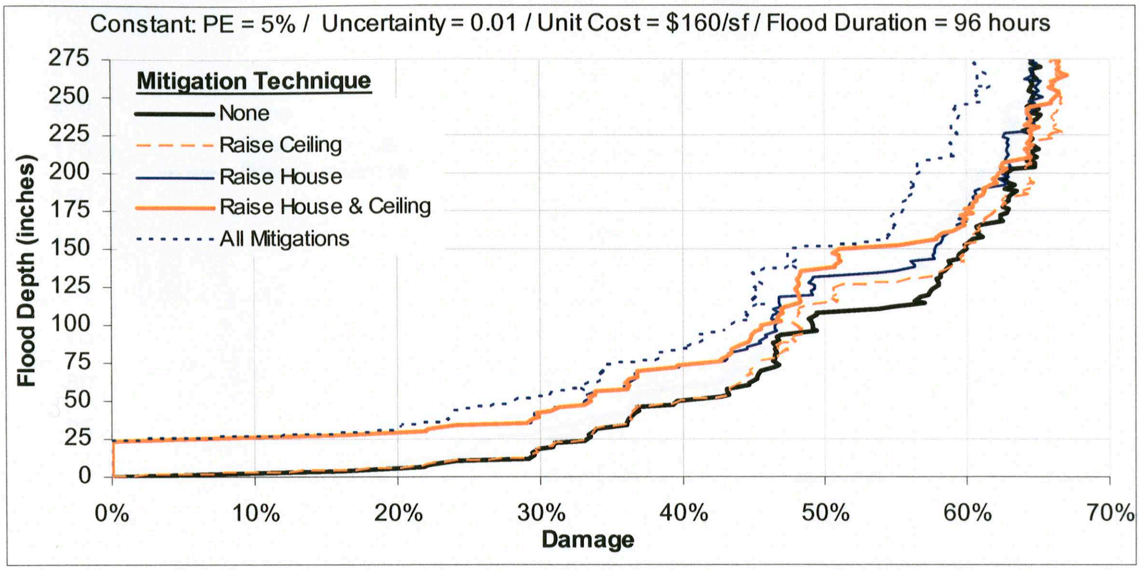


**Figure 67. Flood damage with various mitigation techniques in terms of a 5% probability of exceedance**

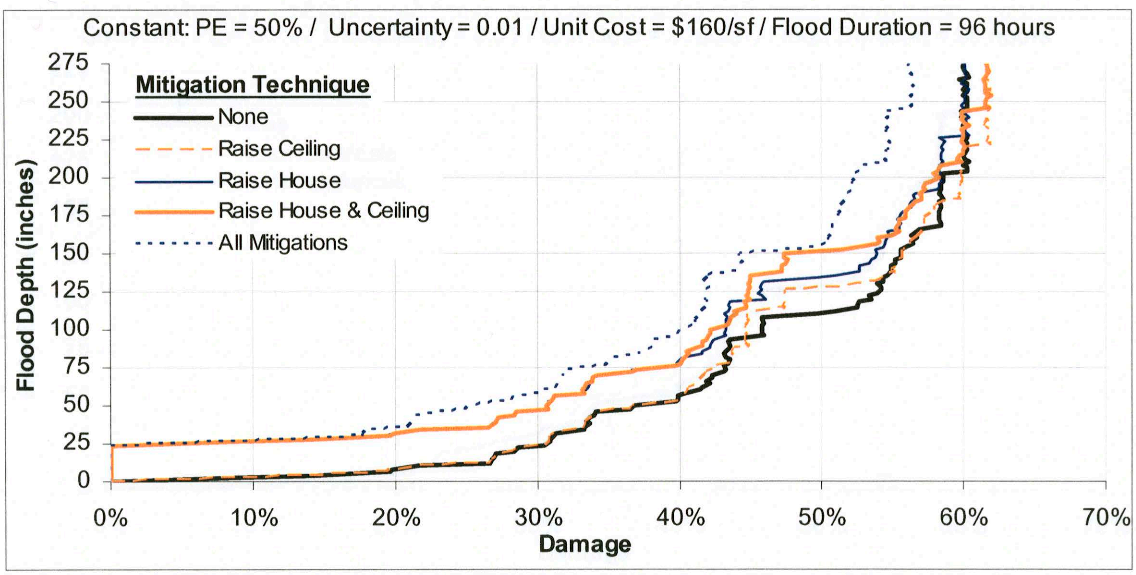


**Figure 68. Flood damage with various mitigation techniques in terms of a 50% probability of exceedance**

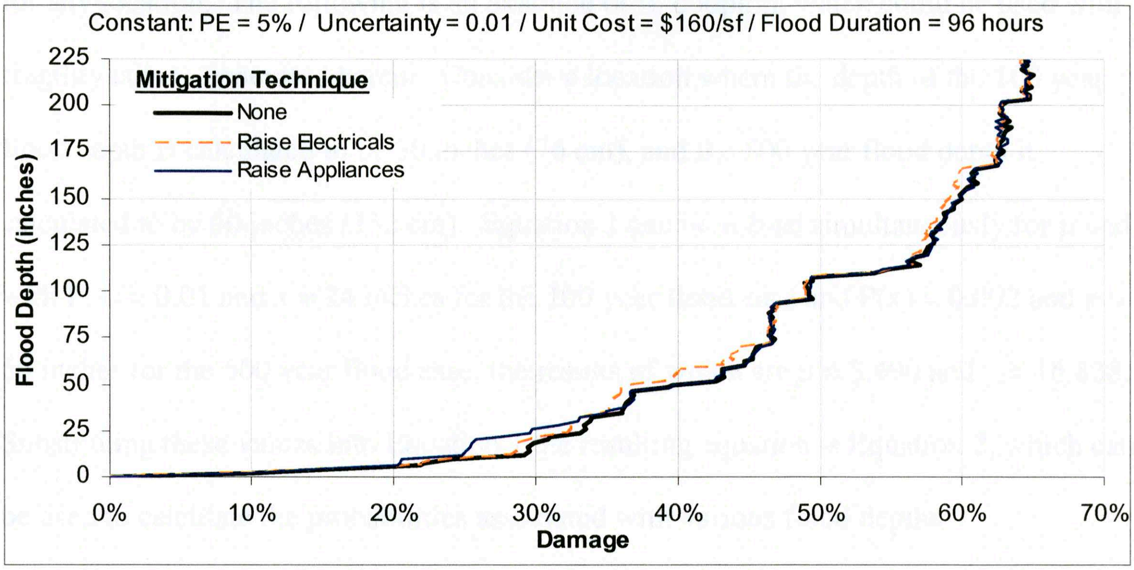


**Figure 69. Flood damage with various mitigation techniques in terms of a 5% probability of exceedance**

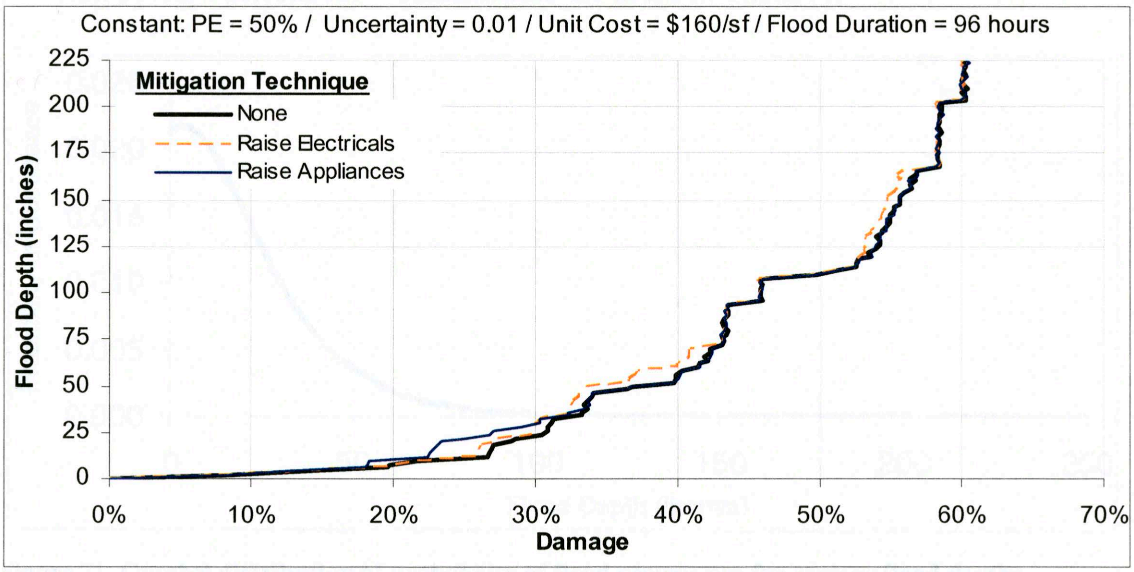


**Figure 70. Flood damage with various mitigation techniques in terms of a 50% probability of exceedance**

## *6.8 Re-coupling Fragility Curves with Probabilities of Flooding*

As previously discussed, the fragility curves were generated without a correlation between the flood depth and associated probability of flooding making the curves valid for any location. The following is an example of re-coupling which could be used with fragility curves generated herein. Consider a location where the depth of the 100 year flood depth is calculated to be 30 inches (76 cm), and the 500 year flood depth it calculated to be 60 inches (152 cm). Equation 1 can be solved simultaneously for $\mu$ and □ with P(x) = 0.01 and x = 24 inches for the 100 year flood case and P(x) = 0.002 and x = 60 inches for the 500 year flood case; the results of which are $\mu$ = 3.490 and □= 16.838. Substituting these values into Equation 1 the resulting equation is Equation 2, which can be used to calculate the probabilities associated with various flood depths.

$$P(x) = [\exp(-(x-3.490)/16.838)*\exp(-\exp(-(x-3.490)/ 16.838))]/ 16.838 \quad (2)$$

This equation has been plotted as shown in Figure 71, and a table of probabilities and associated return periods for various depths are listed in Table 17.

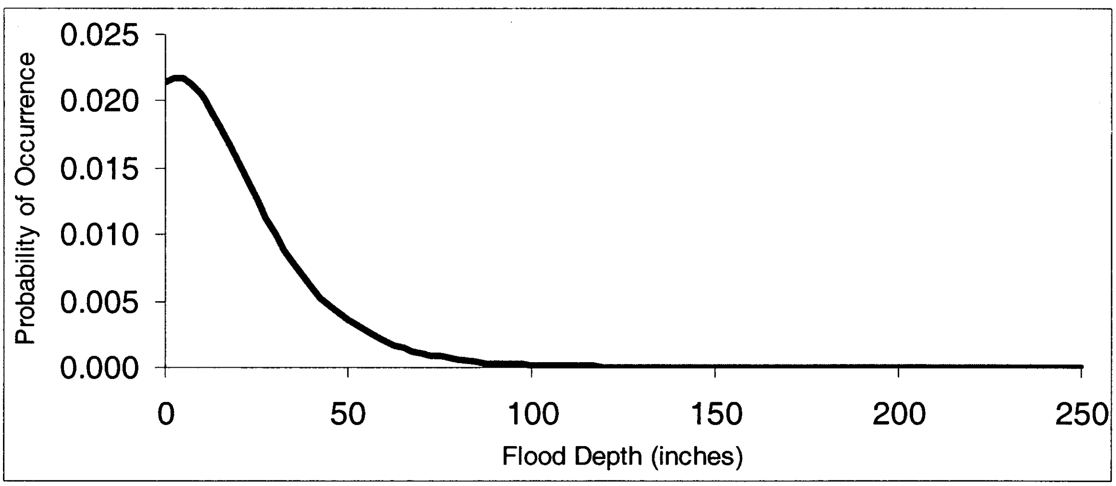


**Figure 71. Gumbel distribution of probability of flood occurrence for various flood depths**

The value of this step is that it proves essential information as to the flood damage mitigation techniques which should be considered. As is evident from this analysis, any decision on flood mitigation techniques for this location would be focused on the savings associated with the lower portions of the fragility curves since the probability of occurrence of flood depths above a single level is extremely unlikely and therefore payback of the initial cost of implementation of these mitigation techniques is unlikely to be realized.

**Table 17. Flood depths and associated probabilities of occurrence and return periods**

| Flood Depth | Probability | Return Period |
|---|---|---|
| 11 | 0.02000 | 50 |
| 24 | 0.01334 | 75 |
| 30 | 0.01000 | 100 |
| 38 | 0.00666 | 150 |
| 44 | 0.00500 | 200 |
| 51 | 0.00333 | 300 |
| 56 | 0.00250 | 400 |
| 60 | 0.00200 | 500 |
| 67 | 0.00133 | 750 |
| 72 | 0.00100 | 1000 |
| 111 | 0.00010 | 10000 |
| 138 | 0.00002 | 50000 |

The calculation of flood depth probabilities can be repeated for the same structure for any location and each set of probabilities can be associated with the fragility curves for guidance on the efficacy of the various flood damage mitigation techniques.

# 7. Summary and Recommendations

## *7.1 Summary*

A method was developed to produce fragility curves relating flood depth to financial losses. The curve accounted for flood duration as well, an important variable in computing water-induced damage. Failure of building components, i.e. siding or drywall, were determined based on the flood duration and depth required to cause damage to these items as compared to the simulated flood event characteristics. The cost of repair of the home was statistically calculated accounting for variations in the costs of repair or replacement of various building items, the overall unit cost of the home and variations in building item dimensions and quantities. Some assumptions were made throughout this study when a dearth of information was present, but all are clearly stated. Finally, a fragility curve was generated relating flood depth to building damage expressed as a percent damage or financial loss quantity with a 50% and 5% probability of exceedance. This process was repeated following numerical application of various flood damage mitigation techniques and these new fragility curves were compared with the original fragility curves to show the related potential savings resulting from the mitigation effort.

The fragility curves from the four examples considered produce results consistent with expectations. Specifically, there is consistency in the damage due to various depths of flooding, as well as in the grouping associated with variations in flood duration, and overall building unit costs.

As is evident from the comparison of the fragility curves with and without the flood damage mitigation techniques, cost savings is quantifiable using the process prescribed by this study. The easy visualization of this cost savings and the associated relationship with the flood return period at various depths, allows the client a simple method by which to judge the value of a variety of flood damage mitigation techniques given their relative initial costs, thereby putting the building owner in a position to make decisions on potential mitigation measures during construction.

This study is meant to be an initial step toward performance-based design of woodframe structures for flooding. As more data becomes available it is likely that models developed herein can improve and eventually result in a more accurate estimation procedure for flood damage to residential structures. The purpose of this study is to develop a robust process for flood damage estimation including provision for various flood characteristics, interactions between flood characteristics and damage to building items, and cost of repair of damaged building items.

## *7.2 Contributions*

To the authors knowledge this is the first time that a fragility analysis methodology has been developed for loss analysis of woodframe buildings to flooding. The concept and illustrative examples presented herein will lay the ground work for investigation of design practices and standards in flood prone areas as well as serve as a model for performance-based design development with respect to flooding.

## *7.3 Recommendations*

Since there is a limited amount of information available on nearly all facets of flood damage estimation the process outlined in this study is meant to be easily modifiable as further information is gathered. It is also meant to be easy to adjust with changing repair costs, construction methodologies and locations. Table 18 shows a list of suggested areas of further improvement.

**Table 18. Suggested areas of follow-up work**

| | |
|---|---|
| **Basement Seepage** | |
| This study: | Flood depth is not altered based on the capacity of the surrounding earth or foundation to reduce it |
| Follow-up: | Perform a study to determine a formula to estimate flood depth inside a basement based on distance to flood waters, soil type, foundation type and any other significant factors. Add this formula to the current process to modify the basement flood depth. |
| **Flood Characteristics** | |
| This study: | Considers flood depth and duration. |
| Follow-up: | Perform a study to determine how each building item reacts to various flood velocities, debris carried by flooding and flood contaminants. |
| **Flood Simulation** | |
| This study: | Approximates the return period of flood depths based on a Gumbel distribution generated using the 100 year and 500 year flood depths from FEMA flood maps and approximates flood duration with a lognormal distribution using a COV of 0.2 and the mean based on engineering judgment of the user of the process. |
| Follow-up: | Perform a study to provide a better way to estimate the probability of all characteristics of flooding including depth, duration, velocity, debris and contaminants. |
| **Building Item Damage Limits** | |
| This study: | Uses the limited amount of data available to estimate the building item failure limits associated with flood depth and duration. |
| Follow-up: | Perform a study to more accurately quantify the actual failure limits associated with flood depth and duration for these building items. |
| **Flooding Repair Costs** | |
| This study: | Uses repair and replacement costs of building items from RS Means *Repair and Remodeling Cost Data (*$24^{th}$ *Annual Edition, 2003).* |
| Follow-up: | Perform a study to verify that the unique situation of repair and replacement of building items which have been damaged by flooding is consistent with those estimates provided by RS Means. |
| This study: | This study uses relationships between whole house unit cost data from RS Means to determine a minimum and maximum unit cost for the home in question and then uses the placement of the actual unit cost of this home within the predetermined range to calculate the unit replacement cost of various building items within their associated cost ranges. |
| Follow-up: | Perform a study to produce increasingly accurate cost models which use minimal overall building information to place unit repair costs of various building items within their minimum and maximum potential values. |
| This study: | Calculates the total repair cost as the summation of the repair cost of each individual damaged building item. |
| Follow-up: | Perform a study to make cost estimates including potential break points such as gutting a house versus each trade removing and replacing their particular damaged items. |
| This study: | Calculates all damage estimates using current cost estimates. |
| Follow-up: | Add approximations to estimate future costs taking into account the time value of money. |

# REFERENCES & CITATIONS

Carll Highley, (1999) "Decay of Wood and Wood-Based Products Above Ground in Buildings", *Journal of Testing and Evaluation*, Vol. 27, No. 2, 150-158.

Charles Carll, (2000), "Rainwater Intrusion in Light-Frame Building Walls", *Proceedings of the 2nd Annual Conference on Durability and Disaster Mitigation in Wood-Frame Housing* , Forest Products Society, Madison, WI, 1-9.

David V. Rosowsky, and Bruce R. Ellingwood, (2002), "Performance-Based Engineering of Wood Frame Housing: Fragility Analysis Method", *Journal of Structural Engineering,* Vol. 128, 32-38.

Federal Emergency Management Agency (FEMA), (1981), "Design Guidelines for Flood Damage Reduction", *FEMA-15,* ALA Research Corporation,1735 New York Avenue, Northwest Washington, D.C.

H. Aglan, (2004), "Field Testing of Energy-Efficient Flood-Damage-Resistant Residential Envelope Systems Summary Report", *College of Engineering, Architecture and Physical Sciences, Tuskegee University*, Tuskegee, Alabama, and, *R. Wendt and S. Livengood Buildings Technology Center, Residential Buildings Group*, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 159 pp.

John van de Lindt, ( 2005) "1st Invitational Workshop on Performance-Based Design of Woodframe Structures", *The e-proceedings of the 1st Invitational Workshop on*

*Performance-Based Design of Woodframe Structures,* Colorado State University, Fort Collins, CO, 1-10.

Keith A. Porter, Anne S. Kiremidjian, and Jeremiah S. LeGrue, (2001), *Assembly-Based Vulnerability of Buildings and Its Use in Performance Evaluation,* Earthquake Engineering Research Institute, Oakland, CA, 23 pp.

National Institute of Standards and Technology (NIST), (2004), Performance Standards for Wood-Based Structural-Use Panels, *Voluntary Product Standard PS 2-04*, Technology Administration, U.S. Department of Commerce

RS Means Co., 2003, *Repair & Remodeling Cost Data,* 2003, 24$^{th}$ Ann. Ed., Kingston, MA,

RS Means Co., 2003, *Square Foot Costs,* 2003, 24$^{th}$ Ann. Ed., Kingston, MA,

S. Yue, T.B.M.J. Ouarda, B. Bobe, P. Legendre, P. Bruneau, (1999), "The Gumbel mixed model for flood frequency analysis", *Journal of Hydrology* 226, 88–100.

Y. K. Wen, (2000), "Reliability and Performance Based Design", *8th ASCE Specialty Conference on Probabilistic Mechanics and Structural Reliability*, University of Illinois at Urbana-Champaign, USA, 29 pp.

# Appendix A. MATLAB Program

## *A1. General Program Description*

This appendix contains the code used to generate the results shown in this study which was programmed using MATLAB. The program consists of 4 parts including a main portion of code and 3 subroutines which include code for calculation of flooding in the basement, first floor and second floor, respectively. There are 6 input files used by the program which include: (1) cost data and code values for proper associations of building materials with their respective quantities or areas (2) building dimensional information (3) building item locations and heights such as location of appliances (4) input values which might be changed with each run of the program such as maximum flood depth, building unit cost, flood duration, and mitigation on/off switches (5) quantitative descriptions of each mitigation technique and (6) file length information. Each of these portions of code and of example input files follows herein.

## *A2. Main Program Code*

```
clear;
%LOAD ALL EXTERNAL FILES--------------------------------------------------------------------------------
load costdata.txt;
load htss.txt;
load qtyss.txt;
load mtechtype.txt;
load filelength.txt
load inputs.txt;
%------------------------------------------------------------------------------------------------------------------------

%INITIALIZE MAX FLOOD DEPTH, NUMBER OF TRIALS AND FLOOD DEPTH
%INCREMENT---------------------------------------------------------------------------------------------------
%number of trails
TRIALS = inputs(6);
%flood depth increment
```

```
STEPSIZE = inputs(7);
%maximum depth of flooding
MSDEPTH = inputs(3);
%number of incremental steps to reach maximum depth
STEP = MSDEPTH/STEPSIZE;
%-------------------------------------------------------------------------------------------------------------

%CALCULATE FLOOD DURATION USING A LOGNORMAL DISTRIBUTION---------------------
%mean flood duration
TMUDUR = inputs(2);
%adjusted mean flood duration
MUDUR = log(TMUDUR);
%COV of flood duration
COVDUR = 0.2;
%calculate standard deviation of flood duration
SIGDUR = 1/(TMUDUR*COVDUR);
%generate an array of flood durations from a lognormal distribution
TDUR = lognrnd(MUDUR,SIGDUR,TRIALS,STEP);
%-------------------------------------------------------------------------------------------------------------

%CALCULATE BUILDING ITEM DIMENSIONAL VALUES USING A NORMAL
DISTRIBUTION-----------------------------------------------------------------------------------------------
NUMQTYSS = filelength(2);
%COV value for building item dimensional data
SURE = inputs(4);
for i = 1:NUMQTYSS
  %gather mean dimensional information from file
  MUBLDG(i)=qtyss(i);
  %generate an array of building item dimensional data from a normal
  %distribution
  TBLDGQTY(:,:,i) = normrnd(MUBLDG(i),(SURE*MUBLDG(i)),TRIALS,STEP);
end
%-------------------------------------------------------------------------------------------------------------

%GATHER BUILDING ITEM LOCATION AND HEIGHT INFORMATION----------------------------
NUMHTSS = filelength(3);
for i = 1:NUMHTSS
  BLDGHTS(i)=htss(i);
end
%-------------------------------------------------------------------------------------------------------------

%GATHER INFORMATION FOR BUILDING ITEM FAILURE LIMTS, UNIT COSTS, AND
%NUMERIC CODES WHICH PROVIDE PROPER ASSOCIATIONS-------------------------------------
-
NUMMAT = filelength(1);
%step through all building items
for itm = 1:NUMMAT;
  MATCODE(itm) = costdata(itm,1);
  MINRPR(itm) = costdata(itm,2);
  MAXRPR(itm) = costdata(itm,3);
  MINRPL(itm) = costdata(itm,4);
  MAXRPL(itm) = costdata(itm,5);
```

```
  ATYPE(itm) = costdata(itm,6);
  SCODE(itm) = costdata(itm,7);
  ACODE(itm) = costdata(itm,8);
  BCODE(itm) = costdata(itm,9);
  SFON(itm) = costdata(itm,10);
  FFON(itm) = costdata(itm,11);
  BSMTON(itm) = costdata(itm,12);
  MINRPRDEP(itm) = costdata(itm,13);
  MAXRPRDEP(itm) = costdata(itm,14);
  MINRPLDEP(itm) = costdata(itm,15);
  MINRPRDUR(itm) = costdata(itm,16);
  MAXRPRDUR(itm) = costdata(itm,17);
  MINRPLDUR(itm) = costdata(itm,18);
%------------------------------------------------------------------------------------------------------------------------

%BUILDING ITEM COST CALCULATIONS-----------------------------------------------------------------
%gather value of home
HOMEVALUE = inputs(1);

%Calculate minimum and maximum values based on RS Means sqare foot costs
%which will be the basis for later linear interpolation
  %if building has a basement
  if BLDGHTS(20) == 1
    %if building does not have a second floor
    if BLDGHTS(8) == 0
      %if building has an unfinished basement
      if MUBLDG(79)==0
        ECONO = 957.03*(qtyss(1)-qtyss(54))^(-0.3532);
        LUXUR = 1999.2*(qtyss(1)-qtyss(54))^(-0.3467);
      %if building has a finished basement
      else
        ECONO = 779.08*(qtyss(1)-qtyss(54))^(-0.3036);
        LUXUR = 1612.5*(qtyss(1)-qtyss(54))^(-0.298);
      end
    %if building has a second floor
    elseif BLDGHTS(8) == 1
      %if building has an unfinished basement
      if MUBLDG(79)==0
        ECONO = 1276.7*(qtyss(1)-qtyss(54))^(-0.3845);
        LUXUR = 2055.2*(qtyss(1)-qtyss(54))^(-0.3655);
      %if building has a finished basement
      else
        ECONO = 1142.7*(qtyss(1)-qtyss(54))^(-0.3591);
        LUXUR = 1854.5*(qtyss(1)-qtyss(54))^(-0.3387);
      end
    end
  %if building does not have a basement
  elseif BLDGHTS(20) == 0
    %if building does not have a second floor
    if BLDGHTS(8) == 0
      ECONO = 827.13*(qtyss(1))^(-0.3468);
      LUXUR = 1907.5*(qtyss(1))^(-0.356);
```

```
    %if building has a second floor
    elseif BLDGHTS(8) == 1
      ECONO = 1152.4*(qtyss(1))^(-0.3795);
      LUXUR = 2042.8*(qtyss(1))^(-0.3748);
    end
  end


%employ linear interpolation using actual unit cost value of the home along
%with gathered maximum and minimum unit cost values from above to find the
%mean unit cost of repair or repalcement of various building items within
%their prescribed maximum and minimum unit cost values
  %limit the adjusted mean minimum unit cost of repair of each building
  %item to no less than 75% of the minimum value prescribed by the
  %input file
  if (((HOMEVALUE/(MUBLDG(1)-MUBLDG(54)))-ECONO)/(LUXUR-ECONO))...
      *(MAXRPR(itm)-MINRPR(itm))+MINRPR(itm) < MINRPR(itm)/1.333
    MURPR(itm)=MINRPR(itm)/1.333;
  %perform linear interpolation to calculate mean building item unit
  %repair costs
  else
    MURPR(itm)=(((HOMEVALUE/(MUBLDG(1)-MUBLDG(54)))-ECONO)/...
      (LUXUR-ECONO))*(MAXRPR(itm)-MINRPR(itm))+MINRPR(itm);
  end
  %limit the adjusted mean minimum unit cost of replacement of each
  %building item to no less than 75% of the minimum value prescribed by
  %the input file
  if (((HOMEVALUE/(MUBLDG(1)-MUBLDG(54)))-ECONO)/(LUXUR-ECONO))...
      *(MAXRPL(itm)-MINRPL(itm))+MINRPL(itm) < MINRPL(itm)/1.333
    MURPL(itm)=MINRPL(itm)/1.333;
  %perform linear interpolation to calculate mean building item unit
  %replacement costs
  else
    MURPL(itm)=(((HOMEVALUE/(MUBLDG(1)-MUBLDG(54)))-ECONO)/...
      (LUXUR-ECONO))*(MAXRPL(itm)-MINRPL(itm))+MINRPL(itm);
  end

  %generate standard deviation for each building item unit cost of repair or
  %replacement using a COV of 0.2
  SIGMARPR(itm)= MURPR(itm)*0.2;
  SIGMARPL(itm)= MURPL(itm)*0.2;

  %generate an array of building item repair and replacement costs from a
  %normal distribution and adjust the values by the location cost
  %multiplier
  TREPAIR(:,:,itm) = normrnd(MURPR(itm),SIGMARPR(itm),TRIALS,STEP)...
    *inputs(5);
  TREPLACE(:,:,itm) = normrnd(MURPL(itm),SIGMARPL(itm),TRIALS,STEP)...
    *inputs(5);
end
%---------------------------------------------------------------------------------------------------------------
```

```
%FLOOD DAMAGE MITIGATION TECHNIQUE INITIALIZATION------------------------------------
NUMMTTYPE = filelength(4);
NUMMTON = filelength(5)-15;

%read in switches which will turn each mitigation technique on or off
%step through all mitigation techniques
for mtc=1:NUMMTON
  MTSWITCH(mtc)=inputs(mtc+15);
end

%step through all building items
for itm=1:NUMMAT
  %initialize variable which will record the change in failure depth
  %limits associated with building item replacement
  MINRPLDEPCNG(itm)=0;
  %initialize variable which will record the change in failure depth
  %limits associated with building item repair
  MINRPRDEPCNG(itm)=0;


  mtc=0;
  %step through all mitigation techniques
  for i=1:2:NUMMTTYPE-1
    mtc=mtc+1;
    %read in changes to building item failure depth for each mitigation
    %technique
    MTITEMDEP(itm,mtc)=mtechtype(itm,i);
    %read in changes to building item failure duration for each
    %mitigation technique
    MTITEMDUR(itm,mtc)=mtechtype(itm,i+1);
  end
end

%modify building item depth and duration failure limits associated with
%failures causing either repair or replacement to the building items
%step through mitigation techniques
for mtc = 1:NUMMTON
  %if mitigation technique is on
  if MTSWITCH(mtc)>0
    %step through all building items
    for itm=1:NUMMAT
      %if the particual building item has a non-zero (positive)
      %adjustment to the item failure depths
      if MTITEMDEP(itm,mtc)>0
        %replace building item depth failure limit associated with
        %required replacement of the building item
        MINRPLDEP(itm)=MINRPLDEP(itm)+MTITEMDEP(itm,mtc);
        %record the building item depth failure limit change
        %associated with required replacement of the building item
        MINRPLDEPCNG(itm)=MTITEMDEP(itm,mtc);
        %replace building item depth failure limit associated with
        %required repair of the building item
```

```
      MINRPRDEP(itm)=MINRPRDEP(itm)+MTITEMDEP(itm,mtc);
      %record the building item depth failure limit change
      %associated with required repair of the building item
      MINRPRDEPCNG(itm)=MTITEMDEP(itm,mtc);
    end
    %if the particual building item has a non-zero (positive)
    %adjustment to the item failure durations
    if MTITEMDUR(itm,mtc)>0
      %replace building item duration failure limit associated
      %with required replacement of the building item
      MINRPLDUR(itm)=MINRPLDUR(itm)+MTITEMDUR(itm,mtc);
      %replace building item duration failure limit associated
      %with required repair of the building item
      MINRPRDUR(itm)=MINRPRDUR(itm)+MTITEMDUR(itm,mtc);
    end
   end
  end
end

%Mitigation technique associated with increasing the distance between
%buildind stories
%read in basement to first floor height increase
MTBSMTCEILING = inputs(13);
%if basement to first floor height change is non-zero (positive)
if MTBSMTCEILING > 0
  %increse ceiling height of basement
  BLDGHTS(21)=BLDGHTS(21)+MTBSMTCEILING;
  %increase basement floor to first floor height
  BLDGHTS(5)=BLDGHTS(5)+MTBSMTCEILING;
end
%read in first floor to second floor height increase
MTFFCEILING = inputs(14);
%if first floor to second floor height change is non-zero (positive)
if MTFFCEILING > 0
  %increase ceiling height of first floor
  BLDGHTS(15)=BLDGHTS(15)+MTFFCEILING;
  %increase first floor to second floor height
  BLDGHTS(4)=BLDGHTS(4)+MTFFCEILING;
end
%-----------------------------------------------------------------------------------------------------------------------

%DAMAGE CALCULATIONS-----------------------------------------------------------------------------------
count = 0;
%step through flood depths in prescribed increments to maximum depth
for q = 1:STEPSIZE:MSDEPTH
  count = count+1;
  %array to be used as the flood depth axis on the fragility curve
  AXIS(count)=q-1;
  %initialize damage variable
  REPCOST = zeros(TRIALS,1);
  %extract building dimensional information for each trial
  BLDGQTY(:,:)=TBLDGQTY(:,count,:);
```

```
%step through prescribed number of trials
for n = 1:TRIALS
  %start flood depth at 0 rather than 1
  DEPTH(n)=q-1;
  %extract flood duration for each trial
  DUR(n)=TDUR(n,count);
  %step through each material
  for itm = 1:NUMMAT;
    %extract building item unit repair costs for each trial
    REPAIR(:,itm)=TREPAIR(:,count,itm);
    %extract building item unit replacement costs for each trial
    REPLACE(:,itm)=TREPLACE(:,count,itm);
    %if it is possible for building item to be located on the 2nd
    %floor (i.e. there would be no garage on the 2nd floor)

    %if the building has a 2nd floor
    if BLDGHTS(8)==1
      %if it is possible for building item to be located on the
      %2nd floor (i.e. there would be no garage on the 2nd floor)
      if SFON(itm)==1
        %go to 2nd floor damage calculation subroutine
        SECONDF
      end
    end
    %if the building has a 1st floor
    if BLDGHTS(14)==1
      %if it is possible for building item to be located on the
      %1st floor
      if FFON(itm)==1
        %go to 1st floor damage calculation subroutine
        FIRSTF
      end
    end
    %if the building has a basement
    if BLDGHTS(20)==1
      %if it is possible for building item to be located in the
      %basement
      if BSMTON(itm)==1
        %go to basement damage calculation subroutine
        BSMT
      end
    end
  end
end


%sort replacement costs from various trials in ascending order to form
%an empirical CDF
SREPCOST = sort(REPCOST);

%extract damage value from CDF with a 50% probability of exceedance
FIFTY(count)=SREPCOST((TRIALS/2))/HOMEVALUE;
```

```
  %extract damage value from CDF with a 10% probability of exceedance
  NINETY(count)=SREPCOST((0.9*TRIALS))/HOMEVALUE;
  %extract damage value from CDF with a 5% probability of exceedance
  NINETYF(count)=SREPCOST((0.95*TRIALS))/HOMEVALUE;

end
%----------------------------------------------------------------------------------------------------------------------

%OUTPUT---------------------------------------------------------------------------------------------------------------
%plot fragility curves for 50%, 90% and 95% probabilities of exceedance
hold on
plot(FIFTY,AXIS,'color','green');
plot(NINETY,AXIS,'color','blue');
plot(NINETYF,AXIS,'color','red');
xlabel('Damage (percent building cost)')
ylabel('Flood Depth (inches)')
legend('PE=50%','PE=10%','PE=5%','location','NorthWest')

%save flood percentage damage data in 3 columns
% [depth,%damage at PE=50%,%damage at PE=10%,%damage at PE=95%]
LOSSES = [AXIS',FIFTY',NINETY',NINETYF'];
save LOSSES LOSSES -ascii
%----------------------------------------------------------------------------------------------------------------------
```

## *A3. Basement Flood Losses Subroutine*

```
%set basement flood depth equal to overall flood depth
BSMTDEP=DEPTH(n);

%AREA COST CALCULATIONS WHEREIN DAMAGE IS TRUE OR FALES AND
%INDEPENDENT OF FLOOD DEPTH (I.E. FLOORING)--------------------------------------------------
if ATYPE(itm) == 1;
  FAIL = 0;
  %if building item is electrical outlets
  if itm == 35
    %if flood depth is above the height of the outlets
    if BSMTDEP>=MINRPLDEP(itm)+BLDGHTS(18)
      FAIL = 2;
    end
  %if building item is electrical switches
  elseif itm == 36
    %if flood depth is above the height of the switches
    if BSMTDEP>=MINRPLDEP(itm)+BLDGHTS(19)
      FAIL = 2;
    end
  %if not electrical switches or outlets
  else
    %if the flood depth is over the minimum flood depth
    %failure limit associated with repair of the item
    if BSMTDEP>= MINRPRDEP(itm);
```

```
      FAIL = 1;
    end
    %if the flood duration is over the minimum flood duration
    %failure limit associated with repair of the item
    if DUR(n)>=MINRPRDUR(itm);
      FAIL = 1;
    end
    %if the flood depth is over the minimum flood depth
    %failure limit associated with replacement of the item
    if BSMTDEP>= MINRPLDEP(itm);
      %if the flood duration is over the minimum flood duration
      %failure limit associated with replacement of the item
      if DUR(n)>=MINRPLDUR(itm);
        FAIL = 2;
      end
    end
  end
  %if item requires repair, calculate repair cost of item
  if FAIL == 1;
    REPCOST(n)=REPCOST(n)+BLDGQTY(n,BCODE(itm))*REPAIR(n,itm);
  end
  %if item requires replacement, calculate replacement cost of item
  if FAIL == 2;
    REPCOST(n)=REPCOST(n)+BLDGQTY(n,BCODE(itm))*REPLACE(n,itm);
  end
end
%------------------------------------------------------------------------------------------------------------------------

%AREA COST CALCULATIONS HAVING TO DO WITH COVERINGS OF INTERIOR WALLS
%(I.E. DRYWALL & INTERIOR PAINTING)-------------------------------------------------------------------
if ATYPE(itm) == 2;
  FAIL=0;
  %if the flood duration is over the minimum flood duration
  %failure limit associated with repair of the item
  if DUR(n)>=MINRPRDUR(itm);
    FAIL = 1;
  end
  %if the flood depth is over the minimum flood depth
  %failure limit associated with repair of the item
  if BSMTDEP>= MINRPRDEP(itm);
    FAIL = 1;
    %if depth of flooding is within 36 inches of the ceiling
    if BSMTDEP>=BLDGHTS(21)-36+MINRPLDEPCNG(itm);
      %modify depth of flooding to be height of ceiling
      TDEPTH=BLDGHTS(21);
      %if flood depth is not within 36 inches of the ceiling
    else
      %modify depth of flooding to be 12 inches above flood depth
      TDEPTH=BSMTDEP+12-MINRPLDEPCNG(itm);
    end
  end
  %if the flood depth is over the minimum flood depth
```

```
  %failure limit associated with replacement of the item
  if BSMTDEP>= MINRPLDEP(itm);
    %if the flood duration is over the minimum flood duration
    %failure limit associated with replacement of the item
    if DUR(n)>=MINRPLDUR(itm);
      FAIL = 2;
    end
  end
  %if item requires repair, calculate repair cost of item
  if FAIL == 1;
    REPCOST(n)=REPCOST(n)+2*BLDGQTY(n,55)*(TDEPTH/12)*REPAIR(n,itm);
  end
  %if item requires replacement, calculate replacement cost of item
  if FAIL == 2;
    REPCOST(n)=REPCOST(n)+2*BLDGQTY(n,55)*(TDEPTH/12)*REPLACE(n,itm);
  end
end
%---------------------------------------------------------------------------------------------------------------

%AREA COST CALCULATIONS HAVING TO DO WITH INTERIOR COVERINGS OF
%EXTERIOR WALLS (I.E. DRYWALL & INTERIOR PAINTING)------------------------------------------
if ATYPE(itm) == 3;
  FAIL=0;
  %if the flood duration is over the minimum flood duration
  %failure limit associated with repair of the item
  if DUR(n)>=MINRPRDUR(itm);
    FAIL = 1;
  end
  %if the flood depth is over the minimum flood depth
  %failure limit associated with repair of the item
  if BSMTDEP>= MINRPRDEP(itm);
    FAIL = 1;
    %if depth of flooding is within 36 inches of the ceiling or greater
    if BSMTDEP>=BLDGHTS(5)-36+MINRPLDEPCNG(itm);
      %modify depth of flooding to be height of ceiling
      TDEPTH=BLDGHTS(5);
    %if flood depth is not within 36 inches of the ceiling
    else
      %modify depth of flooding to be 12 inches above flood depth
      TDEPTH=BSMTDEP+12-MINRPLDEPCNG(itm);
    end
  end
  %if the flood depth is over the minimum flood depth
  %failure limit associated with replacement of the item
  if BSMTDEP>= MINRPLDEP(itm);
    %if the flood duration is over the minimum flood duration
    %failure limit associated with replacement of the item
    if DUR(n)>=MINRPLDUR(itm);
      FAIL = 2;
    end
  end
  %if item requires repair, calculate repair cost of item
```

```
  if FAIL == 1;
    REPCOST(n)=REPCOST(n)+BLDGQTY(n,56)*(TDEPTH/12)*REPAIR(n,itm);
  end
  %if item requires replacement, calculate replacement cost of item
  if FAIL == 2;
    REPCOST(n)=REPCOST(n)+BLDGQTY(n,56)*(TDEPTH/12)*REPLACE(n,itm);
  end
end
%-------------------------------------------------------------------------------------------------------------------

%AREA COST CALCULATIONS HAVING TO DO WITH EXTERIOR COVERINGS OF
%EXTERIOR WALLS (I.E. SIDING, EXTERIOR PAINTING, INSULATION)----------------------------
if ATYPE(itm) == 4;
  FAIL=0;
  %if the flood duration is over the minimum flood duration
  %failure limit associated with repair of the item
  if DUR(n)>=MINRPRDUR(itm);
    FAIL = 1;
  end
  %if the flood depth is over the minimum flood depth
  %failure limit associated with repair of the item
  if BSMTDEP>= MINRPRDEP(itm);
    FAIL = 1;
    %if depth of flooding is within 12 inches of the first floor or
    %greater
    if BSMTDEP>=BLDGHTS(5)-12+MINRPLDEPCNG(itm);
      %modify the depth of flooding to be the height of the first
      %floor above the basement floor
      TDEPTH=BLDGHTS(5);
    %if depth of flooding is not within 12 inches of the first floor
    else
      %modify the depth of flooding to be 12 inches above flood depth
      TDEPTH=BSMTDEP+12-MINRPLDEPCNG(itm);
    end
  end
  %if the flood depth is over the minimum flood depth
  %failure limit associated with replacement of the item
  if BSMTDEP>= MINRPLDEP(itm);
    %if the flood duration is over the minimum flood duration
    %failure limit associated with replacement of the item
    if DUR(n)>=MINRPLDUR(itm);
      FAIL = 2;
    end
  end
  %if item requires repair, calculate repair cost of item
  if FAIL == 1;
    REPCOST(n)=REPCOST(n)+BLDGQTY(n,57)*(TDEPTH/12)*REPAIR(n,itm);
  end
  %if item requires replacement, calculate replacement cost of item
  if FAIL == 2;
    REPCOST(n)=REPCOST(n)+BLDGQTY(n,57)*(TDEPTH/12)*REPLACE(n,itm);
  end
```

```
end
%------------------------------------------------------------------------------------------------------------------------

%QUANTITY COST CALCULATIONS FOR WHICH REPAIR MAY BE CALCULATED FOR
%SPECIFIC DEPTHS AND REPLACEMENT FOR OTHER DEPTHS (I.E. APPLIANCES)------------
if ATYPE(itm) == 5;
  %if item is located in the basement
  if BLDGHTS(BCODE(itm)) == 0
    FAIL = 0;
    %if the flood duration is over the minimum flood duration
    %failure limit associated with repair of the item
    if DUR(n)>=MINRPRDUR(itm);
      FAIL = 1;
    end
    %if the flood depth is over the minimum flood depth
    %failure limit associated with repair of the item
    if BSMTDEP>= MINRPRDEP(itm);
      FAIL = 1;
    end
    %if the flood depth is over the minimum flood depth
    %failure limit associated with replacement of the item
    if BSMTDEP>= MINRPLDEP(itm);
      %if the flood duration is over the minimum flood duration
      %failure limit associated with replacement of the item
      if DUR(n)>=MINRPLDUR(itm);
        FAIL = 2;
      end
    end
    %if item requires repair, calculate repair cost of item
    if FAIL == 1;
      REPCOST(n)=REPCOST(n)+REPAIR(n,itm);
    end
    %if item requires replacement, calculate replacement cost of item
    if FAIL == 2;
      REPCOST(n)=REPCOST(n)+REPLACE(n,itm);
    end
  end
end
%------------------------------------------------------------------------------------------------------------------------

%AREA COST CALCULATIONS HAVING TO DO WITH ITEMS ON THE CEILING
%(I.E. DRYWALL & LIGHT FIXTURES)---------------------------------------------------------------------------
if ATYPE(itm) == 6;
  FAIL = 0;
  %if the flood duration is over the minimum flood duration
  %failure limit associated with repair of the item
  if DUR(n)>=MINRPRDUR(itm);
    FAIL = 1;
  end
  %if the flood depth is over the minimum flood depth
  %failure limit associated with repair of the item
  if BSMTDEP>= BLDGHTS(21)+MINRPRDEP(itm);
```

```
      FAIL = 1;
    end
    %if the flood depth is over the minimum flood depth
    %failure limit associated with replacement of the item
    if BSMTDEP>= BLDGHTS(21)+MINRPLDEP(itm);
      %if the flood duration is over the minimum flood duration
      %failure limit associated with replacement of the item
      if DUR(n)>=MINRPLDUR(itm);
        FAIL = 2;
      end
    end
    %if item requires repair, calculate repair cost of item
    if FAIL == 1;
      REPCOST(n)=REPCOST(n)+BLDGQTY(n,BCODE(itm))*REPAIR(n,itm);
    end
    %if item requires replacement, calculate replacement cost of item
    if FAIL == 2;
      REPCOST(n)=REPCOST(n)+BLDGQTY(n,BCODE(itm))*REPLACE(n,itm);
    end
  end
  %---------------------------------------------------------------------------------------------------------------------

  %COST CALCULATIONS FOR PERSONAL PROPERTY LOSSES-----------------------------------------
  if ATYPE(itm) == 7;
    FAIL = 0;
    %if the flood duration is over the minimum flood duration
    %failure limit associated with repair of the items
    if DUR(n)>=MINRPRDUR(itm);
      FAIL = 1;
    end
    %if the flood depth is over the minimum flood depth
    %failure limit associated with repair of the items
    if BSMTDEP>= MINRPRDEP(itm);
      FAIL = 1;
    end
    %if the flood depth is over the minimum flood depth
    %failure limit associated with partial damage of personal items
    if BSMTDEP> MINRPLDEP(itm);
      %if the flood duration is over the minimum flood duration
      %failure limit associated complete damage of personal items
      if DUR(n)>=MINRPLDUR(itm);
        FAIL = 2;
      end
    end
    %if some personal items require replacement, calculate replacement of
    %a portion of personal items (includes hypothetical curve of
    %increasing damage with depth)
    if FAIL == 1;
      REPCOST(n)=REPCOST(n)+(1-5/...
        (((BSMTDEP/BLDGHTS(21))*100)+5))*BLDGQTY(n,BCODE(itm))...
        *REPLACE(n,itm);
    end
```

```
  %if all personal items are damaged
  if FAIL == 2;
    REPCOST(n)=REPCOST(n)+BLDGQTY(n,BCODE(itm))*REPLACE(n,itm);
  end
end
%--------------------------------------------------------------------------------------------------------------
```

## *A4. First Floor Flood Losses Subroutine*

```
%if building has a basement
if BLDGHTS(20)>0
  %set flood depth to zero at floor level
  FFDEPTH = DEPTH(n)-BLDGHTS(5);
%if building does not have a basement
else
  %set flood depth equal to overall flood depth
  FFDEPTH=DEPTH(n);
end

%do not allow any negative depth
if FFDEPTH < 0
  FFDEPTH = 0;
end

%if flood reaches first floor level
if FFDEPTH > 0

%AREA COST CALCULATIONS WHEREIN DAMAGE IS TRUE OR FALES AND
%INDEPENDENT OF FLOOD DEPTH (I.E. FLOORING)---------------------------------------------------
if ATYPE(itm) == 1;
  FAIL = 0;
  %if building item is electrical outlets
  if itm == 35
    %if flood depth is above the height of the outlets
    if FFDEPTH>=MINRPLDEP(itm)+BLDGHTS(12)
      FAIL = 2;
    end
  %if building item is electrical switches
  elseif itm == 36
    %if flood depth is above the height of the switches
    if FFDEPTH>=MINRPLDEP(itm)+BLDGHTS(13)
      FAIL = 2;
    end
  %if not electrical switches or outlets
  else
    %if the flood depth is over the minimum flood depth
    %failure limit associated with repair of the item
    if FFDEPTH>= MINRPRDEP(itm);
      FAIL = 1;
```

```
    end
    %if the flood duration is over the minimum flood duration
    %failure limit associated with repair of the item
    if DUR(n)>=MINRPRDUR(itm);
      FAIL = 1;
    end
    %if the flood depth is over the minimum flood depth
    %failure limit associated with replacement of the item
    if FFDEPTH>= MINRPLDEP(itm);
      %if the flood duration is over the minimum flood duration
      %failure limit associated with replacement of the item
      if DUR(n)>=MINRPLDUR(itm);
        FAIL = 2;
      end
    end
  end
  %if item requires repair, calculate repair cost of item
  if FAIL == 1;
    REPCOST(n)=REPCOST(n)+BLDGQTY(n,ACODE(itm))*REPAIR(n,itm);
  end
  %if item requires replacement, calculate replacement cost of item
  if FAIL == 2;
    REPCOST(n)=REPCOST(n)+BLDGQTY(n,ACODE(itm))*REPLACE(n,itm);
  end
end
%-----------------------------------------------------------------------------------------------------------------------

%AREA COST CALCULATIONS HAVING TO DO WITH COVERINGS OF INTERIOR WALLS
%(I.E. DRYWALL & INTERIOR PAINTING)-------------------------------------------------------------------
if ATYPE(itm) == 2;
  FAIL=0;
  %if the flood duration is over the minimum flood duration
  %failure limit associated with repair of the item
  if DUR(n)>=MINRPRDUR(itm);
    FAIL = 1;
  end
  %if the flood depth is over the minimum flood depth
  %failure limit associated with repair of the item
  if FFDEPTH>= MINRPRDEP(itm);
    FAIL = 1;
    %if depth of flooding is within 36 inches of the ceiling
    if FFDEPTH>=BLDGHTS(15)-36+MINRPLDEPCNG(itm);
      %modify depth of flooding to be height of ceiling
      TDEPTH=BLDGHTS(15);
      %if flood depth is not within 36 inches of the ceiling
    else
      %modify depth of flooding to be 12 inches above flood depth
      TDEPTH=FFDEPTH+12-MINRPLDEPCNG(itm);
    end
  end
  %if the flood depth is over the minimum flood depth
  %failure limit associated with replacement of the item
```

```
  if FFDEPTH>= MINRPLDEP(itm);
    %if the flood duration is over the minimum flood duration
    %failure limit associated with replacement of the item
    if DUR(n)>=MINRPLDUR(itm);
      FAIL = 2;
    end
  end
  %if item requires repair, calculate repair cost of item
  if FAIL == 1;
    REPCOST(n)=REPCOST(n)+2*BLDGQTY(n,29)*(TDEPTH/12)*REPAIR(n,itm);
  end
  %if item requires replacement, calculate replacement cost of item
  if FAIL == 2;
    REPCOST(n)=REPCOST(n)+2*BLDGQTY(n,29)*(TDEPTH/12)*REPLACE(n,itm);
  end
end
%-----------------------------------------------------------------------------------------------------------------------

%AREA COST CALCULATIONS HAVING TO DO WITH INTERIOR COVERINGS OF
%EXTERIOR WALLS (I.E. DRYWALL & INTERIOR PAINTING)------------------------------------------
if ATYPE(itm) == 3;
  FAIL=0;
  %if the flood duration is over the minimum flood duration
  %failure limit associated with repair of the item
  if DUR(n)>=MINRPRDUR(itm);
    FAIL = 1;
  end
  %if the flood depth is over the minimum flood depth
  %failure limit associated with repair of the item
  if FFDEPTH>= MINRPRDEP(itm);
    FAIL = 1;
    %if depth of flooding is within 36 inches of the ceiling or greater
    if FFDEPTH>=BLDGHTS(4)-36+MINRPLDEPCNG(itm);
      %modify depth of flooding to be height of ceiling
      TDEPTH=BLDGHTS(4);
    %if flood depth is not within 36 inches of the ceiling
    else
      %modify depth of flooding to be 12 inches above flood depth
      TDEPTH=FFDEPTH+12-MINRPLDEPCNG(itm);
    end
  end
  %if the flood depth is over the minimum flood depth
  %failure limit associated with replacement of the item
  if FFDEPTH>= MINRPLDEP(itm);
    %if the flood duration is over the minimum flood duration
    %failure limit associated with replacement of the item
    if DUR(n)>=MINRPLDUR(itm);
      FAIL = 2;
    end
  end
  %if item requires repair, calculate repair cost of item
  if FAIL == 1;
```

```
    REPCOST(n)=REPCOST(n)+BLDGQTY(n,30)*(TDEPTH/12)*REPAIR(n,itm);
  end
  %if item requires replacement, calculate replacement cost of item
  if FAIL == 2;
    REPCOST(n)=REPCOST(n)+BLDGQTY(n,30)*(TDEPTH/12)*REPLACE(n,itm);
  end
end
%----------------------------------------------------------------------------------------------------------

%AREA COST CALCULATIONS HAVING TO DO WITH EXTERIOR COVERINGS OF
%EXTERIOR WALLS (I.E. SIDING, EXTERIOR PAINTING, INSULATION)-------------------------
if ATYPE(itm) == 4;
  FAIL=0;
  %if the flood duration is over the minimum flood duration
  %failure limit associated with repair of the item
  if DUR(n)>=MINRPRDUR(itm);
    FAIL = 1;
  end
  %if the flood depth is over the minimum flood depth
  %failure limit associated with repair of the item
  if FFDEPTH>= MINRPRDEP(itm);
    FAIL = 1;
    %if depth of flooding is within 12 inches of the first floor or
    %greater
    if FFDEPTH>=BLDGHTS(4)-12+MINRPLDEPCNG(itm);
      %modify the depth of flooding to be the height of the first
      %floor above the basement floor
      TDEPTH=BLDGHTS(4);
    %if depth of flooding is not within 12 inches of the first floor
    else
      %modify the depth of flooding to be 12 inches above flood depth
      TDEPTH=FFDEPTH+12-MINRPLDEPCNG(itm);
    end
  end
  %if the flood depth is over the minimum flood depth
  %failure limit associated with replacement of the item
  if FFDEPTH>= MINRPLDEP(itm);
    %if the flood duration is over the minimum flood duration
    %failure limit associated with replacement of the item
    if DUR(n)>=MINRPLDUR(itm);
      FAIL = 2;
    end
  end
  %if item requires repair, calculate repair cost of item
  if FAIL == 1;
    REPCOST(n)=REPCOST(n)+BLDGQTY(n,31)*(TDEPTH/12)*REPAIR(n,itm);
  end
  %if item requires replacement, calculate replacement cost of item
  if FAIL == 2;
    REPCOST(n)=REPCOST(n)+BLDGQTY(n,31)*(TDEPTH/12)*REPLACE(n,itm);
  end
end
```

```
%----------------------------------------------------------------------------------------------------------------------

%QUANTITY COST CALCULATIONS FOR WHICH REPAIR MAY BE CALCULATED FOR
%SPECIFIC DEPTHS AND REPLACEMENT FOR OTHER DEPTHS (I.E. APPLIANCES)-----------
if ATYPE(itm) == 5;
  %if item is located in the basement
  if BLDGHTS(ACODE(itm)) == 1
     FAIL = 0;
     %if the flood duration is over the minimum flood duration
     %failure limit associated with repair of the item
     if DUR(n)>=MINRPRDUR(itm);
       FAIL = 1;
     end
     %if the flood depth is over the minimum flood depth
     %failure limit associated with repair of the item
     if FFDEPTH>= MINRPRDEP(itm);
       FAIL = 1;
     end
     %if the flood depth is over the minimum flood depth
     %failure limit associated with replacement of the item
     if FFDEPTH>= MINRPLDEP(itm);
       %if the flood duration is over the minimum flood duration
       %failure limit associated with replacement of the item
       if DUR(n)>=MINRPLDUR(itm);
         FAIL = 2;
       end
     end
     %if item requires repair, calculate repair cost of item
     if FAIL == 1;
       REPCOST(n)=REPCOST(n)+REPAIR(n,itm);
     end
     %if item requires replacement, calculate replacement cost of item
     if FAIL == 2;
       REPCOST(n)=REPCOST(n)+REPLACE(n,itm);
     end
  end
end
%----------------------------------------------------------------------------------------------------------------------

%AREA COST CALCULATIONS HAVING TO DO WITH ITEMS ON THE CEILING
%(I.E. DRYWALL & LIGHT FIXTURES)--------------------------------------------------------------------
if ATYPE(itm) == 6;
   FAIL = 0;
   %if the flood duration is over the minimum flood duration
   %failure limit associated with repair of the item
   if DUR(n)>=MINRPRDUR(itm);
     FAIL = 1;
   end
   %if the flood depth is over the minimum flood depth
   %failure limit associated with repair of the item
   if FFDEPTH>= BLDGHTS(15)+MINRPRDEP(itm);
     FAIL = 1;
```

```
    end
    %if the flood depth is over the minimum flood depth
    %failure limit associated with replacement of the item
    if FFDEPTH>= BLDGHTS(15)+MINRPLDEP(itm);
      %if the flood duration is over the minimum flood duration
      %failure limit associated with replacement of the item
      if DUR(n)>=MINRPLDUR(itm);
        FAIL = 2;
      end
    end
    %if building item is attic insulation
    if itm == 33
      %if there is a 2nd floor
      if BLDGHTS(8) == 1
        %set to no failure of building item
        FAIL = 0;
      end
    end
    %if item requires repair, calculate repair cost of item
    if FAIL == 1;
      REPCOST(n)=REPCOST(n)+BLDGQTY(n,ACODE(itm))*REPAIR(n,itm);
    end
    %if item requires replacement, calculate replacement cost of item
    if FAIL == 2;
      REPCOST(n)=REPCOST(n)+BLDGQTY(n,ACODE(itm))*REPLACE(n,itm);
    end
  end
  %---------------------------------------------------------------------------------------------------------------------------

  %COST CALCULATIONS FOR PERSONAL PROPERTY LOSSES-----------------------------------------
  if ATYPE(itm) == 7;
    FAIL = 0;
    %if the flood duration is over the minimum flood duration
    %failure limit associated with repair of the items
    if DUR(n)>=MINRPRDUR(itm);
      FAIL = 1;
    end
    %if the flood depth is over the minimum flood depth
    %failure limit associated with repair of the items
    if FFDEPTH>= MINRPRDEP(itm);
      FAIL = 1;
    end
    %if the flood depth is over the minimum flood depth
    %failure limit associated with partial damage of personal items
    if FFDEPTH> MINRPLDEP(itm);
      %if the flood duration is over the minimum flood duration
      %failure limit associated complete damage of personal items
      if DUR(n)>=MINRPLDUR(itm);
        FAIL = 2;
      end
    end
    %if some personal items require replacement, calculate replacement of
```

```
  %a portion of personal items (includes hypothetical curve of
  %increasing damage with depth)
  if FAIL == 1;
    REPCOST(n)=REPCOST(n)+(1-5/...
      (((FFDEPTH/BLDGHTS(15))*100)+5))*BLDGQTY(n,ACODE(itm))...
      *REPLACE(n,itm);
  end
  %if all personal items are damaged
  if FAIL == 2;
    REPCOST(n)=REPCOST(n)+BLDGQTY(n,ACODE(itm))*REPLACE(n,itm);
  end
end
%------------------------------------------------------------------------------------------------------------------------
end
```

## *A5. Second Floor Flood Losses Subroutine*

```
%if building has a basement
if BLDGHTS(20)>0
  %set flood depth to zero at floor level
  SFDEPTH = DEPTH(n)-BLDGHTS(4)-BLDGHTS(5);
%if building does not have a basement
else
  %set flood depth to zero at floor level
  SFDEPTH = DEPTH(n)-BLDGHTS(4);
end

%do not allow any negative depth
if SFDEPTH <0
  SFDEPTH = 0;
end

%if flood reaches second floor level
if SFDEPTH > 0

%AREA COST CALCULATIONS WHEREIN DAMAGE IS TRUE OR FALES AND
%INDEPENDENT OF FLOOD DEPTH (I.E. FLOORING)--------------------------------------------------
if ATYPE(itm) == 1;
  FAIL = 0;
  %if building item is electrical outlets
  if itm == 35
    %if flood depth is above the height of the outlets
    if SFDEPTH>=MINRPLDEP(itm)+BLDGHTS(6)
      FAIL = 2;
    end
  %if building item is electrical switches
  elseif itm == 36
    %if flood depth is above the height of the switches
    if SFDEPTH>=MINRPLDEP(itm)+BLDGHTS(7)
```

```
      FAIL = 2;
    end
  %if not electrical switches or outlets
  else
    %if the flood depth is over the minimum flood depth
    %failure limit associated with repair of the item
    if SFDEPTH>= MINRPRDEP(itm);
      FAIL = 1;
    end
    %if the flood duration is over the minimum flood duration
    %failure limit associated with repair of the item
    if DUR(n)>=MINRPRDUR(itm);
      FAIL = 1;
    end
    %if the flood depth is over the minimum flood depth
    %failure limit associated with replacement of the item
    if SFDEPTH>= MINRPLDEP(itm);
      %if the flood duration is over the minimum flood duration
      %failure limit associated with replacement of the item
      if DUR(n)>=MINRPLDUR(itm);
        FAIL = 2;
      end
    end
  end
  %if item requires repair, calculate repair cost of item
  if FAIL == 1;
    REPCOST(n)=REPCOST(n)+BLDGQTY(n,SCODE(itm))*REPAIR(n,itm);
  end
  %if item requires replacement, calculate replacement cost of item
  if FAIL == 2;
    REPCOST(n)=REPCOST(n)+BLDGQTY(n,SCODE(itm))*REPLACE(n,itm);
  end
end
%-----------------------------------------------------------------------------------------------------------------------

%AREA COST CALCULATIONS HAVING TO DO WITH COVERINGS OF INTERIOR WALLS
%(I.E. DRYWALL & INTERIOR PAINTING)-----------------------------------------------------------------
if ATYPE(itm) == 2;
  FAIL=0;
  %if the flood duration is over the minimum flood duration
  %failure limit associated with repair of the item
  if DUR(n)>=MINRPRDUR(itm);
    FAIL = 1;
  end
  %if the flood depth is over the minimum flood depth
  %failure limit associated with repair of the item
  if SFDEPTH>= MINRPRDEP(itm);
    FAIL = 1;
    %if depth of flooding is within 36 inches of the ceiling
    if SFDEPTH>=BLDGHTS(9)-36+MINRPLDEPCNG(itm);
      %modify depth of flooding to be height of ceiling
      TDEPTH=BLDGHTS(9);
```

```
      %if flood depth is not within 36 inches of the ceiling
    else
      %modify depth of flooding to be 12 inches above flood depth
      TDEPTH=SFDEPTH+12-MINRPLDEPCNG(itm);
    end
  end
  %if the flood depth is over the minimum flood depth
  %failure limit associated with replacement of the item
  if SFDEPTH>= MINRPLDEP(itm);
    %if the flood duration is over the minimum flood duration
    %failure limit associated with replacement of the item
    if DUR(n)>=MINRPLDUR(itm);
      FAIL = 2;
    end
  end
  %if item requires repair, calculate repair cost of item
  if FAIL == 1;
    REPCOST(n)=REPCOST(n)+2*BLDGQTY(n,3)*(TDEPTH/12)*REPAIR(n,itm);
  end
  %if item requires replacement, calculate replacement cost of item
  if FAIL == 2;
    REPCOST(n)=REPCOST(n)+2*BLDGQTY(n,3)*(TDEPTH/12)*REPLACE(n,itm);
  end
end
%--------------------------------------------------------------------------------------------------------------------------

%AREA COST CALCULATIONS HAVING TO DO WITH INTERIOR COVERINGS OF
%EXTERIOR WALLS (I.E. DRYWALL & INTERIOR PAINTING)------------------------------------------
if ATYPE(itm) == 3;
  FAIL=0;
  %if the flood duration is over the minimum flood duration
  %failure limit associated with repair of the item
  if DUR(n)>=MINRPRDUR(itm);
    FAIL = 1;
  end
  %if the flood depth is over the minimum flood depth
  %failure limit associated with repair of the item
  if SFDEPTH>= MINRPRDEP(itm);
    FAIL = 1;
    %if depth of flooding is within 36 inches of the ceiling or greater
    if SFDEPTH>=BLDGHTS(9)-36+MINRPLDEPCNG(itm);
      %modify depth of flooding to be height of ceiling
      TDEPTH=BLDGHTS(9);
    %if flood depth is not within 36 inches of the ceiling
    else
      %modify depth of flooding to be 12 inches above flood depth
      TDEPTH=SFDEPTH+12-MINRPLDEPCNG(itm);
    end
  end
  %if the flood depth is over the minimum flood depth
  %failure limit associated with replacement of the item
  if SFDEPTH>= MINRPLDEP(itm);
```

```
    %if the flood duration is over the minimum flood duration
    %failure limit associated with replacement of the item
    if DUR(n)>=MINRPLDUR(itm);
      FAIL = 2;
    end
  end
  %if item requires repair, calculate repair cost of item
  if FAIL == 1;
    REPCOST(n)=REPCOST(n)+BLDGQTY(n,4)*(TDEPTH/12)*REPAIR(n,itm);
  end
  %if item requires replacement, calculate replacement cost of item
  if FAIL == 2;
    REPCOST(n)=REPCOST(n)+BLDGQTY(n,4)*(TDEPTH/12)*REPLACE(n,itm);
  end
end
%-----------------------------------------------------------------------------------------------------------------------

%AREA COST CALCULATIONS HAVING TO DO WITH EXTERIOR COVERINGS OF
%EXTERIOR WALLS (I.E. SIDING, EXTERIOR PAINTING, INSULATION)----------------------------
if ATYPE(itm) == 4;
  FAIL=0;
  %if the flood duration is over the minimum flood duration
  %failure limit associated with repair of the item
  if DUR(n)>=MINRPRDUR(itm);
    FAIL = 1;
  end
  %if the flood depth is over the minimum flood depth
  %failure limit associated with repair of the item
  if SFDEPTH>= MINRPRDEP(itm);
    FAIL = 1;
    %if depth of flooding is within 12 inches of the first floor or
    %greater
    if SFDEPTH>=BLDGHTS(9)-12+MINRPLDEPCNG(itm);
      %modify the depth of flooding to be the height of the first
      %floor above the basement floor
      TDEPTH=BLDGHTS(9);
    %if depth of flooding is not within 12 inches of the first floor
    else
      %modify the depth of flooding to be 12 inches above flood depth
      TDEPTH=SFDEPTH+12-MINRPLDEPCNG(itm);
    end
  end
  %if the flood depth is over the minimum flood depth
  %failure limit associated with replacement of the item
  if SFDEPTH>= MINRPLDEP(itm);
    %if the flood duration is over the minimum flood duration
    %failure limit associated with replacement of the item
    if DUR(n)>=MINRPLDUR(itm);
      FAIL = 2;
    end
  end
  %if item requires repair, calculate repair cost of item
```

```
  if FAIL == 1;
    REPCOST(n)=REPCOST(n)+BLDGQTY(n,5)*(TDEPTH/12)*REPAIR(n,itm);
  end
  %if item requires replacement, calculate replacement cost of item
  if FAIL == 2;
    REPCOST(n)=REPCOST(n)+BLDGQTY(n,5)*(TDEPTH/12)*REPLACE(n,itm);
  end
end
%-----------------------------------------------------------------------------------------------------------------------

%QUANTITY COST CALCULATIONS FOR WHICH REPAIR MAY BE CALCULATED FOR
%SPECIFIC DEPTHS AND REPLACEMENT FOR OTHER DEPTHS (I.E. APPLIANCES)------------
if ATYPE(itm) == 5;
  %if item is located in the basement
  if BLDGHTS(SCODE(itm)) == 2
    FAIL = 0;
    %if the flood duration is over the minimum flood duration
    %failure limit associated with repair of the item
    if DUR(n)>=MINRPRDUR(itm);
      FAIL = 1;
    end
    %if the flood depth is over the minimum flood depth
    %failure limit associated with repair of the item
    if SFDEPTH>= MINRPRDEP(itm);
      FAIL = 1;
    end
    %if the flood depth is over the minimum flood depth
    %failure limit associated with replacement of the item
    if SFDEPTH>= MINRPLDEP(itm);
      %if the flood duration is over the minimum flood duration
      %failure limit associated with replacement of the item
      if DUR(n)>=MINRPLDUR(itm);
        FAIL = 2;
      end
    end
    %if item requires repair, calculate repair cost of item
    if FAIL == 1;
      REPCOST(n)=REPCOST(n)+REPAIR(n,itm);
    end
    %if item requires replacement, calculate replacement cost of item
    if FAIL == 2;
      REPCOST(n)=REPCOST(n)+REPLACE(n,itm);
    end
  end
end
%-----------------------------------------------------------------------------------------------------------------------

%AREA COST CALCULATIONS HAVING TO DO WITH ITEMS ON THE CEILING
%(I.E. DRYWALL & LIGHT FIXTURES)-------------------------------------------------------------------------
if ATYPE(itm) == 6;
  FAIL = 0;
  %if the flood duration is over the minimum flood duration
```

```
  %failure limit associated with repair of the item
  if DUR(n)>=MINRPRDUR(itm);
    FAIL = 1;
  end
  %if the flood depth is over the minimum flood depth
  %failure limit associated with repair of the item
  if SFDEPTH>= BLDGHTS(9)+MINRPRDEP(itm);
    FAIL = 1;
  end
  %if the flood depth is over the minimum flood depth
  %failure limit associated with replacement of the item
  if SFDEPTH>= BLDGHTS(9)+MINRPLDEP(itm);
    %if the flood duration is over the minimum flood duration
    %failure limit associated with replacement of the item
    if DUR(n)>=MINRPLDUR(itm);
      FAIL = 2;
    end
  end
  %if item requires repair, calculate repair cost of item
  if FAIL == 1;
    REPCOST(n)=REPCOST(n)+BLDGQTY(n,SCODE(itm))*REPAIR(n,itm);
  end
  %if item requires replacement, calculate replacement cost of item
  if FAIL == 2;
    REPCOST(n)=REPCOST(n)+BLDGQTY(n,SCODE(itm))*REPLACE(n,itm);
  end
end
%-------------------------------------------------------------------------------------------------------------------

%COST CALCULATIONS FOR PERSONAL PROPERTY LOSSES-----------------------------------------
if ATYPE(itm) == 7;
  FAIL = 0;
  %if the flood duration is over the minimum flood duration
  %failure limit associated with repair of the items
  if DUR(n)>=MINRPRDUR(itm);
    FAIL = 1;
  end
  %if the flood depth is over the minimum flood depth
  %failure limit associated with repair of the items
  if SFDEPTH>= MINRPRDEP(itm);
    FAIL = 1;
  end
  %if the flood depth is over the minimum flood depth
  %failure limit associated with partial damage of personal items
  if SFDEPTH> MINRPLDEP(itm);
    %if the flood duration is over the minimum flood duration
    %failure limit associated complete damage of personal items
    if DUR(n)>=MINRPLDUR(itm);
      FAIL = 2;
    end
  end
  %if some personal items require replacement, calculate replacement of
```

```
  %a portion of personal items (includes hypothetical curve of
  %increasing damage with depth)
  if FAIL == 1;
    REPCOST(n)=REPCOST(n)+(1-5/...
      (((SFDEPTH/BLDGHTS(9))*100)+5))*BLDGQTY(n,SCODE(itm))...
      *REPLACE(n,itm);
  end
  %if all personal items are damaged
  if FAIL == 2;
    REPCOST(n)=REPCOST(n)+BLDGQTY(n,SCODE(itm))*REPLACE(n,itm);
  end
end
%-----------------------------------------------------------------------------------------------------------------
end
```

# A6. Input Files

## A6.1 Cost data and associative code file

This table includes labels in the top two rows and leftmost one column which are for clarification and are not actually included in the input file. The file has been split into two parts between columns 9 and 10.

| Column Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| | Material Code | Minimum Repair Vales | Maximum Repair Values | Minimum Replacement Values | Maximum Replacement Values | Area calculation type | 2nd Floor Area Lookup Code | 1st Floor Area Lookup Code | Basement Area Lookup Code |
| Drywall Interior Walls | 1 | 0 | 0 | 1.48 | 2.36 | 2 | 0 | 0 | 0 |
| Drywall Exterior Walls | 2 | 0 | 0 | 1.48 | 2.36 | 3 | 0 | 0 | 0 |
| Interior Painting Interior Walls | 3 | 0 | 0 | 0.37 | 3.67 | 2 | 0 | 0 | 0 |
| Interior Painting Exterior Walls | 4 | 0 | 0 | 0.37 | 3.67 | 3 | 0 | 0 | 0 |
| Baseboard | 5 | 0 | 0 | 3.08 | 6.16 | 1 | 16 | 42 | 68 |
| Carpet | 6 | 0 | 0 | 2.63 | 9.13 | 1 | 6 | 32 | 58 |
| Tile Flooring | 7 | 0 | 0 | 8.67 | 14.57 | 1 | 7 | 33 | 59 |
| Wood Flooring | 8 | 0 | 0 | 5.46 | 21.09 | 1 | 9 | 35 | 61 |
| Vinyl Flooring | 9 | 0 | 0 | 3.33 | 5.33 | 1 | 8 | 34 | 60 |
| Lower Cabinets | 10 | 0 | 0 | 133.20 | 295.20 | 1 | 10 | 36 | 62 |
| Upper Cabinets | 11 | 0 | 0 | 133.20 | 295.20 | 1 | 11 | 37 | 63 |
| Counters | 12 | 0 | 0 | 23.00 | 120.00 | 1 | 10 | 36 | 62 |
| Exterior Painting | 13 | 0 | 0 | 1.17 | 1.65 | 4 | 5 | 31 | 57 |
| Siding | 14 | 0 | 0 | 2.74 | 6.61 | 4 | 5 | 31 | 57 |
| Windows (above ground) | 15 | 0 | 0 | 209.20 | 418.20 | 1 | 12 | 38 | 0 |
| Windows (basement) | 16 | 0 | 0 | 209.20 | 418.20 | 1 | 0 | 0 | 64 |
| Interior Doors | 17 | 0 | 0 | 201.40 | 321.40 | 1 | 13 | 39 | 65 |
| Exterior Doors | 18 | 0 | 0 | 360.50 | 1820.50 | 1 | 14 | 40 | 66 |
| Closet Doors | 19 | 0 | 0 | 174.00 | 570.00 | 1 | 15 | 41 | 67 |
| Garage Door | 20 | 0 | 0 | 475.00 | 2200.00 | 1 | 0 | 53 | 0 |
| Trim Board | 21 | 0 | 0 | 3.08 | 6.16 | 1 | 83 | 97 | 111 |
| Furnace | 22 | 150 | 500 | 1125.00 | 2250.00 | 5 | 24 | 24 | 24 |
| Air Conditioning | 23 | 150 | 500 | 2645.00 | 3650.00 | 5 | 25 | 25 | 25 |
| Water Heater | 24 | 150 | 250 | 600.00 | 1850.00 | 5 | 26 | 26 | 26 |
| Washer and Dryer | 25 | 250 | 500 | 1575.00 | 2420.00 | 5 | 27 | 27 | 27 |
| Range | 26 | 0 | 0 | 340.00 | 3500.00 | 5 | 28 | 28 | 28 |
| Refrigerator | 27 | 0 | 0 | 450.00 | 4000.00 | 5 | 29 | 29 | 29 |
| Garbage Disposal | 28 | 0 | 0 | 139.00 | 251.00 | 5 | 30 | 30 | 30 |
| Dishwasher | 29 | 0 | 0 | 505.00 | 1500.00 | 5 | 31 | 31 | 31 |
| Vented Hood | 30 | 0 | 0 | 218.00 | 880.00 | 5 | 32 | 32 | 32 |
| Ceiling | 31 | 0 | 0 | 1.48 | 2.36 | 6 | 2 | 28 | 79 |
| Insulation (walls) | 32 | 0 | 0 | 0.51 | 0.78 | 3 | 5 | 31 | 57 |
| Insulation (attic) | 33 | 0 | 0 | 0.74 | 1.26 | 6 | 2 | 28 | 54 |
| Stairs | 34 | 0 | 0 | 580.00 | 5000.00 | 1 | 18 | 44 | 70 |
| Electricals Outlets | 35 | 0 | 0 | 48.95 | 48.95 | 1 | 80 | 94 | 108 |
| Electricals Switches | 36 | 0 | 0 | 42.40 | 56.00 | 1 | 81 | 95 | 109 |
| Electricals Light Fixtures | 37 | 0 | 0 | 238.35 | 348.00 | 6 | 82 | 96 | 110 |
| Electrical Box | 38 | 0 | 0 | 2874.00 | 3120.00 | 5 | 33 | 33 | 33 |
| Exterior Sheathing | 39 | 0 | 0 | 0.91 | 1.27 | 4 | 5 | 31 | 57 |
| Joists | 40 | 0 | 0 | 2.67 | 3.58 | 6 | 2 | 28 | 54 |
| Subflooring | 41 | 0 | 0 | 1.12 | 1.40 | 1 | 2 | 28 | 54 |
| Framing | 42 | 0 | 0 | 1.00 | 1.41 | 2 | 0 | 0 | 0 |
| Cleaning Products | 43 | 0 | 0 | 1.11 | 1.11 | 1 | 2 | 28 | 54 |
| Personal Loss | 44 | 0 | 0 | 0.00 | 0.00 | 7 | 2 | 28 | 54 |

| Column Number | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|
| | Second Floor Switch | First Floor Switch | Basement Switch | Minimum Repair Depth | Maximum Repair Depth | Minimum Replacement Depth | Minimum Repair Flood Duration | Maximum Repair Flood Duration | Minimum Replacement Duration |
| Drywall Interior Walls | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 144 |
| Drywall Exterior Walls | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| Interior Painting Interior Walls | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 36 |
| Interior Painting Exterior Walls | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| Baseboard | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 36 |
| Carpet | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| Tile Flooring | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 144 |
| Wood Flooring | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 36 |
| Vinyl Flooring | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 36 |
| Lower Cabinets | 1 | 1 | 1 | 0 | 0 | 3 | 0 | 0 | 36 |
| Upper Cabinets | 1 | 1 | 1 | 0 | 0 | 52 | 0 | 0 | 36 |
| Counters | 1 | 1 | 1 | 0 | 0 | 34 | 0 | 0 | 36 |
| Exterior Painting | 1 | 1 | 0 | 0 | 0 | 6 | 0 | 0 | 36 |
| Siding | 1 | 1 | 0 | 0 | 0 | 6 | 0 | 0 | 144 |
| Windows (above ground) | 1 | 1 | 0 | 0 | 0 | 40 | 0 | 0 | 144 |
| Windows (basement) | 0 | 0 | 1 | 0 | 0 | 40 | 0 | 0 | 144 |
| Interior Doors | 1 | 1 | 1 | 0 | 0 | 6 | 0 | 0 | 36 |
| Exterior Doors | 1 | 1 | 0 | 0 | 0 | 6 | 0 | 0 | 36 |
| Closet Doors | 1 | 1 | 1 | 0 | 0 | 3 | 0 | 0 | 36 |
| Garage Door | 0 | 1 | 0 | 6 | 12 | 12 | 0 | 0 | 192 |
| Trim Board | 1 | 1 | 1 | 0 | 0 | 6 | 0 | 0 | 36 |
| Furnace | 1 | 1 | 1 | 10 | 20 | 20 | 0 | 0 | 0 |
| Air Conditioning | 1 | 1 | 1 | 4 | 10 | 10 | 0 | 0 | 0 |
| Water Heater | 1 | 1 | 1 | 2 | 4 | 4 | 0 | 0 | 0 |
| Washer and Dryer | 1 | 1 | 1 | 4 | 12 | 12 | 0 | 0 | 0 |
| Range | 1 | 1 | 1 | 18 | 24 | 24 | 0 | 0 | 0 |
| Refrigerator | 1 | 1 | 1 | 8 | 12 | 12 | 0 | 0 | 0 |
| Garbage Disposal | 1 | 1 | 1 | 16 | 20 | 20 | 0 | 0 | 0 |
| Dishwasher | 1 | 1 | 1 | 4 | 12 | 12 | 0 | 0 | 0 |
| Vented Hood | 1 | 1 | 1 | 62 | 64 | 64 | 0 | 0 | 0 |
| Ceiling | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 144 |
| Insulation (walls) | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| Insulation (attic) | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Stairs | 0 | 1 | 1 | 6 | 12 | 12 | 0 | 0 | 192 |
| Electricals Outlets | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Electricals Switches | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Electricals Light Fixtures | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Electrical Box | 1 | 1 | 1 | 0 | 0 | 48 | 0 | 0 | 0 |
| Exterior Sheathing | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 192 |
| Joists | 0 | 1 | 1 | 0 | 0 | 3 | 0 | 0 | 192 |
| Subflooring | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 192 |
| Framing | 1 | 1 | 1 | 0 | 0 | 6 | 0 | 0 | 192 |
| Cleaning Products | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| Personal Loss | 1 | 1 | 1 | 1 | 48 | 48 | 0 | 0 | 0 |

## A6.2 Building dimensional data file

The information for this file is included in completeness previously in tables 13 through 16, however, an example is included herein to demonstrate the formatting of the file.

| | | |
|---|---|---|
| 2608 | % | Total area of building |
| 0 | % | Area of 2nd floor |
| 0 | % | Length of interior walls (2nd floor) |
| 0 | % | Total length of exterior walls covered on the interior surface (2nd floor) |
| 0 | % | Total length of exterior walls covered on the exterior surface (2nd floor) |
| 0 | % | Area of carpet (2nd floor) |
| 0 | % | Area of tile flooring (2nd floor) |
| 0 | % | Area of vinyl flooring (2nd floor) |
| 0 | % | Area of wood flooring (2nd floor) |
| 0 | % | Length of lower cabinets (2nd floor) |
| 0 | % | Length of upper cabinets (2nd floor) |
| 0 | % | Number of windows (2nd floor) |
| 0 | % | Number of interior doors (2nd floor) |
| 0 | % | Number of exterior doors (2nd floor) |
| 0 | % | Number of closet doors (2nd floor) |
| 0 | % | Length of baseboard (2nd floor) |
| 0 | % | Value of personal items (2nd floor) |
| 0 | % | Not used |
| 0 | % | Blank 2 |
| 0 | % | Blank 3 |
| 0 | % | Blank 4 |
| 0 | % | Blank 5 |
| 0 | % | Blank 6 |
| 0 | % | Blank 7 |
| 0 | % | Blank 8 |
| 0 | % | Blank 9 |
| 0 | % | Blank 10 |
| 1304 | % | Area of 1st floor |
| 137 | % | Length of interior walls (1st floor) |
| 146 | % | Total length of exterior walls covered on the interior surface (1st floor) |
| 164 | % | Total length of exterior walls covered on the exterior surface (1st floor) |
| 992 | % | Area of carpet (1st floor) |
| 72 | % | Area of tile flooring (1st floor) |
| 96 | % | Area of vinyl flooring (1st floor) |
| 144 | % | Area of wood flooring (1st floor) |

| | | |
|---|---|---|
| 33 | % | Length of lower cabinets (1st floor) |
| 18 | % | Length of upper cabinets (1st floor) |
| 7 | % | Number of windows (1st floor) |
| 4 | % | Number of interior doors (1st floor) |
| 2 | % | Number of exterior doors (1st floor) |
| 8 | % | Number of closet doors (1st floor) |
| 420 | % | Length of baseboard (1st floor) |
| 0 | % | Value of personal items (1st floor) |
| 0 | % | Number of staircases (1st floor) |
| 0 | % | Blank 2 |
| 0 | % | Blank 3 |
| 0 | % | Blank 4 |
| 0 | % | Blank 5 |
| 0 | % | Blank 6 |
| 0 | % | Blank 7 |
| 0 | % | Blank 8 |
| 0 | % | Blank 9 |
| 0 | % | Number of Garage Doors |
| 1304 | % | Area of basement |
| 110 | % | Length of interior walls (basement) |
| 137 | % | Total length of exterior walls covered on the interior surface (basement) |
| 0 | % | Total length of exterior walls covered on the exterior surface (basement) |
| 1018 | % | Area of carpet (basement) |
| 0 | % | Area of tile flooring (basement) |
| 102 | % | Area of vinyl flooring (basement) |
| 0 | % | Area of wood flooring (basement) |
| 3 | % | Length of lower cabinets (basement) |
| 0 | % | Length of upper cabinets (basement) |
| 5 | % | Number of windows (basement) |
| 5 | % | Number of interior doors (basement) |
| 0 | % | Number of exterior doors (basement) |
| 5 | % | Number of closet doors (basement) |
| 357 | % | Length of baseboard (basement) |
| 0 | % | Value of personal items (basement) |
| 1 | % | Number of staircases (basement) |
| 0 | % | Blank 2 |
| 0 | % | Blank 3 |
| 0 | % | Blank 4 |
| 0 | % | Blank 5 |
| 0 | % | Blank 6 |
| 0 | % | Blank 7 |
| 0 | % | Blank 8 |
| 0 | % | Blank 9 |
| 1120 | % | SF Finished (basement) |

| | | |
|---|---|---|
| 0 | % | Number of outlets (2nd floor) |
| 0 | % | Number of switches (2nd floor) |
| 0 | % | Number of light fixtures (2nd floor) |
| 0 | % | Length of trim board (2nd floor) |
| 0 | % | Blank 1 |
| 0 | % | Blank 2 |
| 0 | % | Blank 3 |
| 0 | % | Blank 4 |
| 0 | % | Blank 5 |
| 0 | % | Blank 6 |
| 0 | % | Blank 7 |
| 0 | % | Blank 8 |
| 0 | % | Blank 9 |
| 0 | % | Blank 10 |
| 52 | % | Number of outlets (1st floor) |
| 16 | % | Number of switches (1st floor) |
| 21 | % | Number of light fixtures (1st floor) |
| 336 | % | Length of trim board (1st floor) |
| 0 | % | Blank 1 |
| 0 | % | Blank 2 |
| 0 | % | Blank 3 |
| 0 | % | Blank 4 |
| 0 | % | Blank 5 |
| 0 | % | Blank 6 |
| 0 | % | Blank 7 |
| 0 | % | Blank 8 |
| 0 | % | Blank 9 |
| 0 | % | Blank 10 |
| 44 | % | Number of outlets (basement) |
| 14 | % | Number of switches (basement) |
| 19 | % | Number of light fixtures (basement) |
| 240 | % | Length of trim board (basement) |
| 0 | % | Blank 1 |
| 0 | % | Blank 2 |
| 0 | % | Blank 3 |
| 0 | % | Blank 4 |
| 0 | % | Blank 5 |
| 0 | % | Blank 6 |
| 0 | % | Blank 7 |
| 0 | % | Blank 8 |
| 0 | % | Blank 9 |
| 0 | % | Blank 10 |

## A6.3 Building item locations and heights

The information for this file is also included in completeness previously in tables 13 through 16, with an example included herein to demonstrate the formatting of the file. The locations of the appliances by floor are defined as zero for the basement, one for the first floor and two for the second floor.

| | | |
|---|---|---|
| 0 | % | Not used |
| 0 | % | Not used |
| 0 | % | Not used |
| 108 | % | Height of second floor above first floor |
| 108 | % | Height of first floor above basement |
| 12 | % | Electrical outlet height (2nd floor) |
| 48 | % | Electrical switch height (2nd floor) |
| 0 | % | Does building have a 2nd floor |
| 96 | % | Ceiling height (2nd floor) |
| 0 | % | Blank 3 |
| 0 | % | Blank 4 |
| 12 | % | Electrical outlet height (1st floor) |
| 48 | % | Electrical switch height (1st floor) |
| 1 | % | Does building have a 1st floor |
| 96 | % | Ceiling height (1st floor) |
| 0 | % | Blank 3 |
| 0 | % | Blank 4 |
| 12 | % | Electrical outlet height (basement) |
| 48 | % | Electrical switch height (basement) |
| 1 | % | Does building have a basement |
| 96 | % | Ceiling height (basement) |
| 0 | % | Blank 3 |
| 0 | % | Blank 4 |
| 0 | % | Location of furnace (floor) |
| 1 | % | Location of AC compressor (floor) |
| 0 | % | Location of water heater (floor) |
| 0 | % | Location of washer and dryer (floor) |
| 1 | % | Location of range (floor) |
| 1 | % | Location of refrigerator (floor) |
| 1 | % | Location of garbage disposal (floor) |
| 1 | % | Location of dishwasher (floor) |
| 1 | % | Location of vented hood (floor) |
| 0 | % | Location of electrical panel box (floor) |
| 0 | % | Blank 1 |
| 0 | % | Blank 2 |
| 0 | % | Blank 3 |
| 0 | % | Blank 4 |

## A6.4 Changeable input file

| | | |
|---|---|---|
| 99832 | % | Home value |
| 24 | % | Duration of flooding |
| 100 | % | Max flood depth |
| 0.01 | % | Building demensional uncertainty (COV) |
| 1 | % | Location cost multiplier |
| 20 | % | Number of Trials |
| 2 | % | Flood increment distance (inches) |
| 0 | % | Blank 1 |
| 0 | % | Blank 2 |
| 0 | % | Blank 3 |
| 0 | % | Blank 4 |
| 0 | % | Blank 5 |
| 0 | % | Quantity to increase floor to floor height between basement and 1st floor (inches) |
| 0 | % | Quantity to increase floor to floor height between 1st floor and 2nd floor (inches) |
| 0 | % | REMAINDER ARE ON IF > 0 OR OFF IF EQUAL TO 0 |
| 0 | % | Raise entire house 2 feet |
| 0 | % | Raise electrical switches, outlets to 60 inches and panel box to 72 inches |
| 0 | % | Raise furnace, water heater, AC compressor and washer and dryer by 18 inches |
| 0 | % | Modify insulation |
| 0 | % | Modify siding |
| 0 | % | Other mitigation 1 |
| 0 | % | Other mitigation 2 |
| 0 | % | Other mitigation 3 |
| 0 | % | Other mitigation 4 |
| 0 | % | Other mitigation 5 |
| 0 | % | Other mitigation 6 |
| 0 | % | Other mitigation 7 |
| 0 | % | Other mitigation 8 |
| 0 | % | Other mitigation 9 |
| 0 | % | Other mitigation 10 |
| 0 | % | Other mitigation 11 |
| 0 | % | Other mitigation 12 |
| 0 | % | Other mitigation 13 |
| 0 | % | Other mitigation 14 |
| 0 | % | Other mitigation 15 |
| 0 | % | Other mitigation 16 |
| 0 | % | Other mitigation 17 |
| 0 | % | Other mitigation 18 |
| 0 | % | Other mitigation 19 |
| 0 | % | Other mitigation 20 |

## A6.5 Quantitative mitigation technique file

This table includes labels in the top 2 rows and leftmost one column which are for clarification and are not actually included in the input file; the input file also extends to include 20 different mitigation techniques for a total of 40 columns.

| | Raising House (Mitigation Technique #1) | Raising House (Mitigation Technique #1) | Raising Electricals (Mitigation Technique #2) | Raising Electricals (Mitigation Technique #2) | Raising Appliances (Mitigation Technique #3) | Raising Appliances (Mitigation Technique #3) | Change Wall Insulation Type (Mitigation Technique #4) | Change Wall Insulation Type (Mitigation Technique #4) | Extra Mitigation Technique (continuing to # 20) | Extra Mitigation Technique (continuing to #20) |
|---|---|---|---|---|---|---|---|---|---|---|
| | Depth Change | Duration Change | Depth Change | Duration Change | Depth Change | Duration Change | Depth Change | Duration Change | Depth Change | Duration Change |
| Drywall Interior Walls | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Drywall Exterior Walls | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 144 | 0 | 0 |
| Interior Painting Interior Walls | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Interior Painting Exterior Walls | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 36 | 0 | 0 |
| Baseboard | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Carpet | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Tile Flooring | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Wood Flooring | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Vinyl Flooring | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Lower Cabinets | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Upper Cabinets | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Counters | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Exterior Painting | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Siding | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Windows (above ground) | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Windows (basement) | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Interior Doors | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Exterior Doors | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Closet Doors | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Garage Door | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Trim Board | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Furnace | 24 | 0 | 0 | 0 | 18 | 0 | 0 | 0 | 0 | 0 |
| Air Conditioning | 24 | 0 | 0 | 0 | 18 | 0 | 0 | 0 | 0 | 0 |
| Water Heater | 24 | 0 | 0 | 0 | 18 | 0 | 0 | 0 | 0 | 0 |
| Washer and Dryer | 24 | 0 | 0 | 0 | 18 | 0 | 0 | 0 | 0 | 0 |
| Range | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Refrigerator | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Garbage Disposal | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Dishwasher | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Vented Hood | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Ceiling | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Insulation (walls) | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 1000 | 0 | 0 |
| Insulation (attic) | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Stairs | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Electricals Outlets | 24 | 0 | 48 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Electricals Switches | 24 | 0 | 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Electricals Light Fixtures | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Electrical Box | 24 | 0 | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Exterior Sheathing | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Joists | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Subflooring | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Framing | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cleaning Products | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Personal Loss | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

## A6.6 File length file

The file length file simply tells MATLAB how many rows are in each file.

```
 44  %     Cost data file (A6.1)
121  %     Dimensions file (A6.2)
 37  %     Location file (A6.3)
 50  %     Changeable input file (A6.4)
 40  %     Quantitative mitigation file (A6.5)
```

# *A7 Program user guide*

This section walks through how to use the MATLAB program presented in this study.

## A7.1 General Instructions

1. Make sure all program files have the extension *.m and all input files have the extension *.txt.
2. Make sure all program and input files are located in the same directory.
3. Type the filename of the main program file (A6.2), without the extension, in the command line of MATLAB
4. A chart of fragility curves will appear with curves representing a 50%, 10% and 5% probability of exceedance (these curves will remain present throughout future runs if the chart window is not closed)

5. An ASCII file of percentage damages will appear called Losses and it will include 4 columns, the first of which will be the depth of flooding and the second will be the associated percent damage with a 50% PE and the third will be the percent damage with a 10% PE and the fourth will be the percent damage with a 5% PE.

## A7.2 Modifying the Cost data and associative code file

Appendix A6.1 can be used to understand the makeup of this file. This file can be used for many trials and needs most necessarily to be updated as construction costs increase or as more information is known about the duration or depth of failures of various building items.

1. To change minimum and maximum repair costs, modify the 2nd and 3rd numeric columns as desired (dollar values).
2. To change minimum and maximum replacement costs, modify the 4th and 5th numeric columns as desired (dollar values).
3. To change depth repair and replacement failure limits, modify 13th, 14th and 15th numeric columns as desired (depth in inches)
4. To change the duration repair and replacement failure limits, modify the 16th, 17th and 18th numeric columns as desired (duration in hours)
5. Other information:
    a. Numeric column 6 is used to determine the type of damage calculation used within each subroutine

b. Numeric columns 7, 8 and 9 are used as building item lookup values corresponding to the row number of the building dimensional data file.

c. Numeric columns 10, 11 and 12 are to turn on the specific building item for the 2nd floor, 1st floor and basement, respectively.

## A7.3 Modifying the Building dimensional data file and the Building item locations and heights file

These files are self explanatory as each row is labeled and each value should be carefully entered according to the specific home design of concern. This file needs to be changed with each new home design considered.

## A7.4 Modifying the Changeable input file

This file consists of the most commonly changed items and can be left open while running the program so that it can easily be changed and the program re-run to make comparisons of various options. This file includes the overall value of the home, the mean duration of flooding in hours, the maximum depth to which the program will consider the building to be flooded, an uncertainty value which can be added to all building dimensional data, a location cost multiplier to be used if the area of concern is known to have a higher or lower than average cost of construction, The number of trials which the computer will run through for each flood depth increment, the flood depth increment which is the change in flood depth between each set of trials, and various mitigation techniques which can either be turned on by entering a one or turned off by entering a two.

## A7.5 Modifying the Quantitative mitigation technique file

Appendix A6.5 can be used to clarify the values in this file. Each set of two consecutive columns is a single mitigation technique which will be turned on by the changeable input file. The first of the set of columns is the depth in inches which will be added to the failure depth of a specific building item and the second set of columns is the duration in hours which will be added to the failure duration of a specific building item. With modifications to these values it is possible to essentially raise various building items or to consider an upgrade which will increase the duration of flooding to which a building item may be exposed without sustaining damage.