Probabilistic Evaluation of Flood Damage in Buildings

by

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Diplôme d'Ingénieur, 2014
Ecole Spéciale des Travaux Publics, Paris

Submitted to the Department of Civil and Environmental Engineering Partial Fulfillment
of the Requirements for the Degree of

Master of Engineering in Civil and Environmental Engineering
at the
Massachusetts Institute of Technology

June 2014

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Abstract

Because the ocean level keeps rising and because hurricanes and storms become increasingly destructive in terms of damage and economic loss, the built environment has become very vulnerable to floods. Every city is building a resilient plan to decrease its vulnerability. However, the studies are often reduced to case studies and if engineers manage to build smarter, to upgrade or strengthen existing systems, they do not necessarily evaluate accurately their effect on damage.

This is why this thesis starts by identifying the key factors that define and impact flood damage, then defining other parameters that are more oriented towards resilience. Based on these considerations, a probabilistic evaluation of flood damage in buildings can be conducted and the sensitivity of each parameter is evaluated in order to reduce the total loss. Then a new objective becomes to find how modifying parameters, and consequently the structure, leads to less damage without losing its cost-effectiveness.

The first thesis' aim was to evaluate flood damage on buildings. However, building's damage is more diverse than expected and evaluating flood damage effect turns out to be actually only the beginning in the process of resilience.

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Acknowledgements

I would like to thank Dr Pierre Ghisbain for his guidance and constant support to complete this thesis. His encouragements and confidence in me were the driving forces in my research. I would also like to thank Professor Jerome Connor for his advice, support and patience throughout my time at MIT.

At 23 years old, knowing what we want to do later is not always easy and I would like to thank my family for their constant support in my reflection. I know that this year was intense not only for me but also for them constantly trying to help me even far from me. I took the decision to leave home to make them proud of me, and despite all my whims, I hope they are.

To finish, I would like to thank 3 MIT students that have taken an important place in my MIT life Renata, Cecile, and Virgile. This year without their constant help and support would have never been the same. The long nights spent with the Meng students will provide a long lasting memory.

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1 Introduction

The increase in the frequency and intensity of natural hazards results in a rise in damages and victims all over the world. Moreover, according the Intergovernmental Panel on Climate Change (IPCC, 2007), that climate change will continue to worsen. One type of hazard that has become particularly frequent these years and that has caused significant damage is flood. The latest highly-publicized catastrophic flood event occurred in October 2012 during the Hurricane Sandy which struck the Atlantic coastline of the U.S. It resulted in structural damage and caused the shutdown of New York City because of its flooded streets, tunnels and subways. What is striking is that flood hazard causes not only direct physical damage on infrastructure and buildings but also social and indirect economic losses. After a flood, a weakened building is not necessarily habitable thus its inhabitants might need to be relocated until repairs are completed. This temporary situation has a cost for society that cannot be neglected.

Because the consequences of floods are more than structural, a new approach, which would also include both human safety and economy, needed to be considered. Now, studying the resistance of buildings and infrastructures to flood impacts is no longer adequate and a resilience approach is necessary. Indeed, Resistance only refers to its ability to withstand to and remain unchanged whereas Resilience in buildings refers to its ability to recover after a disaster and how efficiently it can be made operable again. For a building that must resist to natural disasters, improving its resilience consists of developing its resistance to collapse, and being habitable afterwards. As a result a new management approach needs to be adopted (Thomas Naumann et al., 2011). As resilience does not only concern physical damage to built structures it is necessary to evaluate flood impacts as a potential loss to society.

However, while good progress in design is conducted to upgrade structural design against loads, the loss reduction and the evaluation of potential damage is often disregarded. As a result, this thesis is aiming first to set a methodology that could help engineers to evaluate how resilient the structure is. Numerous study cases have already been done about flood hazards. One which particularly inspired me was a recent study in Rotterdam in which the loss estimation process is very similar to the one described in the following. (H.Moel et al., 2013) However, none of the case studies provides a general methodology that could be applicable and adaptable to each case. It often tackles the problem by trying to build smarter, to upgrade or strengthen an existing and particular asset, but without making progress on analysis or assessment method. This is why this thesis aims at implementing a simple procedure to evaluate flood damage. Once the damage is evaluated, it is interesting to try to ameliorate each parameter in order to decrease damage. This is a critical step toward resilience.

To study resilience on a building scale, engineers need to highlight the significant structural parameters that firstly would have a direct impact on the built structure and then parameters that would have an indirect one. The aim is to evaluate how to adjust them in order to reduce flood damage. A future use of this first work could be to discover how modifying the parameters and consequently the structure could lead to decrease damage without losing its cost-effectiveness.

To that end, FEMA's work, studies from the Federal Emergency Management Agency, has been very proficient. Numerous Flood Insurance Survey Reports have been regularly published. FEMA defines it as a description of flood risk data for a specific location within a community. These surveys include detailed flood elevation data and maps. Among these surveys, FEMA also produced an estimation process called the Multi-Hazard Loss Estimation Methodology, which is based on previous data estimates for physical, economic, and social losses from flood. This procedure is intended to help a community to evaluate the risk they might suffer. The Hazus Technical Manual specifically mentioned that the Flood Loss Estimation Methodology conducted by FEMA is not applicable to the study of a single building. Indeed, their works result from comparisons with regional data and damage attributed to a single building is neither obvious nor underline.

Therefore, this thesis aims at establishing flood loss estimation starting from the HAZUS' methodology but to make it operable at a building scale. This is why the first part is an overview of the Hazus Technical Manual in order to highlight the significant steps and parameters for the flood loss evaluation. Instead of focusing on one single building, this manual aims at upgrading a block of buildings' resilience. As a result it focuses on some characteristics that are not necessarily applicable to a particular building. This is why this chapter is also describing the parameters that could impact society and participate in building a resilient city. Using different characteristics highlighted in the first part, the next chapters introduce a simplified methodology to produce probabilistic evaluation of flood damage in buildings. However, this methodology needs to be improved and to consider news parameters described in Part 1 so that this methodology could serve resilience instead of resistance.

2 Overview of the FEMA methodology for Flood Loss Estimation

This chapter aims at highlighting the significant parameters that intervene into flood damage. The study of the Flood Loss Estimation Methodology in the Hazus-MH Technical Manual edited by FEMA makes it possible. Hazus is a software that allows to estimate potential losses from flood at a national scale. The Hazus-MH Technical Manual FEMA publication is a methodology for estimating flood damage on a regional basis. National database is the starting point of this methodology, which makes it unable to set up a process for evaluating flood losses on a single building. Therefore, the first goal of this chapter is to find the parameters in the Hazus methodology that can be useful for the study of a single building. Secondly, this chapter provides other factors of influence that could lead to more precise estimation of building damage. This thesis' aim is to be a first attempt of a damage methodology in order to facilitate the progress for a more evolved procedure.

From an structural engineering point of view, the most important chapters of the Hazus-MH Technical Manual are chapters 3, 4, 5, 14 and 15. The fist part of this thesis reflects what these five chapters overview.

There are two principal steps to perform flood losses estimation and they can be studied independently. The flood hazard analysis produces a flood depth grids for a location, which provides the different flood depth and velocities associated with different occurrence frequencies. The second step is the flood loss estimation analysis, which focuses on the damage caused by the floods.

2.1 Flood hazard analysis

FEMA defines the flood hazard as "the chance that a certain depth of flooding is exceed at any given year". Therefore, flood depth, which is the difference between the flood and the ground surface elevation, and flood frequency are the two major components of this analysis. A more profound study requires also the implication of flood peak discharge and velocity and the distinction between a Riverine flood and a Coastal flood hazard and the combination of different disasters as the combined hurricane and flood impacts.

FEMA provides 3 levels of technical manual for users. The Level 1 requests a Digital Elevation Model (DEM) which is a combination of grid cell that shows the extent of the floodplain, which is a term to define the limit where the flood and the ground elevation are equals. The Hazus software is in charge to transform the data given by a DEM to then define a drainage area and provide the flood characteristics at a precise location. The Level 2 is based on the Flood Information Tool, so that particular flood data can be incorporated and then processed to define the flood parameters used during the flood loss estimation analysis. Level 3 requires technical experts for all the details of structural damage needs to be added by the users.

2.1.1 Riverine Flood Hazard

Weather it is level 2 or level 3, the riverine flood hazard is based on the Digital Elevation Model, DEM, or on the Flood Information Tool. A Digital Elevation Model represents the elevation of the ground surface. DEM's are built from data collecting during surveying. The Flood Information Tool is a tool that, given some inputs such as the ground elevations, the flood elevations, and the floodplain boundary, computes the flood depth and elevation for a riverine (and also coastal) flood hazards. The aim is to create a drainage area thanks to the study of the flow direction and the watersheds to device a flow accumulation grid. Once the watershed grids are established, the hydraulic analysis can take place.

2.1.1.1 Hydraulic analysis

The hydraulic analysis described in the Hazus Technical Manual consists of providing flood depths along the reach. The drainage area and a flood surface mapping are computed and identified so that it can correspond to the DEM provided in the first place. Then, a flood depth grid is created by substracting the DEM ground elevations to the flood surface grid computed.

To obtain this flood surface mapping, the flood elevation is computed using Manning's equation that is based on the discharge value of the flood. A discharge value is a term that describes the flow of water usually expressing its peak in m^3/s. It is usually combined to a return period for a certain flood. The return period refers to the expected time between two events with similar discharge flows and flood characteristics. The U.S. Geological Survey provides for each state a regional regression equation that relate the discharge value to different types of parameters. Each grid cell is then linked to a discharge value.

An example of the type of equation used for flood hazard analysis is Manning's equation times area whose expression is:

$$Q = \frac{1.486}{n} \times A \times R^{2/3} \times \sqrt{s_f}$$

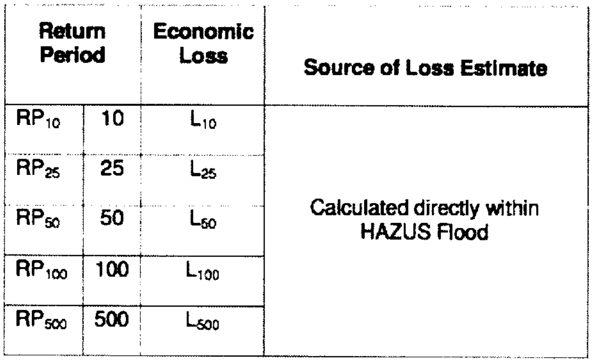
Q is the discharge value in m^3/s
n is the roughness with a default value of 0.08
A is the submerged area
R is the hydraulic radius
S_f is the friction slope calculated using the DEM

The result of this equation is that given the discharge value, the roughness, the area and the friction slope. The unknowns depend of the flood elevation. Using a reversed equation, the elevation can be easily computed. Because, the Hazus methodology is based on a grid, an iterative process is required. However, Manning's equation remains the basis of the calculation.

2.1.1.2 Flood depth for other return frequencies

The frequency of the flood is then added to the process. Each cell is assigned to a drainage area and a 2-, 5-, 10-, 25-, 50-, 100-, 200-, and 500-year flood discharge values and flood elevations. The different elevations are added to a table representing each grid cell. As a result each cell is associated to a flood frequency and depth. To combine them, the Hazus Technical Manual computes the Average Annualized Loss by examining losses in each return period range. To that end, FEMA combines five return periods considering the following table and formula.

Table 1 Return and associated economic loss



Return Period		Economic Loss	Source of Loss Estimate
RP_{10}	10	L_{10}	Calculated directly within HAZUS Flood
RP_{25}	25	L_{25}	
RP_{50}	50	L_{50}	
RP_{100}	100	L_{100}	
RP_{500}	500	L_{500}	

Source - Hazus Technical Manual

$$AAL = (f_{10} - f_{25}) \times \frac{L_{10} + L_{25}}{2} + (f_{10} - f_{25}) \times \frac{L_{10} + L_{25}}{2} + (f_{10} - f_{25}) \times \frac{L_{10} + L_{25}}{2}$$
$$+ (f_{10} - f_{25}) \times \frac{L_{10} + L_{25}}{2} + f_{500} \times L_{500}$$

$f_{10} = \frac{1}{10}$ Probability of occurrence of a 10-year flood

2.1.2 Coastal Flood Hazard

The second Flood hazard is calculated using a process similar to the one FEMA used to produce coastal Flood Insurance Rate Maps. This thesis does not describe the Coastal Flood process whose aim is still to identify the flood depths and flood hazard zones.

To give an idea of the requirement of this methodology, here are the inputs required: the region studied, the shoreline, the coastal flood period, the wave exposure, the 10-, 50-, 100-year flood stillwater elevation, the 100-year wave setup, the significant wave height and the peak wave period at the shoreline. Given these inputs, given a similar process to the one of the Riverine Flood Hazard, the Hazus Flood Model sets a similar grid to the riverine one.

2.1.3 The Combined Hurricane and Flood Hazard

FEMA also creates a Hazus Hurricane Model in which damage results not only from the wind but also from storm surges and waves. Some of these damages are consequently estimated as flood losses.

Tha Hazus hurricane loss methodology is interesting in that it consists of summing the losses of all the building components, such as structural frame, plumbing, cabinets, or roof frame. Both methodologies are based on individual, technical and insurance claims. However, the Hazus Hurricane Model computes first damage by sub-assemblies and then combined the different assemblies to have a total damage, whereas based on claims, the Flood methodology evaluates the total damages without showing at what point and for which depth in the methodology which components is impacted. The Flood Methodology is more global.

The aim of the combined hurricane and flood losses is to avoid counting twice flood damage in a single hurricane event. Therefore constraints have been defined. If L_{wind},, L_{flood}, $L_{combined}$ respectively refer to the losses due to hurricane (mainly due to the wind) , flood, and the combined losses, then the constraints are:

$$\max(L_{wind}, L_{flood}) \leq L_{combined} \leq \min(L_{wind} + L_{flood}, 1)$$

Assuming the effects of the wind and flood are two independent events, the combined loss ratio is computed thanks this probabilistic formula:

$$L_{combined} = L_{wind} + L_{flood} - L_{wind} \times L_{flood}$$

The Table 2 below is issued from the Hazus Manual and shows the results from this previous equation for an idealized case of Hurricane and Flood Losses that are uniformly and randomly distributed throughout the building. This assumption means that, for example, 10% of building loss does not point out only the first floor of a two-story building but that the all building is in total damaged of 10%. The grey boxes show the results of the combined loss for a given wind-only building loss and a flood-only building loss.

Table 2 Combined hurricane and flood loss matrix for idealized case of hurricane and flood losses that are uniformly and randomly distributed throughout the Building

		Wind-Only Building Loss										
		0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Flood-Only Building Loss	0%	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
	10%	10%	19%	28%	37%	46%	55%	64%	73%	82%	91%	100%
	20%	20%	28%	36%	44%	52%	60%	68%	76%	84%	92%	100%
	30%	30%	37%	44%	51%	58%	65%	72%	79%	85%	93%	100%
	40%	40%	46%	52%	58%	64%	70%	76%	82%	88%	94%	100%
	50%	50%	55%	60%	65%	70%	75%	80%	85%	91%	95%	100%
	60%	60%	64%	68%	72%	76%	80%	84%	88%	94%	96%	100%
	70%	70%	73%	76%	79%	82%	85%	88%	91%	97%	97%	100%
	80%	80%	82%	84%	86%	88%	90%	92%	94%	98%	98%	100%
	90%	90%	91%	92%	93%	94%	95%	96%	97%	99%	99%	100%
	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Source - Hazus Technical Manual

The approximation in this table is that it does not take into account that a hurricane hit first the roof frame whereas flood damage is first found at the foundation and below the first floor of the structure. As mentioned earlier, what is interesting is that unlike the flood loss estimation methodology, the hurricane and earthquakes methodology, set by FEMA, are both based on a sub-assembly approach which is simply a function that links the sub-assembly losses to the overall building losses.

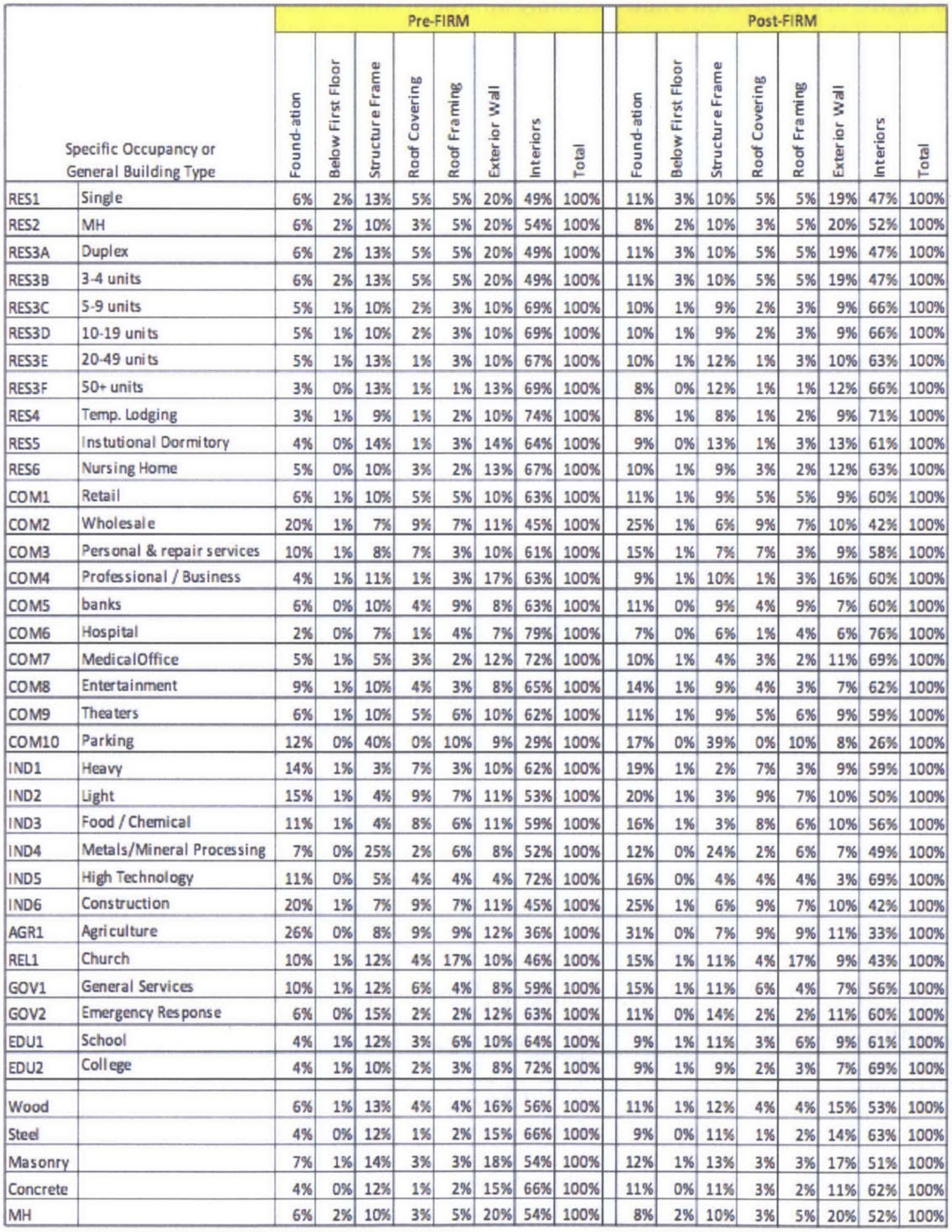
So to adapt the results obtained with the Hurricane method, FEMA engineers chose to regroup seven sub-assemblies that match with the hurricane's one. These sub-assemblies are:

- Foundation
- Below First Floor
- Structure Framing
- Roof Covering
- Roof Framing
- Exterior Walls
- Interiors

According to the Hazus Manual, the sub-assembly foundation includes site work, footings, walls, slabs, piers and piles; "Below First Floor" consists of all the items that does not belong to foundation and that are located below the first floor of the structure such as mechanical equipment, stairways, or parking pad. The Structure Framing accounts for all the structural elements that are carrying the load below the roof framing and above the foundation. The Roof membrane includes the roof membrane material and the roof flashing while the Roof framing includes trusses, rafters and sheathing. The Exterior Walls includes wall coverings, windows, exterior doors and insulation. The Interiors not only consists of the interior wall, but also of floor framing, drywall, paint, interior trim, floor coverings, cabinets, counters, mechanical and electrical.

The flood hazard analysis allows the users to relate a certain flood depth to a certain amount of damage in the overall building. Moreover, for each category of building Hazus manage to associate the percentage of each sub-assembly to the overall building. The table above is showing the percentage in term of replacement value for each category of building. Table 3 is edited by the Hazus Technical Manual, which is using RS Means (2009) data for typical model building.

Table 3 Sub-assembly replacement values by specific occupancy or general building type as a percentage of total building replacement value table



Specific Occupancy or General Building Type		Pre-FIRM								Post-FIRM							
		Found-ation	Below First Floor	Structure Frame	Roof Covering	Roof Framing	Exterior Wall	Interiors	Total	Found-ation	Below First Floor	Structure Frame	Roof Covering	Roof Framing	Exterior Wall	Interiors	Total
RES1	Single	6%	2%	13%	5%	5%	20%	49%	100%	11%	3%	10%	5%	5%	19%	47%	100%
RES2	MH	6%	2%	10%	3%	5%	20%	54%	100%	8%	2%	10%	3%	5%	20%	52%	100%
RES3A	Duplex	6%	2%	13%	5%	5%	20%	49%	100%	11%	3%	10%	5%	5%	19%	47%	100%
RES3B	3-4 units	6%	2%	13%	5%	5%	20%	49%	100%	11%	3%	10%	5%	5%	19%	47%	100%
RES3C	5-9 units	5%	1%	10%	2%	3%	10%	69%	100%	10%	1%	9%	2%	3%	9%	66%	100%
RES3D	10-19 units	5%	1%	10%	2%	3%	10%	69%	100%	10%	1%	9%	2%	3%	9%	66%	100%
RES3E	20-49 units	5%	1%	13%	1%	3%	10%	67%	100%	10%	1%	12%	1%	3%	10%	63%	100%
RES3F	50+ units	3%	0%	13%	1%	1%	13%	69%	100%	8%	0%	12%	1%	1%	12%	66%	100%
RES4	Temp. Lodging	3%	1%	9%	1%	2%	10%	74%	100%	8%	1%	8%	1%	2%	9%	71%	100%
RES5	Instutional Dormitory	4%	0%	14%	1%	3%	14%	64%	100%	9%	0%	13%	1%	3%	13%	61%	100%
RES6	Nursing Home	5%	0%	10%	3%	2%	13%	67%	100%	10%	1%	9%	3%	2%	12%	63%	100%
COM1	Retail	6%	1%	10%	5%	5%	10%	63%	100%	11%	1%	9%	5%	5%	9%	60%	100%
COM2	Wholesale	20%	1%	7%	9%	7%	11%	45%	100%	25%	1%	6%	9%	7%	10%	42%	100%
COM3	Personal & repair services	10%	1%	8%	7%	3%	10%	61%	100%	15%	1%	7%	7%	3%	9%	58%	100%
COM4	Professional / Business	4%	1%	11%	1%	3%	17%	63%	100%	9%	1%	10%	1%	3%	16%	60%	100%
COM5	banks	6%	0%	10%	4%	9%	8%	63%	100%	11%	0%	9%	4%	9%	7%	60%	100%
COM6	Hospital	2%	0%	7%	1%	4%	7%	79%	100%	7%	0%	6%	1%	4%	6%	76%	100%
COM7	MedicalOffice	5%	1%	5%	3%	2%	12%	72%	100%	10%	1%	4%	3%	2%	11%	69%	100%
COM8	Entertainment	9%	1%	10%	4%	3%	8%	65%	100%	14%	1%	9%	4%	3%	7%	62%	100%
COM9	Theaters	6%	1%	10%	5%	6%	10%	62%	100%	11%	1%	9%	5%	6%	9%	59%	100%
COM10	Parking	12%	0%	40%	0%	10%	9%	29%	100%	17%	0%	39%	0%	10%	8%	26%	100%
IND1	Heavy	14%	1%	3%	7%	3%	10%	62%	100%	19%	1%	2%	7%	3%	9%	59%	100%
IND2	Light	15%	1%	4%	9%	7%	11%	53%	100%	20%	1%	3%	9%	7%	10%	50%	100%
IND3	Food / Chemical	11%	1%	4%	8%	6%	11%	59%	100%	16%	1%	3%	8%	6%	10%	56%	100%
IND4	Metals/Mineral Processing	7%	0%	25%	2%	6%	8%	52%	100%	12%	0%	24%	2%	6%	7%	49%	100%
IND5	High Technology	11%	0%	5%	4%	4%	4%	72%	100%	16%	0%	4%	4%	4%	3%	69%	100%
IND6	Construction	20%	1%	7%	9%	7%	11%	45%	100%	25%	1%	6%	9%	7%	10%	42%	100%
AGR1	Agriculture	26%	0%	8%	9%	9%	12%	36%	100%	31%	0%	7%	9%	9%	11%	33%	100%
REL1	Church	10%	1%	12%	4%	17%	10%	46%	100%	15%	1%	11%	4%	17%	9%	43%	100%
GOV1	General Services	10%	1%	12%	6%	4%	8%	59%	100%	15%	1%	11%	6%	4%	7%	56%	100%
GOV2	Emergency Response	6%	0%	15%	2%	2%	12%	63%	100%	11%	0%	14%	2%	2%	11%	60%	100%
EDU1	School	4%	1%	12%	3%	6%	10%	64%	100%	9%	1%	11%	3%	6%	9%	61%	100%
EDU2	College	4%	1%	10%	2%	3%	8%	72%	100%	9%	1%	9%	2%	3%	7%	69%	100%
Wood		6%	1%	13%	4%	4%	16%	56%	100%	11%	1%	12%	4%	4%	15%	53%	100%
Steel		4%	0%	12%	1%	2%	15%	66%	100%	9%	0%	11%	1%	2%	14%	63%	100%
Masonry		7%	1%	14%	3%	3%	18%	54%	100%	12%	1%	13%	3%	3%	17%	51%	100%
Concrete		4%	0%	12%	1%	2%	15%	66%	100%	11%	0%	11%	3%	2%	11%	62%	100%
MH		6%	2%	10%	3%	5%	20%	54%	100%	8%	2%	10%	3%	5%	20%	52%	100%

As it will be developed in the next part of this thesis the flood loss estimation is mainly based on insurance claims and each specific type of building is associated to a depth-damage curve that relates the depth of flood to the percentage of the total building loss. However, it does not provide the distribution of the flood damage within the building. Therefore using data for typical model building in Table 3 and given an overall percentage of building damage, which is the loss that results from an accurate depth-flood curve, it is possible to compute the distribution of flood losses in the building. The building sub-assemblies' loss can be expressed as a function of flood building loss. This new function is very significant for a flood estimation methodology. This distribution of flood losses has been established by FEMA for each specific building. Table 4 is an example. One can notice that starting from column 2 to 7 in Table 4 and using the repartition of Table 1, it miss 20% to reach the total building loss in the Tables given by the Hazus Technical Manual. It is likely that these 20% are attributed to the content losses of the building. However, the following part of the Hazus manual is using more specific content repartitions. There is an incoherence here that does not really affect FEMA's results as they are already based on collection of regional data that can be questionable.

Table 4 : Flood sub-assembly loss table for a Pre-FIRM, one-story, single-family residential homes

Building loss/pre A	Foundation	Below First Floor	Structure Frame	Roof covering	Roof framing	Exterior walls	Interior
0%	0%	0%	0%	0%	0%	0%	0%
10%	0%	20%	0%	0%	0%	4%	14%
20%	0%	40%	0%	0%	0%	12%	26%
30%	0%	60%	0%	0%	0%	21%	37%
40%	0%	100%	0%	0%	0%	30%	48%
50%	0%	100%	0%	0%	0%	39%	60%
60%	0%	100%	0%	0%	0%	47%	74%
70%	0%	100%	0%	0%	0%	56%	86%
80%	0%	100%	5%	14%	5%	68%	94%
90%	5%	100%	26%	27%	26%	83%	96%
100%	10%	100%	50%	50%	50%	86%	100%

Source - Hazus Technical Manual

2.2 The inventory data collection and classification

The inconvenience with the Hazus' methodology is that flood damage inventory mainly stems from insurance claims, owners' testimonies, or real-estate agencies. As every step in the process is correlated to regional data, these regional and general sources prevent an engineer from estimating the flood effects at a building scale. However, FEMA has gathered a significant amount of data collection and classification to make the Hazus Technical Manual become a useful source of information. At first, only direct damage is considered.

2.2.1.1 General Building Stock

To simplify, the methodology is based on a regional collection of data corresponding to a flood depth and an amount of damage. The effect of a flood on a building also depends on the flood's location. The studied flood impacts a particular block of building which are subjected to damage. As a result, Hazus also needed to build a rich database of the General Building Stock to be able to evaluate correctly building damage.

The General Building Stock is composed of different class of occupancy that range from residential, commercial, industrial, agricultural, religious, government to education buildings. A given census block relates to a block of buildings in a precise location in which all the buildings have been identified. A given census block is the reference in the Hazus' study cases and the composition of the census block is assumed to be evenly distributed throughout the block. Therefore, damage is estimated in percentage at a given depth that has been estimated and weighted throughout the census block.
As a result, the General Building Stock is classified according to the following criteria:

- Square footage by occupancy
- Full replacement value by occupancy
- Building count by occupancy, which is the number of building a certain occupancy (ex: residential) have given a census block
- General occupancy mapping, which includes occupancy building class type (e.g., residential), and construction building type (e.g., wood)

- Demographic data, which provide the housing and population statistic for a given census block.

At the end, the flood estimation established by Hazus Manual is based on 33 occupancy classes that are listed below in

Table 6 and on five General Construction Classification that are: wood, concrete, masonry, steel, and manufactured housing. Moreover, except for the wood and manufacturing housing construction class, the general building classification is divided in three classes according to the number of stories: this methodology does not consider buildings with more than 8 floors. The General Building Type classes are described in the Table 5.

Table 5 :Hazus General Building Type

Number	Label/Description	Height Name	Range of Stories
1	Wood Frame	All	All
2	Steel Frame	Low-Rise	1 –3
3		Mid-Rise	4 – 7
4		High-Rise	8 and up
5	Concrete Frame	Low-Rise	1 – 3
6		Mid-Rise	4 – 7
7		High-Rise	8 and up
8	Masonry	Low-Rise	1 –3
9		Mid-Rise	4-7
10		High-Rise	8 and up
11	Manufactured Housing		All

Source - Hazus Technical Manual

Table 6 :Hazus Building Occupancy Classes

Class	Description
RES1	Single Family Dwelling
RES2	Manufactured Hosuing
RES3A	Duplex
RES3B	Triplex/Quads
RES3C	Multi-dwellings (5 to 9 units)
RES3D	Multi-dwellings (10 to 19 units)
RES3E	Multi-dwellings (20 to 49 units)
RES3F	Multi-dwellings (50+ units)
RES4	Temporary Lodging
RES5	Institutional Dormitory
RES6	Nursing Home
COM1	Retail Trade
COM2	Wholesale Trade
COM3	Personal and Repair Services
COM4	Professional/ Technical Services
COM5	Banks
COM6	Hospital
COM7	Medical Office/Clinic
COM8	Entertainment & Recreation
COM9	Theaters
COM10	Parking
IND1	Heaving Industry
IND2	Light Industry
IND3	Food/Drug/Chemicals
IND4	Metals/Minerals Processing
IND5	High Technology
IND6	Construction
AGR1	Agriculture
REL1	Churches and Other non-profit Org.
GOV1	Genral Services
GOV2	Emergency Response
EDU1	Grade Schools
EDU2	Colleges Univeristies

Source - Hazus Technical Manual

To constitute a database of the General Building Stock, the Hazus Technical Manual benefits from the work of numerous sources. For this rubric, they principally used the following sources:

- Census of Population and Housing, 2000: Summary Tape File 1B Extract on CD-ROM / prepared by the Bureau of Census.
- Census of Population and Housing, 2000: Summary Tape File 3 on CD-ROM / prepared by the Bureau of Census.
- Dun & Bradstreet, Business Population Report aggregated by Standard Industrial Classification (SIC) and Census Block, May 2006.

- Department of Energy, Housing Characteristics 1993. Office of Energy Markets and End Use, DOE/EIA-0314 (93), June 1995.
- Department of Energy, A Look at Residential Energy Consumption in 1997, DOE/EIA- 0632(97), November 1999.
- Department of Energy, A Look at Commercial Buildings in 1995: Characteristics, Energy Consumption, and Energy Expenditures, DOE/EIA-0625(95), October 1998.

2.2.1.2 Average area

The depth-damage curves provide a percentage of damage given a building type and depth. As the aim of Hazus is to evaluate the flood effect on a regional basis, the income of this region plays necessarily a role in the economic valuation of the damage. The Department of Energy and the Energy Information Administration provides access to income factors that allows Hazus to consider the wealth of the population and the region. To consider this last criterion, Hazus uses an income ratio which is the ratio of the census block group income over the average income from the region. The income criterion is especially important for such residences as the single-family residential housing. Five relative incomes are used to weigh the typical area of single-family residences for each regional census division. Table 7 below shows a typical square footage per unit in New England that corresponds to a certain income ratio. As can be seen the presence of a basement is considered in the average resulting surface area. Note that if a basement is present, the typical square footage per unit is diminished of 25%. Each region is associated to a similar table and to another one giving the basement distribution by census region.

Table 7 : Typical Square Footage Per Unit (Main Living Area) by Census Division, New England

Income Ratio:	**Basement**	
	No $(j=1)$	***Yes*[2] $(j=2)$**
$I_k < 0.5$	1300	975
$0.5 \le I_k < 0.85$	1500	1125
$0.85 \le I_k < 1.25$	1800	1350
$1.25 \le I_k < 2.0$	1900	1425
$I_k \ge 2.0$	2200	1650

Source - based on data from the Energy Information Administration, Housing Characteristics 1993.

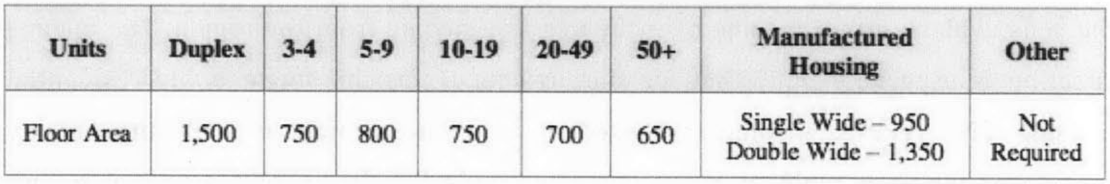
Then, for the entire region, an estimation of the RES1 square footage is given by the following relation:

$$RES1(sq.ft) = Number\ of\ RES1\ units\ \times$$
$$(\%unit_{Basement} \times floor_{area_{Income\ ratio}} + \%unit_{NOBasement} \times floor_{area_{Income\ ratio}})$$

$$\%unit_{Basement} = Percent\ of\ units\ in\ the\ census\ block\ with\ basement$$
$$\%unit_{NOBasement} = Percent\ of\ units\ in\ the\ census\ block\ without\ basement$$
$$floor_{area_{Income\ ratio}} = Floor\ area\ attributed\ to\ the\ Income\ ratio$$

For the other occupancy residential class, this income adjustment is not necessary but a certain distribution is still necessary. Hazus is again using the Housing Characteristics of 1993 but this time thanks to their own experts managed to come with a distribution of an average floor area by unit described in the Table 8 below.

Table 8: Hazus Floor Areas for Multi-Family Dwellings (RES2 & RES3A-RES3F)



Units	Duplex	3-4	5-9	10-19	20-49	50+	Manufactured Housing	Other
Floor Area	1,500	750	800	750	700	650	Single Wide – 950 Double Wide – 1,350	Not Required

Source - Hazus Technical Manual

First, the ratio of the distribution of the specific occupancy needs to be computed, then the number of units of this specific occupancy is computed to then obtain the corresponding floor area.

The basic equations are:

$$r = \frac{Total\ housing\ units\ by\ census\ block}{total\ housing\ units\ per\ census\ block\ group}$$
$$units\ per\ block = number\ of\ units\ in\ the\ census\ block\ \times\ r$$
$$Area\ (sq.ft) = units\ per\ block\ \times\ area_{units\ Table}$$

For the non-residential occupancy classification, Dun & Bradstreet provide the necessary data that are then homogeneously distributed, and adapted as above.

2.2.1.3 Building height

Another criterion considered in the General Building Stock is the building height, which is related to the number of stories. For instance, the distribution of the height for Single Family Residences is given in the next Table 9 for four census regions. The distribution of the RES2 and RES3 is given in tables in which buildings with more than five floors have been neglected. Commercial buildings are them range in function of three categories low rise, mid rise, and high rise but this time there are also ranked by census year built.

Table 9 :Hazus Distribution of Floors for Single Family Residences

US Census Region	States within the Region	Number of Stories (% of Structures)			
		1-Story	2-Story	3-Story	Split Level
Northeast	CT, MA, ME, NH, NJ, NY, PA, RI, VT	29	61	8	2
Midwest	IA, IL, IN, KS, MI, MN, MO, NE, ND, OH, SD, WI	44	45	5	6
South	AL, AR, DE, DC, FL, GA, KY, LA, MD, MS, NC, OK, SC, TN, TX, VA, WV	72	23	3	2
West	AK, AZ, CA, CO, HI, ID, MT, NV, NM, OR, UT, WA, WY	68	26	3	3

Source – A Look at Residential Energy Consumption in 1997 (Nov 1999) Table HC1-13a converted to percent of total family dwellings.

2.2.1.4 Building Foundation Type

2.2.1.4.1 Foundation types

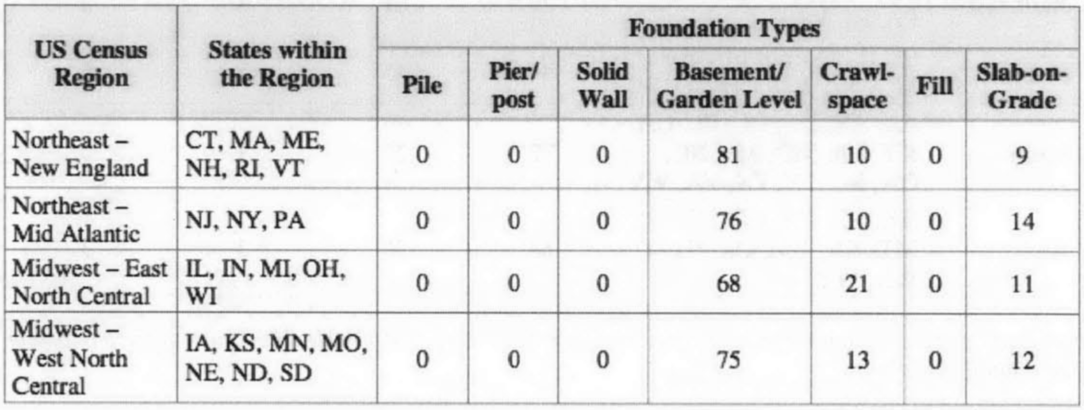
Building foundation type is a significant criterion to estimate flood losses. To constitute the database, Hazus gathered the distribution of foundations within the census block, the associated first floor height, the age of the building height considering if they are issued on Pre or Post-FIRM. FEMA defines Pre-FIRM buildings as those built before the effective date of the first Flood Insurance Rate Map (FIRM) established for a community. These last three criteria constitute the "key controlling parameters affecting flood damages" according Hazus.

There are 8 principal foundation types:

- Pile
- Pier
- Solid Wall
- Basement or garden level basement
- Crawlspace
- Fill
- Slab-on-Grade

To classify foundation types, a first distinction is made between riverine and coastal hazard as well as between Pre and Post-FIRM, so that the percentage of the foundation types by census region and by occupancy building category is then distributed. The classification next requires the study of the first floor elevation, which is associated to each foundation type. Below an example shows the Hazus distribution foundation types.

Table 10: Distribution of Foundation Types for Single Family and Multi-Family Residences (Riverine)



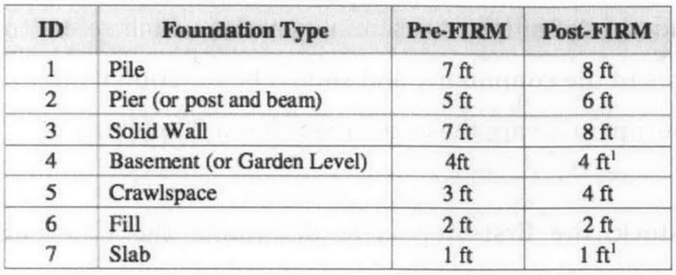
US Census Region	States within the Region	Foundation Types						
		Pile	Pier/ post	Solid Wall	Basement/ Garden Level	Crawl-space	Fill	Slab-on-Grade
Northeast – New England	CT, MA, ME, NH, RI, VT	0	0	0	81	10	0	9
Northeast – Mid Atlantic	NJ, NY, PA	0	0	0	76	10	0	14
Midwest – East North Central	IL, IN, MI, OH, WI	0	0	0	68	21	0	11
Midwest – West North Central	IA, KS, MN, MO, NE, ND, SD	0	0	0	75	13	0	12

Source – A look at Residential Energy Consumption in 1997 (Nov 1999)

2.2.1.4.2 First Floor elevation

The first floor elevation, also called the floor height above grade, constitute another aspect of the foundation criteria. It refers to the height between the grade and the top of the finished floor. Each foundation type is being assigned a default floor height above grade with varies with whether census belongs to the Pre-FIRM or Post-FIRM period. Hazus' experts are responsible for the choice of Default Flood Heights.

Table 11 :Default Floor Heights Above Grade to Top of Finished Floor (Riverine)



ID	Foundation Type	Pre-FIRM	Post-FIRM
1	Pile	7 ft	8 ft
2	Pier (or post and beam)	5 ft	6 ft
3	Solid Wall	7 ft	8 ft
4	Basement (or Garden Level)	4ft	4 ft[1]
5	Crawlspace	3 ft	4 ft
6	Fill	2 ft	2 ft
7	Slab	1 ft	1 ft[1]

Source - Hazus Technical Manual

The Hazus manual develops rich tables of data that show the distribution of the foundation including all the criteria mentioned above.

2.2.1.5 Garage distribution

The presence or absence of garage is also taken into account. Indeed it is not only a potential structural and economic damage but it is also a way to determine if the structure is luxury, custom, average home or economy. As a result, Hazus has set up a valuation function to estimate the percentage of different types of garage within a census block.

2.2.2 Essential facilities losses

As mentioned before, flood damage does not only concern structural building damage but they also result in significant impacts on the society. As a result, flood damage also needs to be evaluated throughout other facilities. This section becomes important if a resilient approach is conducted. The methodology implemented later in this thesis does not consider these others components. This part suggests new parameters that the methodology implemented in Part 2 and 3 could be included in a fully-resilient approach.

2.2.2.1.1 Essential facilities

The Hazus Technical Manual provides a definition of essential facilities which refers to "those facilities that provide services to the community and should be functional after a flood". This is simply evaluating how operable are these facilities after a flood hazard.

As for the residential building stock, the first step is to determine the different occupancy classes. They are listed in the following Table 12.

Table 12 :Essential Facilities Classification

Hazus Label	Occupancy Class	Description
Medical Care Facilities		
MDFLT	Default Hospital	Assigned features similar to EFHM
EFHS	Small Hospital	Hospital with less than 50 Beds
EFHM	Medium Hospital	Hospital with beds between 50 & 150
EFHL	Large Hospital	Hospital with greater than 150 Beds
EFMC	Medical Clinics	Clinics Labs Blood Banks
Emergency Response		
FDFLT	Default Fire Station	
EFFS	Fire Station	
PDFLT	Default Police Station	
EFPS	Police Station	
EDFLT	Default EOC	
EFEO	Emergency Operation Centers	
Schools		
SDFLT	Default School	Assigned features similar to ESF1
EFS1	Grade Schools Primary/ High Schools	
EFS2	Colleges/Universities	

Source - Hazus Technical Manual

Unlike the residential building stock, five assumptions on significant parameters that impact the loss estimation are made in the Hazus essential facilities section.

- Damage functions should be similar to the General Building Stock.
- Flood-Depth: the facility is assumed to be closed and people evacuated as soon as the flood depth is more than 0.5 feet.

- Basement: EFFS, EFSA and EFS2 do not have basements. The other occupancy class can have ones.
- First Floor Elevation: EFEO, EFFS, EFS1 and EFS2 are supposed to be at grade whereas the other occupancies are 3 feet above grade.
- Number of stories: ESF1, EFHS, EFMC, EFFS, EFPS, and EFEO are all supposed to be low-rise structures, e.g. 1-3 floors; EFHM and EFHL are assumed to be mid-rise, e.g. 3-7 floors.

It is interesting to note that since essential facilities are located at a precise point and are more or less isolated from other facilities, the loss estimation can be done just from the depth obtained with the grid cell, the basement, the first floor elevation and the number of stories. There is no need in establishing an occupancy mapping as for the General Building Stock. Indeed, a damage function similar to the General Building Stock can then be used.

2.2.2.1.2 Transportation systems

It is important to notice that even aiming at evaluating the overall damage caused by a flood, Hazus does not consider bridges and other high potential loss facilities such as tunnels. Similarly to the General Building Stock, the Hazus database contains the geographical location, the classification, but also the replacement cost of all system components. For each transportation systems that are listed below, Hazus provides tables which allows users to rank their systems by categories of occupancy and then to assign a replacement cost to it.

The transportation systems are composed of:

- Highways systems, e.g. roadways, bridges, tunnels
- Railway systems
- Light railway systems
- Bus systems
- Ports and Harbors, e.g. waterfront structures, cranes/cargo handling equipment, warehouses and fuel facilities
- Ferry transportation systems, e.g. waterfront structures, passenger terminals, warehouses, fuel facilities, and dispatch and maintenance facilities.

- Airports, e.g. control towers, runways, terminal buildings, parking structures, fuel facilities and maintenance and hanger facilities

2.2.2.1.3 The Lifeline Utility System

The system of classification is the same as the transportation systems. Hazus provides tables which allow the user to rank his systems by category of occupancy and then to assign a replacement cost. The only difference is that, this time, the section called "Hazus valuation" alludes to the replacement cost for the facilities and the repair cost for communications lines. The lifelines utilities include:

- Potable water systems
- Wastewater systems
- Oils systems
- Electric power systems
- Communication systems

2.2.2.1.4 Agricultural Product

A damage function is developed based on curves collected from the various district of the U.S. Army Corps of Engineers. The cost of this damage is developed in the Hazus Technical Manual in its chapter 14.

2.2.2.1.5 Parking supply and Vehicles population

This section is very detailed in the Hazus manual and should require more attention than this thesis was able to devote. The following procedure aims at computing the vehicle losses and is divided into four main steps:

- Calculating the vehicles inventory
- Allocating vehicles by time of day to different locations
- Estimating the value of vehicles
- Applying a percent loss damage function according to the flood depth

During this process the parking generation rate is computed and it associates the number of parked vehicles to an occupancy class. Most of the data is available at the Institute Transportation of Engineer, ITE, that has compiled the most comprehensive parking generation study.

The repartition of the parking is ranked according a census block and an area type: on-street, surface log, garage, and underground. Each area type is associated to a parking space, occupancy and a distribution of the vehicles within the occupancy class.
The vehicle population is also ranked in 5 age groups and 3 types: car, light truck and heavy truck. The distribution of the parking area type and of the vehicle value estimation is very well described in the Hazus methodology but relies on regional database and so it was too complicated to incorporate this criterion in the methodology detailed in Part 2 and 3.

2.2.2.1.6 Direct economic and social loss

The census data allow the users to estimate the direct social loss which includes the casualities of the flood, the new homelessness due to non-operable buildings, and the quality of the remaining buildings. The Census Bureau provides the needed data that include age, income, housing, and ethnic origin.

2.3 Estimation of the Physical Damage – General Building Stock

2.3.1 Important Parameters

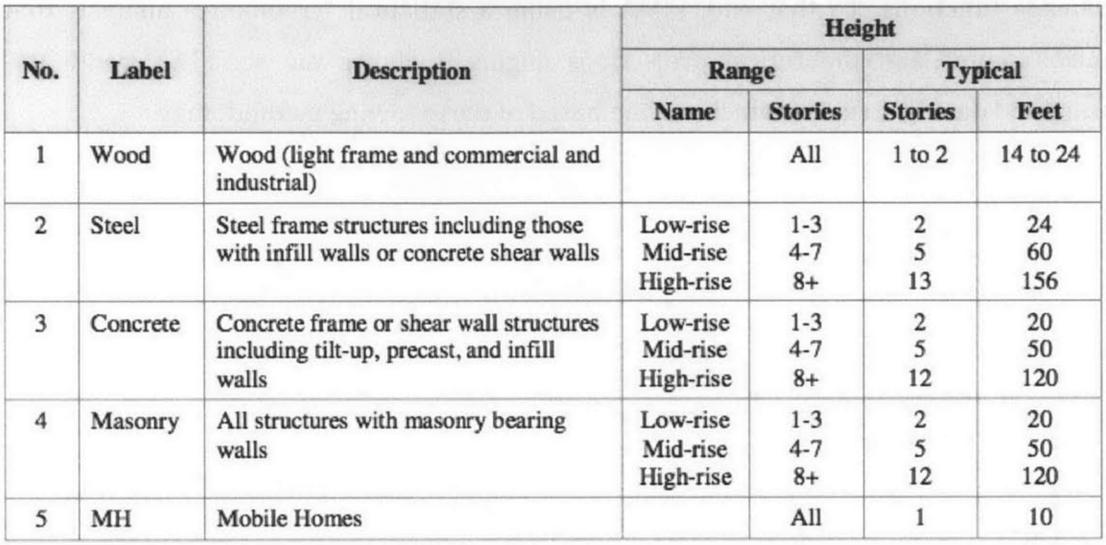
The aim of this chapter is to highlight the loss estimation process which is simply evaluating at a given depth both the structural and content loss. Indeed content and structural damage are evaluated separately. Based on their flood hazard analysis and their important database gathered within the General Building Stock, Hazus can then establish the flood estimation loss analysis. This second analysis consists of producing or gathering depth-damage curves which relate the depth flooding to the damage expressed as a percent of replacement cost. As the velocity is unlikely to cause structural damage, except if the building collapses, damage can be only attributed to the flood.

The depth damage curves require the following information given a census block:

- Flood depth
- Flood frequency
- Occupancy class
- Foundation type
- First floor elevation
- Building age
- Model building types

As it has already been mentioned before, the inventory of the occupancy class, foundation type or first floor elevation have been evenly distributed over the census block. The impact of the building age is a little more complicated to estimate because the building and the flood's regulation code regularly change. The description of the General Building Stocks contains tables that describe throughout the different occupancy of the census block: the census block group age distribution, the foundation type and the first floor elevation which depends of the nature of the flood (riverine, coastal or Great Lakes' flood, i.e., floods resulting from the rising of the Great Lakes' water). Lastly, the model building types are also described in the Table 13 in which the materials and the height of the building are the two main criteria. The material is composed of wood, steel, concrete, masonry, mobile home and the height is split between low-rise, mid-rise and high-rise building.

Table 13 :Hazus Model Building Types



No.	Label	Description	Height			
			Range		Typical	
			Name	Stories	Stories	Feet
1	Wood	Wood (light frame and commercial and industrial)		All	1 to 2	14 to 24
2	Steel	Steel frame structures including those with infill walls or concrete shear walls	Low-rise	1-3	2	24
			Mid-rise	4-7	5	60
			High-rise	8+	13	156
3	Concrete	Concrete frame or shear wall structures including tilt-up, precast, and infill walls	Low-rise	1-3	2	20
			Mid-rise	4-7	5	50
			High-rise	8+	12	120
4	Masonry	All structures with masonry bearing walls	Low-rise	1-3	2	20
			Mid-rise	4-7	5	50
			High-rise	8+	12	120
5	MH	Mobile Homes		All	1	10

Source - Hazus Technical Manual

2.3.2 Compilation of depth damage function

According the difference sources, for each census block and occupancy class there is at least one damage-function assigned to it. Generally, a depth-damage curve is established for an occupancy class associated to a building age range, an occupancy class, and a foundation and first floor elevation type. For each occupancy class one default damage curve has been selected. The sources are available in the Hazus model but the direct access to the damage function is not. The different sources used to set default depth-damage curves are:

- FIMA (FIA) Residential Depth-Damage Curves – Riverine
- FIMA (FIA) Residential Depth-Damage Curves – Coastal
- USACE Depth-Damage Curves (Residential and Non-Residential)
- USACE Institute for Water Resources (IWR)

The default damage functions for estimation of contents damage are gathered in the Appendices of the Hazus manual.

The ones that deserves more attention are the damage function that results from the National Flood Insurance Program's report (NFIP) that provides updated annually damage functions. To that end, FIMA is using a statistical "credibility" analysis that mixes claims and theoretical projections. Figure 1 shows the six FIA "credibility-weighted damage" curves which are the based of the following methodology.

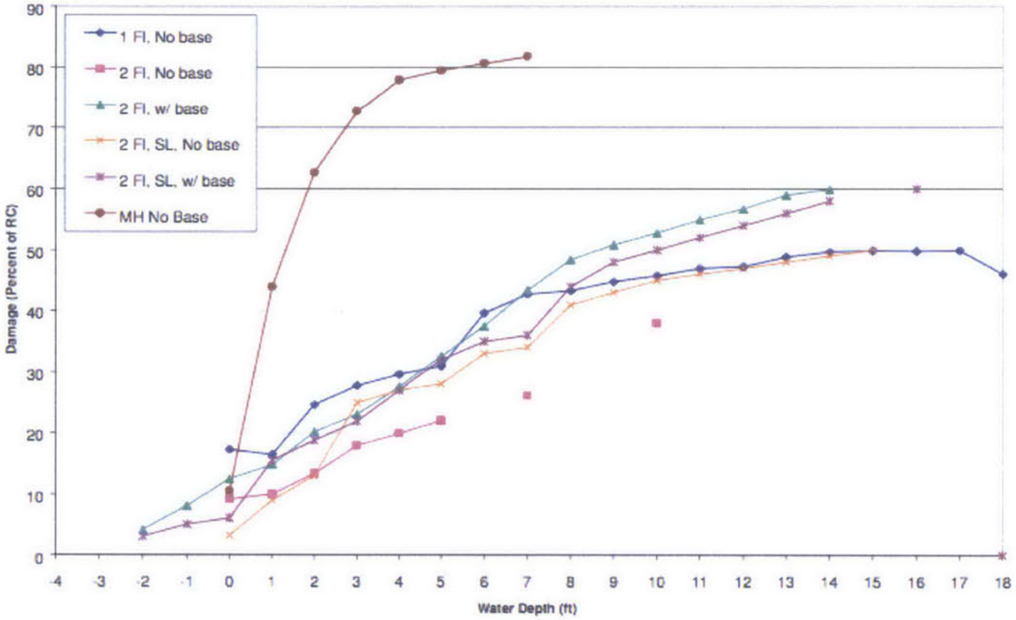


Figure 1: FIA Credibility-Weighted Building Depth-Damage Curves as of 12/31/1998
Source: Flood Model – Hazus MH Technical Manual (2006)

This FIA's curves are based on insurance claims which were not covering all basement losses. As some basement components such as the flooring were not included, curves which concern residences with basements need to be modified to consider these forgotten components. Based on claims and the adaptation of replacement costs provided by "Means Square Foot Costs"(Means, 2006), the Hazus technical manual provides an approximation of the curves' changes needed. Based on their claims, 8% should be added between -4 feet and -1 foot, and from -1 foot to the end a total of 11% should be added to the curves in Figure 1. An other modification is suggested as the claims' estimation of contents is not always reliable and even less regarding basement.

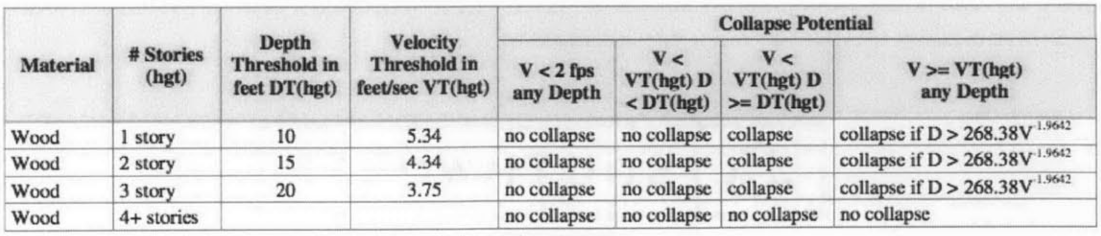
To simplify, the Hazus Manual offers to consider that one third of the content should be awarded to the basement, and the rest should be distribute with a proportion of 40%-60% between the first and second floor. Assuming this repartition, FEMA considers that the contents will always be split in that disposition. As a result, such effects as the one of transporting contents with the highest value to the second floor can not be highlighted. These oversights are aimed to be improve in Part 2 and 3 of this Thesis.

2.3.3 Building damage due to velocity

The impact of the velocity has been limited thanks to the guidelines of the Ontario Ministry of Natural Resources which states "Structural Integrity (structures above ground) - A depth of 0.8m is the safe upper limit for the above ground/super structure of conventional brick veneer, and certain types of concrete block buildings. The structural integrity of elevated structures is more a function of flood velocities (e.g., erosion of foundations, footings or fill) than depth. The maximum permissible velocity depends on soil type, vegetation cover and slope but ranges between 0.8-1.5m/s *(2.62 ft/sec – 4.92 ft/sec)*". (OMNR, 1997)

To summarize, it is the ability to resist collapse for a flood's velocity and depth given. The conditions of collapse given a certain flood's velocity and depth are given for three building construction types. These functions are described in the following tables. It is important to notice that usually under 2ft/(sec) it is assumed that damage is only due to inundation. This assumption constitutes an essential basis in the procedure described in Part 2 and 3.

Table 14 :Velocity-Depth Damage Relationship for Wood Buildings

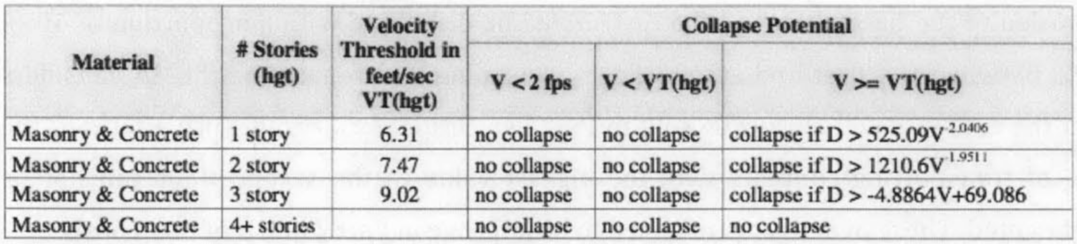


Material	# Stories (hgt)	Depth Threshold in feet DT(hgt)	Velocity Threshold in feet/sec VT(hgt)	Collapse Potential			
				V < 2 fps any Depth	V < VT(hgt) D < DT(hgt)	V < VT(hgt) D >= DT(hgt)	V >= VT(hgt) any Depth
Wood	1 story	10	5.34	no collapse	no collapse	collapse	collapse if $D > 268.38V^{-1.9642}$
Wood	2 story	15	4.34	no collapse	no collapse	collapse	collapse if $D > 268.38V^{-1.9642}$
Wood	3 story	20	3.75	no collapse	no collapse	collapse	collapse if $D > 268.38V^{-1.9642}$
Wood	4+ stories			no collapse	no collapse	no collapse	no collapse

Source: Flood Model – Hazus MH Technical Manual (2006)

Ft^-1
ft^{-1}

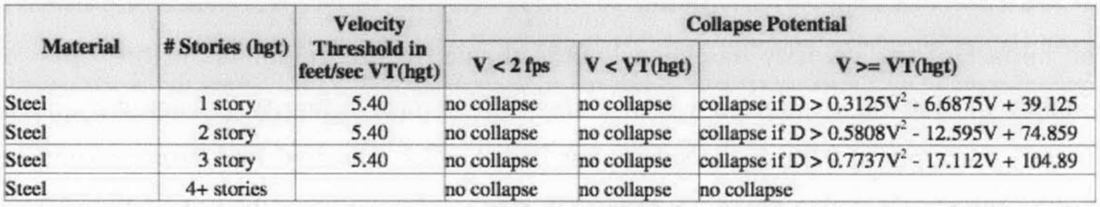
Table 15 : Velocity-Depth Damage Relationship for Masonry and Concrete Buildings



Material	# Stories (hgt)	Velocity Threshold in feet/sec VT(hgt)	Collapse Potential		
			V < 2 fps	V < VT(hgt)	V >= VT(hgt)
Masonry & Concrete	1 story	6.31	no collapse	no collapse	collapse if $D > 525.09V^{-2.0406}$
Masonry & Concrete	2 story	7.47	no collapse	no collapse	collapse if $D > 1210.6V^{-1.9511}$
Masonry & Concrete	3 story	9.02	no collapse	no collapse	collapse if $D > -4.8864V+69.086$
Masonry & Concrete	4+ stories		no collapse	no collapse	no collapse

Source: Flood Model – Hazus MH Technical Manual (2006)

Table 16 : Velocity-Depth Damage Relation for Steel Buildings



Material	# Stories (hgt)	Velocity Threshold in feet/sec VT(hgt)	Collapse Potential		
			V < 2 fps	V < VT(hgt)	V >= VT(hgt)
Steel	1 story	5.40	no collapse	no collapse	collapse if $D > 0.3125V^2 - 6.6875V + 39.125$
Steel	2 story	5.40	no collapse	no collapse	collapse if $D > 0.5808V^2 - 12.595V + 74.859$
Steel	3 story	5.40	no collapse	no collapse	collapse if $D > 0.7737V^2 - 17.112V + 104.89$
Steel	4+ stories		no collapse	no collapse	no collapse

Source: Flood Model – Hazus MH Technical Manual (2006)

2.4 Direct Economic Loss

This section shows how the Hazus Technical Manual estimate the percent damage to turn it into a dollar loss. This dollar loss actually represents a replacement cost. Chapter 14 of the Hazus Technical Manual provides a new approach to estimate the building repair cost, the associated loss of building contents and the business inventory. In its estimation, this section intends to consider the ability of the building to recover or to be operable after a flood hazard. To that end, the notion of a business interruption and rental income losses are also addressed. This last part can not be developed a lot and yet more attention should be paid to address resiliency issues.

There are two aspects in economic loss, the direct and indirect economic loss. Buildings and inventories represent more than structural objects and properties they also represent investments. These investments change in value as we are evolving in a capitalized system and an income loss also exists. So evaluating the economic building damage and the income loss due to the non-functionality of the building can lead to an over-estimation of the indirect economic loss.

The direct economic loss has been done based on the same methodology for the seismic hazard than the publication 227, 228, 255, 256 edited by FEMA. The important difference is that flood loss depends on depth-related percent damage which have an impact on both the structure and the content but these two components are only related by the flood depth.

The aim of this estimation is to include both the building related losses and the income losses over the time. This is why this section includes:

- The building repair and replacement costs
- The building contents loss
- The building inventory loss
- The relocation expenses
- The capital related income losses
- The wage losses
- The rental income losses

As mentioned before, the direct economic loss is an estimation of the cost of repaired damage. It includes facilities loss, which are transportation, water, wastewater, petroleum, natural gas, telecommunications, and electrical power. The previous methodology allows to estimate the damage according two approaches: a full building replacement cost and a depreciation cost model.

2.4.1 Replacement Cost Model

For the replacement cost model, the Hazus methodology provides replacement data that has been computed using Means Square Foot Costs (R.S Means 2006). Each occupancy class is associated with a Means replacement cost.

Assumptions:

- The presence or absence of a basement is not included in cost and is considered to be an additional component.
- The presence of garages is also considered as an additional component. The criteria of the number of cars and the construction class, e.g. economy, average, custom and luxury, are taken into account.

Residential Single Family housings form a specific case for Means computation. The basic idea is that the content and the structural economic loss are evaluated separately and then added. To evaluate the structural loss, the algorithm used for a specific occupancy table is for a given census block:

$$
\begin{aligned}
VRes1 = A_{buil} \times \sum_{i=1}^{4}\sum_{j=1}^{4} w_i \times w_j \times C_{i,j} + A_{base} \times w_b \times \sum_{i=1}^{4} \times \sum_{j=1}^{4} w_i \times w_j \times C_{i,j,b} + N_{Res1} \\
\times \sum_{i=1}^{4} \times \sum_{j=1}^{4} w_i \times w_g \times C_{i,j,g}
\end{aligned}
$$

$VRes1$ = dollar exposure value for single-family residences

A_{buil} = total floor area for the associated RES1

A_{base} = total floor area of the basement if present

N_{Res1} = number of RES1 structures within the given census block

w_i = weighting factor for Means construction class

w_j = weithing factor for the Number of Stories class

w_b = weighting factor for basements

w_g= weighting factor for the garage type

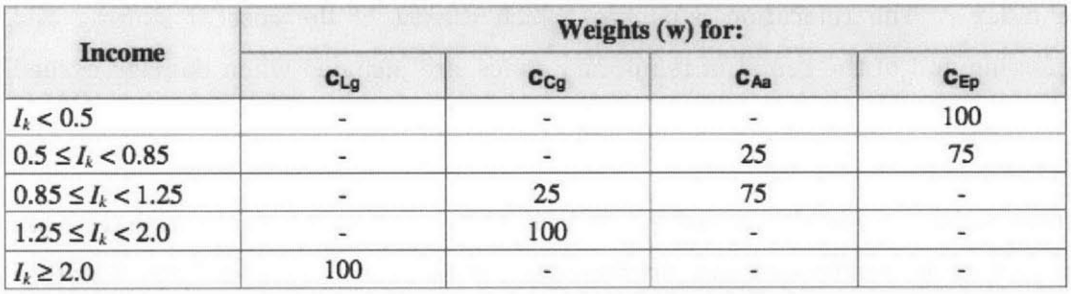
$C_{i,j}$= additional replacement cost for a Res1 given a construction and a stories class.

$C_{i,j,b}$= additional replacement cost for a basement given a construction class

$C_{i,j,g}$ = additional replacement cost for a given garage type and given a construction class

The weighting factors are based on the same income ratio defined earlier which is the ratio of the census block group income over the average income from the region. They are defined in the Table below. Indeed, the Hazus Manual's aim is to consider the income loss and to adjust the cost of replacement depending on the region and the population. Means 2006 provides construction class -Luxury, Custom, Average, Economy – and Hazus tries to improve its first approximation. The consumer price index allows the users to adjust the cost over the years.

Table 17 :Weights (percent) for Luxury, Custom, Average and Economy Construction class



Income	Weights (w) for:			
	C_{Lg}	C_{Cg}	C_{Aa}	C_{Ep}
$I_k < 0.5$	-	-	-	100
$0.5 \le I_k < 0.85$	-	-	25	75
$0.85 \le I_k < 1.25$	-	25	75	-
$1.25 \le I_k < 2.0$	-	100	-	-
$I_k \ge 2.0$	100	-	-	-

Source - Hazus Technical Manual

To summarize, the valuation is a function of the Means construction class, the number of stories, and an additional cost if a basement and a parking exist. The results are given in dollars. For the other occupancy class, the computation of the loss is easier and only consists of the product of the floor area with the associated Means costs. As for the content replacement cost, the depth-damage curve provides a percent of content loss that needs to be replaced. They account for 50% of the replacement value of the structure of the building and Hazus is using national average costs. The inventory loss is evaluated using the appropriate curve among the 144 inventory depth damage curves provided by the Us Army Corps of Engineer. A simplified formula for its estimation is for a specific occupancy:

$INV = \sum_j \%Dam_j \times A_j \times S \times B$

INV = value of inventory losses

$\%Dam_j$ = inventory damage in percent for a depth j

A_j = floor area of the occupancy group for a depth j

S= annual gross sales or production

B = business inventory as a percentage of annual gross sales

2.4.2 Other parameters

The hazus methodology also considers the relocation expenses and has gathered a comprehensive database of rental costs. However, their numbers have to be adapted throughout the years as the income and means costs are adjusted using the Consumer Price index . The relocation expenses, which consist of the cost of shifting and transferring and of the rental of temporary space, are included when damage exceed 10%.

The restoration time is also accounted. Indeed, some important hypotheses have been made such as the destruction and reconstruction when damage exceeds 50%. An other interesting point is that outside the 100-year flood plain, the reconstruction is assumed to last eighteen months which allows twelve months for physical construction and six months for determination, permits, approvals. Inside this same plain, the reconstruction is not allowed. Other factors as income loss, rental income loss, utility systems, bridges, vehicles and agricultures losses are also described in the Chapter 14 of Hazus Technical Manual.

This first part is a description the Hazus Technical Manual in order to provide an overview of what can still be done. As mentioned before, the Hazus Technical Manual is based on a regional scale prevents an engineer from using it as an easy tool to evaluate flood damage in buildings. The following part is a simplified methodology of this first part to allow an engineer to estimate building damage.

3 Practical Method for Flood Damage Evaluation in Buildings

3.1 Crucial Parameters

The aim of this chapter is to provide a simple methodology for estimating potential flood losses at a building scale. FEMA has provided a detailed methodology based on a wide range of data but this procedure is not really appropriate for a single building. This chapter intends to be the first step of future numerous extensions in a probabilistic evaluation of flood damage.

The loss estimation methodology established by FEMA for floods is different from the other hazard procedure because the damage is estimated from depth-damage curves. These curves are based on an important collection of data. As a result, one difficulty was to find an expression of a damage function. Each specific building is related to a default function assigned by the manual. For example, one function can represent the curve for a single-family one-story residential building on a slab foundation. However, this does not allow an engineer to understand the sensibility of each parameter, e.g., the type of foundation, on the damage.

In order to circle the problem, based on Hazus database, this thesis interpolates the curves described in the Manual. Then it correlates the results to the parameters in order to estimate a total damage and to see how it affects the structure.

The estimation process can be split into 3 principal steps. The first one consists in evaluating the total damage. It includes structural damage, content damage, determining whether the building collapses or not, and then the reactiveness of the population only if they are warned about the hazard soon enough to reduce losses. Once the expected loss is computed for any flood depth, another step is to evaluate the expected annual flood loss given the frequency of exceedance of the flood depth. An other final step can be added using the example of hurricane and earthquake methodologies which approaches the estimation loss through a sub-assembly procedure. Indeed, once the total damage is estimated, based on the sub-assembly approach, a resulted damage in each assembly can be determined.

This first part describes the different instruments needed in the estimation process. This section is based on the database supplied by the Hazus Technical Manual.

3.1.1 Damage Functions

As the Hazus Manual does not provide the depth-damage function expressions, the FIA credibility-weighted building depth-damage curves issued by the NFIP Actuarial Information System (1998) have been approximated to build a sample damage function. However, the FIA curves, which concern the residential single-family housing, RES1, are based on insurance claims that mislead the total loss especially concerning the basements. As a result, Hazus has taken the initiative to adapt the FIA curves to add this forgot loss by FIA. After studying the claims and calculations in order to consider the lack of accuracy of the FIA curves regarding the basement, it has been assumed that all structure losses with a basement should be increased in two ways. A first rise is added until the ground elevation after which the rise becomes even more important.

An interpolation in Excel of the curves provided by Hazus' graph gives the equations of the depth-damage functions that are used to start the following estimation process. The depth-damage function are respectively corresponding to the following structures:

- One-story building without basement - curve
- One-story building with basement - modified curve
- Two-story building without basement - curve
- Two-story building with basement - modified curve
- Two-story split level building without basement - curve
- Two-story split level with basement - modified curve
- Mobile home no basement - curve

The curves in Figure 2 indicate how the FIAs' curves have been approximated. An interesting trend is that they all tend to a percentage of damage that never reaches

100%. This is due to the fact that these curves only concern structural damage, and floods are unlikely to make structures collapse. A last remark is that, with or without a basement, at the level of the ground (d=0 foot), damage in the building never equals zero percent.

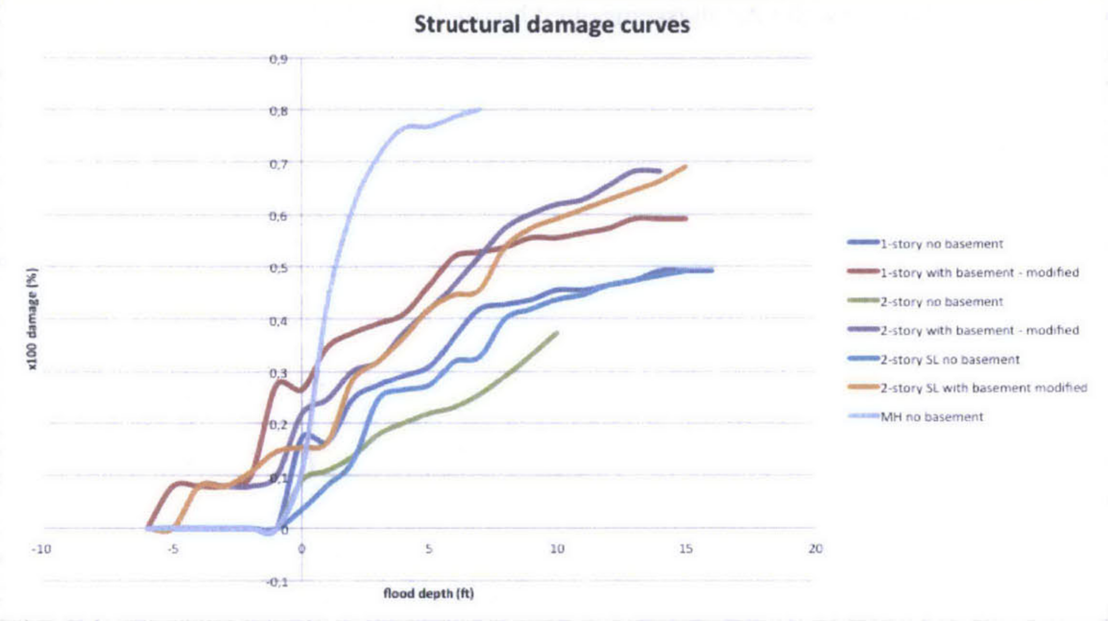


Figure 2 : Approximation of the FIA's curves provided by the Hazus Technical Manual

Then the Excel interpolated curves are adapted to Matlab. The objective is to extend them to a broad range of depths ensuring the functions respect the non-100% damage observed in Figure 2, as well as the presence of a basement which results in losses starting from six feet under the ground elevation. An important assumption is that, to make the separation clear, in a building without a basement, a 0 % loss is assumed for negative depth. The functions in Figure 2 have been programmed in Matlab as described in Figure 3 to 6.

```
function [y]=onestory_nobase(d)
%function of the depth-damage curve of a one story building without basement
if d<0
  y=0;
elseif (0<=d) && (d<=9)
  y = -1E-06*d^5 + 7E-05*d^4 - 0.0013*d^3 + 0.0091*d^2+0.0138*d + 0.1669;
else
  y=0.5;
end
```

Figure 3 :One-story building without basement Matlab Code

```
function [y]=onestory_wbase(d)

%function of the depth-damage curve of a one story building with a basement and modified curve to estimate likely basement losses

if d<9
  y = 2E-05*d^4-0.0004*d^3+0.001*d^2+0.0498*d+0.2092;
else
  y=0.6;
end
```

Figure 4 :One-story building with basement Matlab Code

```
function [y]=twostory_nobase(d)

%function of the depth-damage curve of a two story building without basement

if d<0
  y=0;
elseif (0<=d) && (d<=14)
  y = 0.0005*d^2+0.0219*d+0.0954;
else
  y=0.5;
end
```

Figure 5 :Two-story building without basement Matlab Code

```
function [y]=twostory_wbase(d)

%function of the depth-damage curve of a two story Split Level building with basement and modified curve to estimate likely basement losses

if d<-4
  y=0.0674;

elseif (-4<=d) && (d<=10)
  y = 1E-05*d^4-0.0004*d^3+0.0027*d^2+0.0458*d+0.1792;
else
  y=0.7;
end
```

Figure 6 :Two-story building with basement Matlab Code

The principal objective is to conserve the different trends of the Hazus damage curves. These functions provide the structural loss in respect with the type of building. The Matlab functions above compute the percent of loss in the structure, L_S. Then to evaluate the cost of structural damage, a structural value VS is assigned to the building. VS might represent a dollar value to imitate the replacement cost of R.S. Means (2006) used in the Hazus Technical Manual.

3.1.2 Content Damage Functions

The depth-damage functions for the contents have again been approximated from curves provided by the Hazus Technical Manual. Similarly, as for the structural damage, the manual associates one content curve to each building type, e.g. one for a two-story building and it associates a different one with a one-story building. It divides the content between different stories and the basement, attributing one-third to the basement and 60% of the rest to the first floor and the last 40% to the second floor. In this section, another approach is undertaken. Instead of using a fixed repartition of content, a one-floor content function, which is approximated from the one-story building FIA content curve and called *fstory*, computes the content loss L_c for each floor, and a different value, V_c , can be assigned to a each content loss L_c. Unlike FEMA's methodology, the same depth-damage content curve has been used for the basement's contents and those of the building. So the process consists of computing the content damage for each floor and then adding them to estimate the overall content damage.
The program delivers a content loss estimate: $\sum_{\substack{number \\ of\ floors}} L_c \times V_c$

The Matlab code corresponding to the computation of the content damage through the floors can be found in Appendix 8.3. An important assumption has been made in order to estimate the content damage: as a content value is assigned by floor, a floor height of 10 feet has been assumed.

3.1.3 Effect of Flood Velocity

In the previous chapters, it is shown that velocity has a certain impact on the structure. The same assumptions have been used. The Hazus Technical Manual specifies functions that reflects the ability of the building to resist collapse, given a flood velocity, a flood depth, a number of stories, and a construction building type, e.g. wood, masonry and concrete, and steel. These functions are described in the following tables taken from the Hazus Technical Manual.

The results of this function allow to determine if the building does or does not collapse under the flood conditions. A building that collapses implies 100% of content and structural components are lost. On the contrary, if the building resists, then damage are assumed to only result from the inundation loss.

Table 18 :Velocity-Depth Damage Relationship for Wood Buildings

Material	# Stories (hgt)	Depth Threshold in feet DT(hgt)	Velocity Threshold in feet/sec VT(hgt)	Collapse Potential			
				V < 2 fps any Depth	V < VT(hgt) D < DT(hgt)	V < VT(hgt) D >= DT(hgt)	V >= VT(hgt) any Depth
Wood	1 story	10	5.34	no collapse	no collapse	collapse	collapse if $D > 268.38V^{-1.9642}$
Wood	2 story	15	4.34	no collapse	no collapse	collapse	collapse if $D > 268.38V^{-1.9642}$
Wood	3 story	20	3.75	no collapse	no collapse	collapse	collapse if $D > 268.38V^{-1.9642}$
Wood	4+ stories			no collapse	no collapse	no collapse	no collapse

Source: Flood Model – Hazus MH Technical Manual (2006)

Table 19 : Velocity-Depth Damage Relationship for Masonry and Concrete

Material	# Stories (hgt)	Velocity Threshold in feet/sec VT(hgt)	Collapse Potential		
			V < 2 fps	V < VT(hgt)	V >= VT(hgt)
Masonry & Concrete	1 story	6.31	no collapse	no collapse	collapse if $D > 525.09V^{-2.0406}$
Masonry & Concrete	2 story	7.47	no collapse	no collapse	collapse if $D > 1210.6V^{-1.9511}$
Masonry & Concrete	3 story	9.02	no collapse	no collapse	collapse if $D > -4.8864V+69.086$
Masonry & Concrete	4+ stories		no collapse	no collapse	no collapse

Source: Flood Model – Hazus MH Technical Manual (2006)

Table 20 : Velocity-Depth Damage Relation for Steel Buildings

Material	# Stories (hgt)	Velocity Threshold in feet/sec VT(hgt)	Collapse Potential		
			V < 2 fps	V < VT(hgt)	V >= VT(hgt)
Steel	1 story	5.40	no collapse	no collapse	collapse if $D > 0.3125V^2 - 6.6875V + 39.125$
Steel	2 story	5.40	no collapse	no collapse	collapse if $D > 0.5808V^2 - 12.595V + 74.859$
Steel	3 story	5.40	no collapse	no collapse	collapse if $D > 0.7737V^2 - 17.112V + 104.89$
Steel	4+ stories		no collapse	no collapse	no collapse

Source: Flood Model – Hazus MH Technical Manual (2006)

Table 18 to Table 20 are describing the collapse conditions for Wood, Masonry, and frame and Figure 7 represents the collapse curve for masonry and concrete frame.

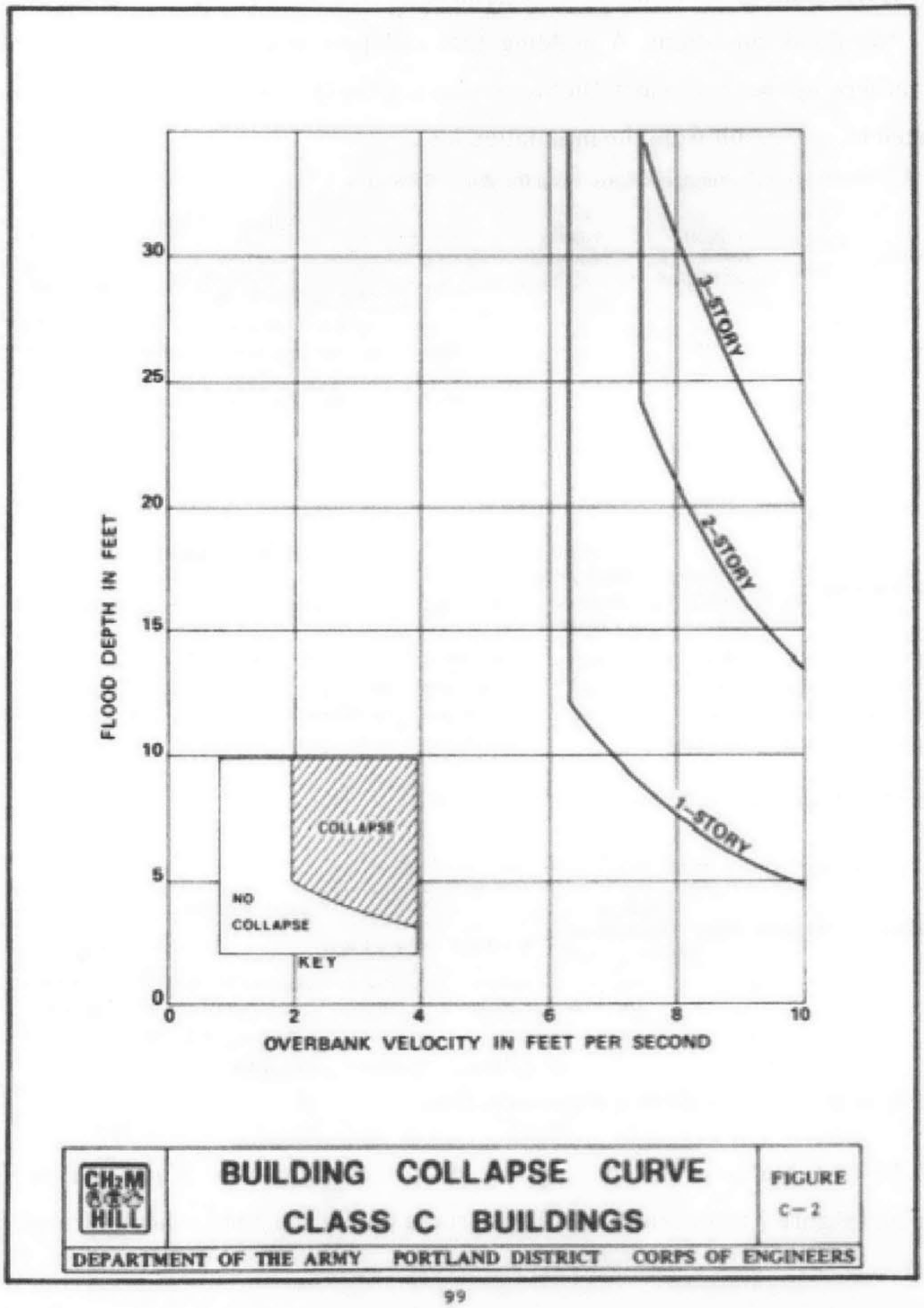


Figure 7: Building collapse curve for masonry and concrete bearing wall buildings developed by the USACE Portland District (USACE, 1985)

3.1.4 Early Warning of the Population

The Hazus methodology also considers the result of warning the population. Indeed, depending on how long, before the hazard the population is warned, this one has the time to react and to protect both the structure and the content of buildings. In that case, a reduction of damage should result from this attitude. In 1984, the New York District the U.S. Army Corps of Engineers has published a Day Curve that reflects the decline of damage in percent that can be observed if the population is warned. A maximum damage reduction of 35% of total damage has been estimated. (USACE, 1984). Similarly to the damage curves, the Day curve has been estimated from the one provided by Hazus, and programmed in Matlab as follows.

```
function [y]=reaction(t)
% represent the decrease of the damage if people are warned about the hazard and have enough time to react.
if t<1
  y=0;
elseif t>1 && t<42
  y=-(0.081*log(t)+0.0256);
else
  y=-0.35;
end
```

Figure 8: Reaction function, Matlab code

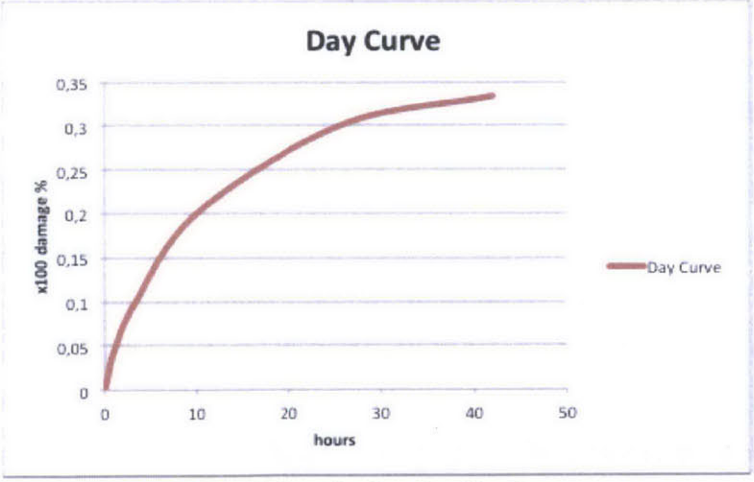


Figure 9: Reaction function, Day Curve

3.2 Estimation of Total Damage

3.2.1 Main Process for a Given Flood

The overall appendix provides a program which includes all the previous functions and allows to estimate the percent of damage in the overall building. The main function *damage* is described in Appendix 8.1. This methodology considers the content loss, the structural loss, the velocity's impact, and the population's reaction. The main steps are:

- Computing the cost of structural damage: $L_s \times V_s$
- Computing the cost of content damage: $\sum_{\substack{number \\ of\ floors}} L_c \times V_c$
- Computing the cost of total damage: $L_s \times V_s + \sum_{\substack{number \\ of\ floors}} L_c \times V_c$
- Calculating the total building value

$V_b = V_s + \sum_{\substack{number \\ of\ floors}} V_c$

V_b *is* the value of the total building including its content

The total building loss is then:

$$L_b = (L_s \times V_s + \sum_{\substack{number \\ of\ floors}} L_c \times V_c) \times \frac{1}{V_b}$$

3.2.2 Sub-Assembly

As mentioned in the previous chapter, the Hazus flood methodology is not similar to the Earthquake and Hurricane one. The flood estimation process does not permit to highlight the damage on each component and only computes the overall damage. The intention of this function is to provide an estimation of the damage in the different building's components. Using Table 3 and the value of the overall building damage, Hazus produces a distribution of flood losses to building sub-assemblies as a function of flood-only building loss. These tables also allow to consider the age of the building as the distinction between Post and Pre-FIRM has been done. The percent damage attributed to each assembly according the Hazus Methodology is shown in the following tables.

Table 21 : Flood Sub-Assembly Loss Table for a Pre-FIRM, Single-Family Residential Homes

Building loss Pre A	Foundation	Below First Floor	Structure Frame	Roof covering	Roof framing	Exterior walls	Interior
0%	0%	0%	0%	0%	0%	0%	0%
10%	0%	20%	0%	0%	0%	4%	14%
20%	0%	40%	0%	0%	0%	12%	26%
30%	0%	60%	0%	0%	0%	21%	37%
40%	0%	100%	0%	0%	0%	30%	48%
50%	0%	100%	0%	0%	0%	39%	60%
60%	0%	100%	0%	0%	0%	47%	74%
70%	0%	100%	0%	0%	0%	56%	86%
80%	0%	100%	5%	14%	5%	68%	94%
90%	5%	100%	26%	27%	26%	83%	96%
100%	10%	100%	50%	50%	50%	86%	100%

Table 22 : Flood Sub-Assembly Loss Table for a Post-FIRM, Single-Family Residential Homes

Building loss Post A	Foundation	Below First Floor	Structure Frame	Roof covering	Roof framing	Exterior walls	Interior
0%	0%	0%	0%	0%	0%	0%	0%
10%	0%	20%	0%	0%	0%	4%	14%
20%	0%	40%	0%	0%	0%	12%	26%
30%	0%	60%	0%	0%	0%	21%	38%
40%	0%	100%	0%	0%	0%	30%	49%
50%	0%	100%	0%	0%	0%	39%	63%
60%	0%	100%	0%	0%	0%	47%	77%
70%	0%	100%	0%	0%	0%	56%	90%
80%	0%	100%	5%	14%	5%	74%	96%
90%	5%	100%	26%	27%	26%	90%	98%
100%	16%	100%	55%	55%	55%	93%	100%

The program in Appendix 8.4 shows that given a total building loss value, the damage in the foundation, the below first floor assembly, the structure frame, the roof covering, roof framing, the exterior walls and the interior can be computed.

3.2.3 Flood Depth for Different Return Frequencies

The previous functions compute the expected loss for a flood depth, L(d). This last consideration implies that L(d) corresponds to a specific flood, i.e. defined by a depth, a velocity and a frequency. This last criterion has still not been treated in the procedure. The depth frequency is the probability that the point considered will suffer from a flood that have at least this flood depth. If N(d) represents the number of flood of depth greater than d per year, and n(d) is the derivative then the expected annual loss can be computed with the following formula :

$$L = \int_0^{\infty} (L(d) * (-n(d)))dd$$

The probability of occurrence of any flood depth varies greatly among the probabilistic models used and the location where floods are being predicted. So one approach is to use generic functions representing the annual frequency of exceedance of the depth, which is actually the function N(d).

For a first approach of the depth-frequency relation, instead of considering a broad combination of return period and associated depth, only two relations are considered. Moreover an inverse power law function is considered to parameterize a curve that would relate the values in Table 23 in which d1 and d100 are depth values. For each specific depth, d1 and d100, a density function with the shape $y = \frac{A}{x^B}$ with A and B constant is determined through Matlab.

Return Period	Depth
1-year	d1
100-year	d100

Table 23 : Depth-Frequency relationship

It is then interesting to see how could vary the expected damage in function of the depth attributed to a 1-year and a 100-year flood. Figure 10 shows how should look like a density curve before being approximate with the previous equation. This curves has been made using more than 2 return period. It is important to note that the equation $y = \frac{A}{x^B}$ results in very high values near the origin. This is why a constant value needs to be assigned for values near the ordinate axis, which is in Figure 10 at (x=-6) ft.

Moreover, the second important characteristic is that for high values of depth, the curve tends to reach zero.

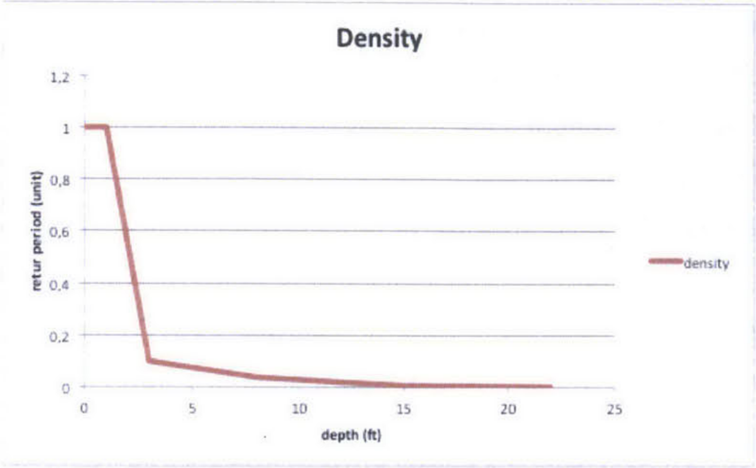


Figure 10 : Density curve

3.3 The estimation process for a given flood

The loss estimation process implemented in Matlab contains four principal programs:

- The function called *Damage* whose process is described in Figure 11 and computes a total loss for a given depth, velocity, type of structure, content and structural value, and a warning time.
- The function called *Damage2* whose process is described in Figure 12 and computes the number of stories, the structural loss, the content loss at each floor, the total content loss and the total damage loss for the same inputs as *Damage.*
- The function called *Sub_Assembly* whose process is described in Figure 13 and computes the loss in the following sub-assemblies - Foundation, Below-First-Floor, Structure Frame, Roof Covering, Roof Framing, Exterior Walls, Interiors - for a given depth, velocity, type of structure, content and structural value, warning time and building age.
- The function called *Annual_Loss* whose process is described in Figure 14 and computes the Expected Annual Loss given a depth, velocity, type of structure, content and structural value, and warning time.

3.3.1 Description of "Damage"

Figure 11 below describes the inputs required for running the program and the resulting outputs.

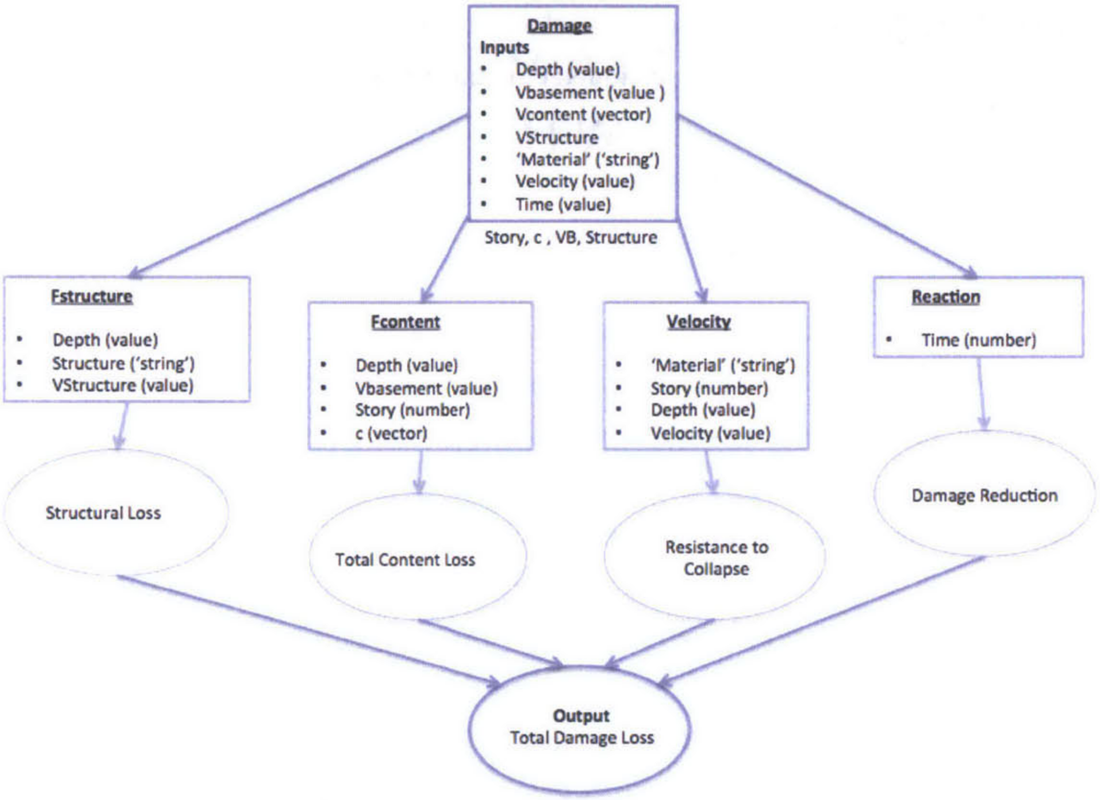


Figure 11 "Damage" Process Description

The users must enter as inputs:

- *d*, the flood depth, which is a number
- *Vbasement*, the value of the basement, which testifies of its presence or not. *Vbasement=0* means that the building does not have any basement.
- *Vcontent*, the value of the building content, which is represented by a vector. Each component represents the content floor of the building. The basement content is not included in *Vcontent.*
- *VS*, the value of the building's structure, which is a number
- *'Material'* defines the material in which the building is built. This parameter requires to use the velocity function and it can takes as value either: *'wood', 'steel' or 'masonry'.*
- *v,* the value of the velocity of the flood

- *t,* the time that was awarded to warn the population of a future hazard which is also a number.

Once these parameters are entered, the program starts computing the number of stories of the building. Then it creates a vector, *c*, which has, for its first component, the value of the basement, and then "*c*" will be completed by the vector *Vcontent*. The next step is to assign a damage function to the structure. Now that the number of stories and the presence of a basement are determined, it is possible to assign a particular damage function, e.g., '*twostory_wbase'*, for example. The structure loss is then computed thanks to the function *fstructure* which, given VS and the name of the *'structure'*, provides $L_s \times V_s$ which represents the product of the loss of the structure times the value of the structure, i.e., the cost of the structural loss. To compute the content loss, *Damage* needs to call the function *fcontent* that, given a content vector *c* (which now includes the basement's contents), a depth, and a number of stories, can compute the total content damage. To that end, a new vector with the same size as c is computed and, using the function which describes the content loss for a single floor, each component i, which corresponds to a floor, is computed according to the equation $L_c(i) = c(i) \times fstory(e)$, *e* being the elevation of the flood with respect of each floor. To obtain the total content loss, all the components of the vector L_c are added and the *content* function computes $\sum_{\substack{number \\ of\ floors}} L_c \times V_c$.

Until now, the program has computed:

- The cost of structural damage: $L_s \times V_s$
- The cost of content damage: $L_c(i) = c(i) \times fstory(e)$

$$\sum_{\substack{number \\ of\ floors}} L_c \times V_c$$

Then, the function *damage* needs to check if the building can resist collapse. To that end, the *damage* function refers to the *velocity* function which, given the material, the number of stories, the depth, and the velocity, returns *'collapse'* if the building collapses. As mentioned before, the function *velocity* is using Hazus' velocity functions. This verification is necessary to see if the value of 100% of damage needs to be assigned. Otherwise, it is assumed that damage is only a result of the flood inundation. The last function *damage* refers to the *reaction* function which only depends of *t* and which could provide a reduction of damage depending on whether *reaction(t)* is negative or zero.

If V_b is the total value of the building then $V_b = V_s + \sum_{\substack{number\\ of\ floors}} V_c$ and the total damage loss is expressed according to the formula:

$$L_b = (L_s \times V_s + \sum_{\substack{number\\ of\ floors}} L_c \times V_c - reaction(t)) \times \frac{1}{V_b}$$

3.3.2 Description of "Damage2"

The Figure 12 below describes the inputs required for running the program and the resulted outputs.

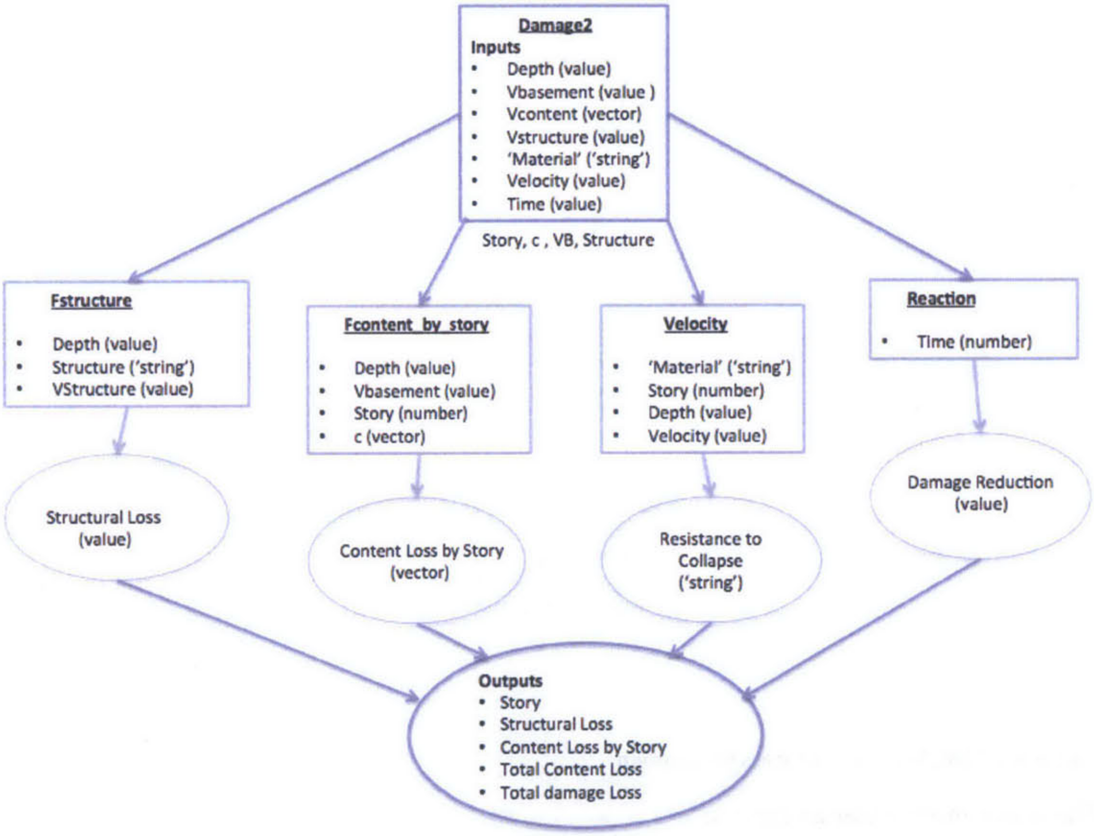


Figure 12: "Damage2" Process Description

The inputs and the functions used are exactly the same as for *Damage*, except that *Damage2* uses the function *fcontent_by_story* which this time return the content loss by story instead of the total content loss. *Damage2* is using the same process as *Damage* but it shows different steps in the process that gives more information about the building studied. Indeed the outputs are the number of stories, the structural loss, the content loss by story (which is still represented by a vector), the total content loss, and the total damage loss.

3.3.3 Description of Sub_Assembly

The Figure 13 below describes the inputs required for running the program and the resulted outputs.

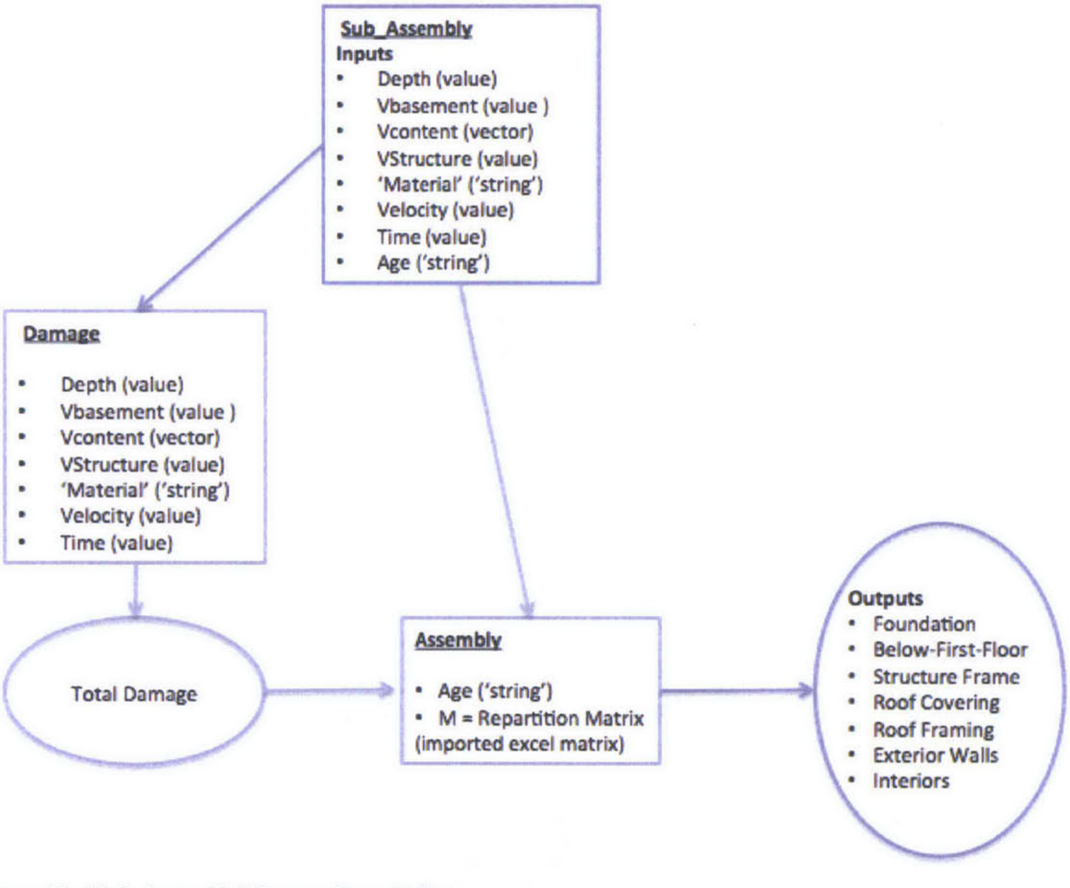


Figure 13: "Sub_Assembly" Process Description

The users must enter as inputs:

- *d,* the flood depth, which is a number
- *Vbasement* , the value of the basement, which testify of its presence or not. *Vbasement=0* means that the building does not have any basement.

- *Vcontent*, the value of the building's content, which is represented by a vector. Each component represents the contents of a floor in the building. The basement content is not included in *Vcontent.*
- *VS*, the value of the building's structure, which is a number
- *'Material'* defines the material in which the building is built. This parameter is necessary to use the velocity function and it can take as value either: *'wood', 'steel' or 'masonry'.*
- v, the value of the velocity of the flood
- t, the to warn the population of a future hazard which is also a number.
- *'Age'* reflects if the building has been built before or after the effective date of the initial Flood Insurance Rate Map, which corresponds to *'Pre'* or *'Post'* as inputs.

Once the parameters are entered, the function *sub_assembly* refers to the function "damage" that computes the total loss of the building L(d). In the database, a matrix representing Table 21 or Table 22, is stocked and called M. The vector *Dassembly* allows to interpolate L(d) between the value 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%. Then the product of *Dassembly* with the column corresponding to a precise *sub_assembly* of *M* allows to compute the damage in each sub-assembly: foundation, below-first-floor, structure frame, roof covering, roof framing, exterior walls, interiors.

The outputs of *Sub_Assembly* are the losses attributed to each sub-assembly. This function allows the users to the loss caused by the flood on each component.

3.3.4 Description of *Annual Loss*

Figure 14 below describes the inputs required for running the program and the resulting outputs.

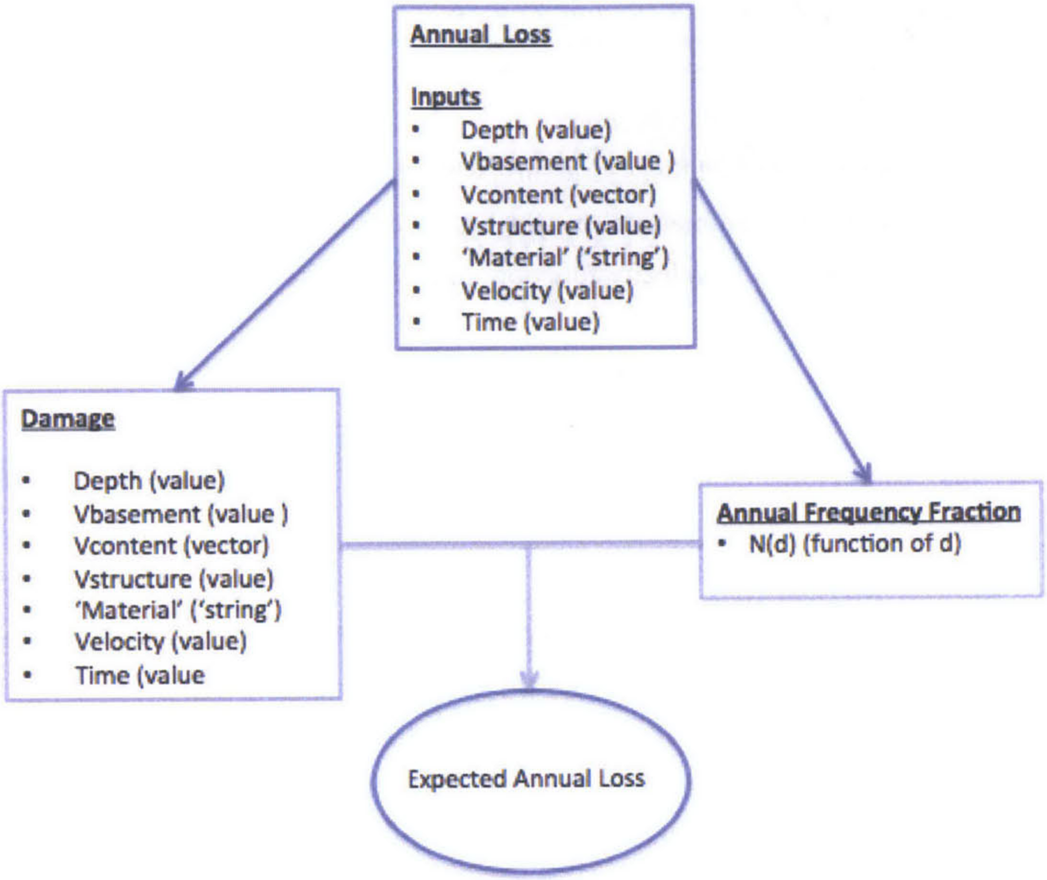


Figure 14"Annual_Loss" Process Description

The aim of the annual loss program is to compute the expected annual loss. That requires to compute the loss caused by all the floods of any depth per year. The damage function computes the loss of the building at a given depth, *L(d)*. Then section 3.2.3 explains that the annual loss is given by the formula:

$$L = \int_0^{\infty} (L(d) * (-n(d)))dd.$$

However, because of the nature of the function *damage*, a simple integral can not be computed. So the process approximates it, using a numerical integration, a sum of rectangles, with a very small step to make it sufficiently accurate. As a result, the formula used to approximate the annual expected loss is :

$$L = \sum_{i=1}^{\infty} L(d_i) \times [N(d_i) - N(d_{i+1})]$$

Figure 15 describes how the density curves (n(d)) has been modeled. To program them, it was assumed that the area under each curve equals one which means that there is one flood each year, which is reasonable. The issue in the model is that as the approximation is done between d1 and d100, the constant depends of d1, and so, for a high depth d1 the density function becomes less accurate in terms of shape. Indeed, we could have make the curve constant before d1 as the value was not too high. Yet, in that case the integral will not be equal to 1. For Figure 15, it is assumed that one flood occurs each year.

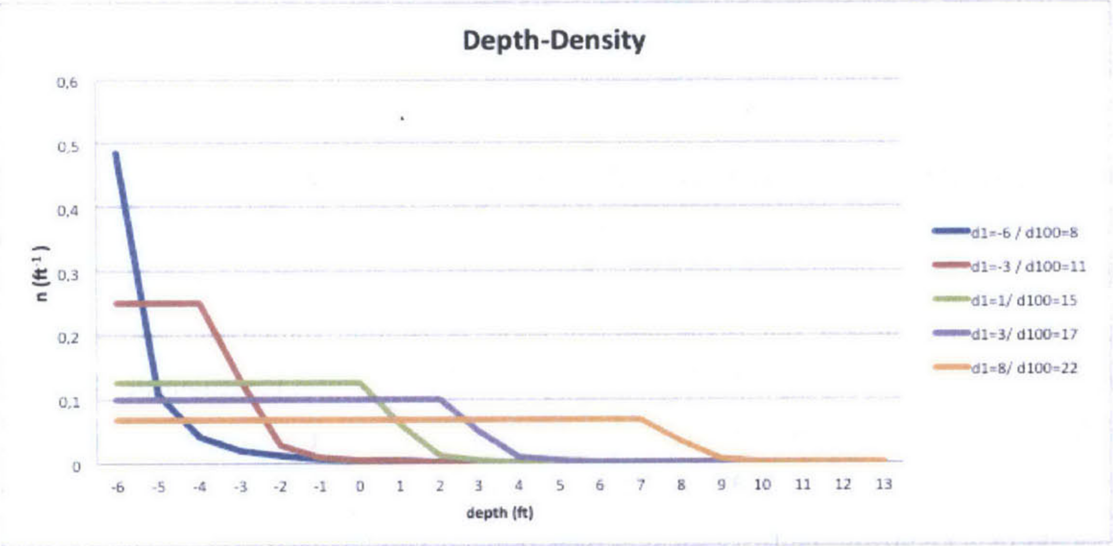


Figure 15: Density curves depending the 1-year and 100-year depth

4 Sensitivity Study

The estimation of flood damage aims at decreasing future damage. The purpose of this chapter is to look at the sensibility of each parameter or input in order to optimize the diminution of flood damage. The *velocity function,* as explained previously govern the collapse, is critical because of its only two outcomes: either damage is total; either damage is only due to the inundation. The choice of material is therefore a first step for reducing damages.

4.1 Sensitivity to Building Material and Flood Velocity

To evaluate the sensitivity, according to the velocity, the effect of each material on a one-story building was not really efficient. Therefore, the comparison between the materials has been conducted on a two-story building without a basement at different velocity. The following figures are showing the influence of the material chosen for respectively a velocity of 4.5 ft.s^{-1}, 6.5 ft.s^{-1}, and 9 ft.s^{-1}. As a result , to compute the loss at a depth of i feet, for Figure 16 the following functions are invoked:

- damage(i,0,[1 1],4,'steel',4.5,0)
- damage(i,0,[1 1],4,'masonry',4.5,0)
- damage(i,0,[1 1],4,'wood',4.5,0)

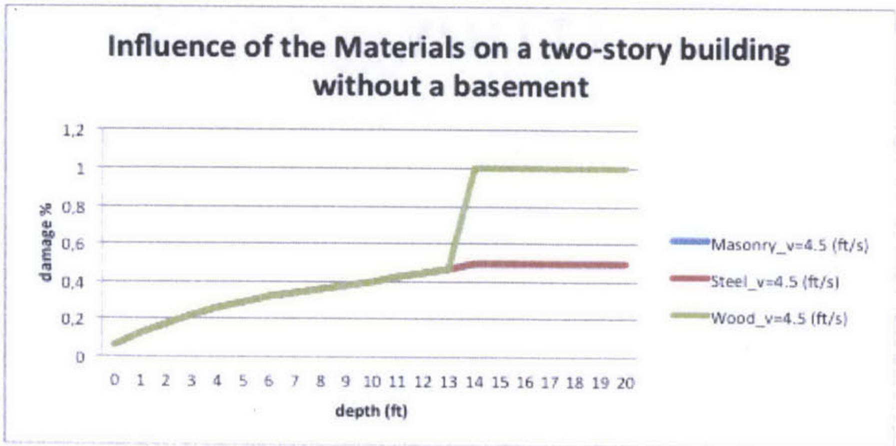


Figure 16: Influence of the construction material on a two-story building without a basement for a flood velocity of 4.5 ft.s^{-1} (blue and red lines are superposed)

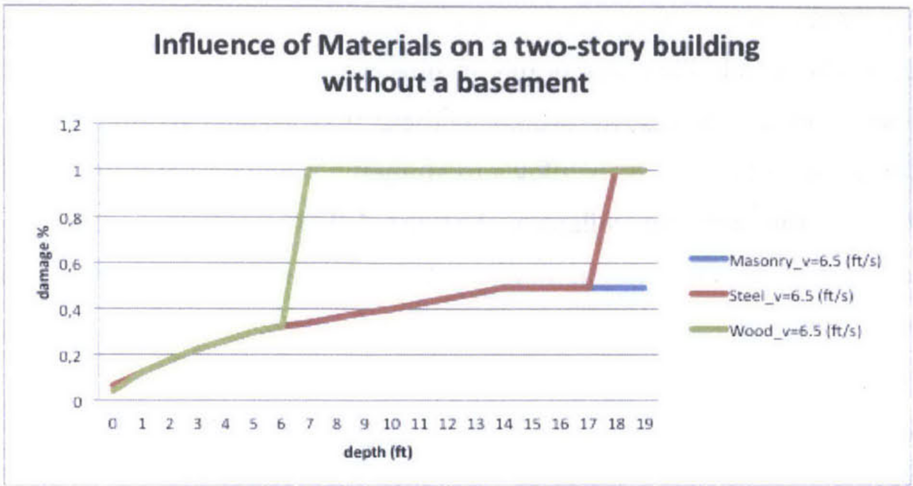


Figure 17: Influence of the construction material on a two-story building without a basement for a flood velocity of 6.5 ft.s^{-1}

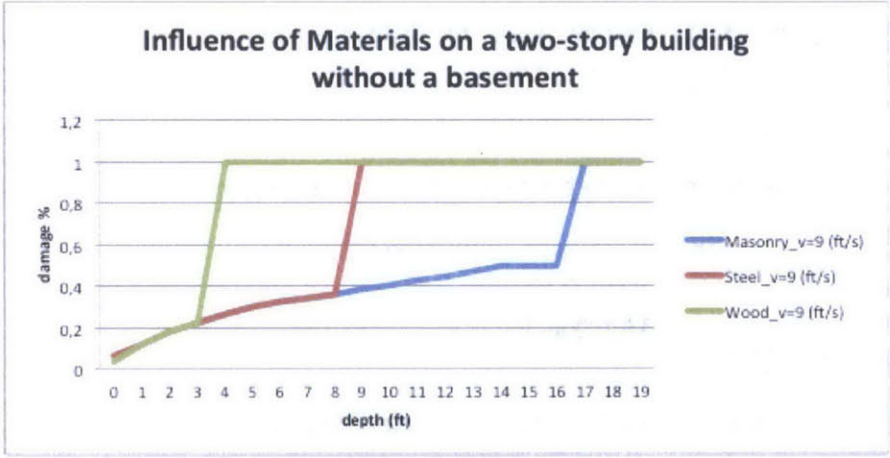


Figure 18 :Influence of the construction material on a two-story building without a basement for a flood velocity of 9 ft.s^{-1}

On Figure 16, Figure 17 and Figure 18, when a single color curve reaches 100% of damage, this corresponds to building collapses. This creates discontinuities corresponding to collapse. On Figure 16, it can be seen that to resist a flood of a velocity that do not exceed 4.5 ft.s^{-1} Masonry and Steel have the same resistance to collapse. Only the wood can not resist a flood depth that will exceed 13 feet for a velocity of 4.5 ft.s^{-1}. Therefore for a location that will not experienced intense floods, the designer can work with the material he desires and would probably choose the cheapest. Figure 17 shows that to resist a flood velocity of 6.5 ft.s^{-1}, for a higher flood depth than 16 feet, this time the use of steel is not efficient against collapse, but masonry is. The architect has, consequently, to be certain that the location of his building is not in an unwelcoming area. Figure 18 shows that whatever the materials, for a velocity of 9 ft.s^{-1} the building cannot resist the flood. This last graph is interesting because it shows the three breaking points of the curves. According to these first graphs, assuming a masonry building for a 2 ft.s^{-1} flood velocity allows to study the sensitivity of other parameters without fearing the building collapses. For the following studies, these previous hypotheses are assumed. It is also assumed that the population has no time to react and protect themselves against flood damage (e.g., *reaction(0)=0*).

4.2 Sensitivity to Presence of Basement and Number of Stories

Another interesting parameter is how damage can vary in function of the number of stories. The Figure 19 below describes the influence of the number of stories on a masonry building without a basement. The value of the content is assumed to be the same for each floor. Moreover, the Hazus Technical Manual estimates that the value assigned to the content should represent 50% of the structure's value. As a result , to compute the loss at a depth of i feet, the following functions are running:

- damage(i,0,[1],2,'masonry',2,0)
- damage(i,0,[1,1],4,'masonry',2,0)
- damage(i,0,[1,1,1],6,'masonry',2,0)

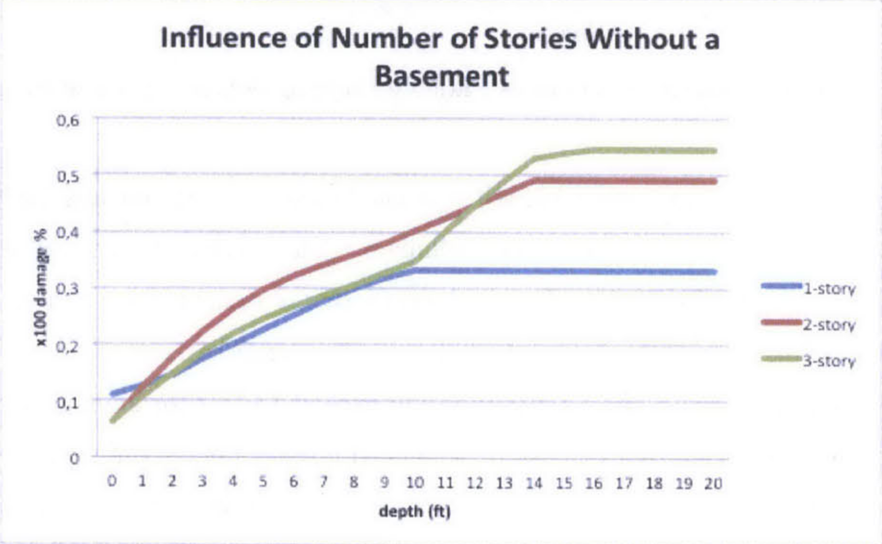


Figure 19 :Influence of the Number of Stories Without a Basement

As can be seen, before 10 feet, which corresponds to the change of floor, the damage is quite similar and they all reach a constant level under 100% of damage. One can notice that the one-story building experiences less final damage than the other one which is realistic. As the access to the structure damage curve for a three-story building is not available, the two-story and three-story building are using the same *damage function* for the structure. As a result, it is normal that, proportionally, for a same depth, a three-story building is less damaged than a two-story one. What is less accurate is the jump experienced by the three-story after 10 feet. It might result from the fact that the effect of the *content damage* is more important at this depth compared to the structure damage. Indeed, at this depth, the *structural function* is constant while the *content function* is highly increasing. Both functions combined together result in a change of behavior for the three-story building. A last remark is that it is natural that between 14 and 20 feet, the three-story damage tends to be constant. Firstly, the third floor has not been reached yet and secondly, the *damage content by story* and the *structural curve* have both a constant shape.

Figure 20 is studying the same criteria but assuming the presence of a basement. It is interesting to note that compared to Figure 19, the curves keep the same shape but are closer from each other in values. Because of the basement's presence, damage is higher for smaller depths especially for the one-story building that tends to behave as a two-story building. Again, it is reasonable that, for lower depths, a three-story building is less impacted than a two-story building as the loss is expressed as a percentage.

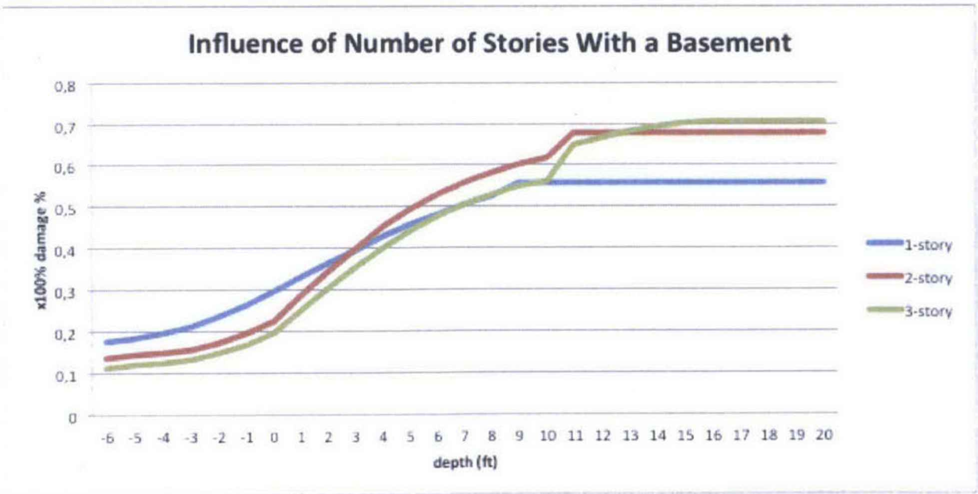
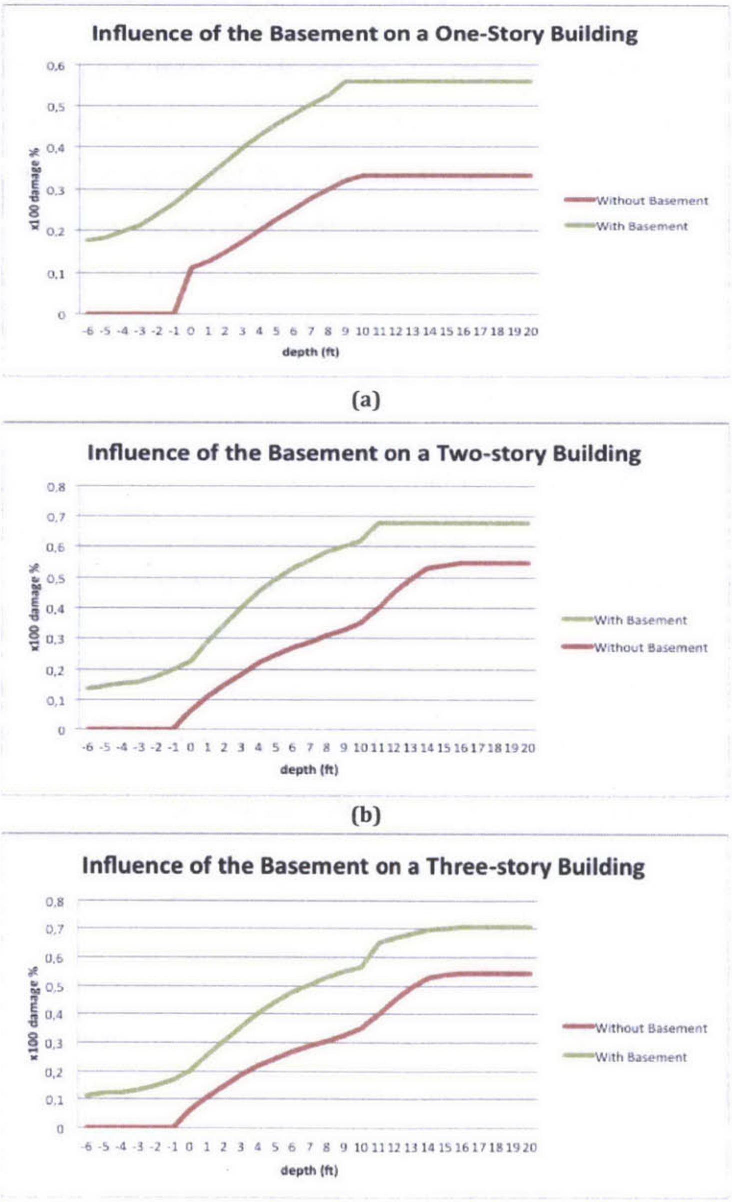


Figure 20 :Influence of Number of Stories with a basement

Figure 21 shows the influence of the basement on a same building. For the same reason as before, it can be notice that the gap between the curves which represents a building with a basement and the curves without a basement decreases with the number of stories increasing. It can be surprising that the curve (c) is slightly higher than 100%. This error is likely to stem from the use of a two-story structural curve instead of an accurate three-story one that would have provided a smaller structural damage for a same depth.



(a)

(b)

(c)

Figure 21 : Influence of the Basement depending the number of stories (a) one story (b) two stories (c) three stories

4.3 Sensitivity to Contents

As mentioned above, the content seems to be an important factor and so it could be interesting to see how the damage changes depending the location of the content. To that end, the previous assumptions are maintained. To highlight the role of the content, no basement is assumed at all. The focus is done on a two-story masonry building, because, regarding the hypothesis and previous results, it is most representative and allows to show numerous impacts. Figure 22 shows that putting all the contents on the second floor can reduce significantly the damage. The *reaction* function, that has not been used yet in this study, makes more sense now. Indeed, if the population is warned about the hazard in time, they will have time to put the content upstairs so that they can diminish the damage.

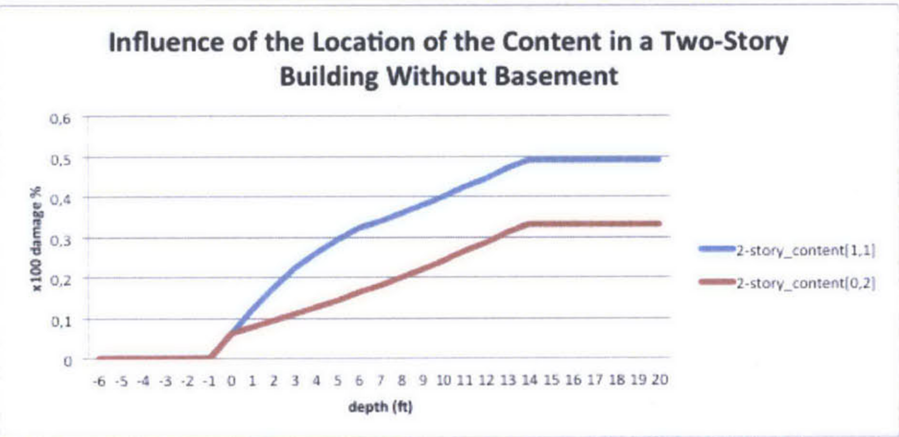


Figure 22 : Influence of the location of the content in a 2-story building without a basement

4.4 Sub-Assemblies' Sensibility

Another interesting point could be the effect of the presence of a basement on the sub-assemblies. It could highlight how sensitive is each sub-assemblies. To underline the effects of the basement on a sub-assembly, the study was done on a one-story building. Indeed, the damage affects at first such assemblies as foundation and below-first-floor. Figure 23 and Figure 24 show that the sub assemblies the more affected are below-first-floor, interior and exterior walls. The interior accounts for a significant part of the damage but can be easily protected. It may be an easy first solution to diminish flood damage. It is also interesting to note that the foundations are not impacted by damage. Foundations are designed according the building code and aim at resisting numerous hazard. So it is reassuring that the foundations are not weakened especially for a flood velocity of 2 ft.s-1. Moreover, it is not surprising that neither the roof covering, the roof framing, or the structure frame are impacted. Indeed for a one-story building the total loss does not exceed 34%, which, looking at Table 21 corresponds to 0% of damage for these sub-assemblies.

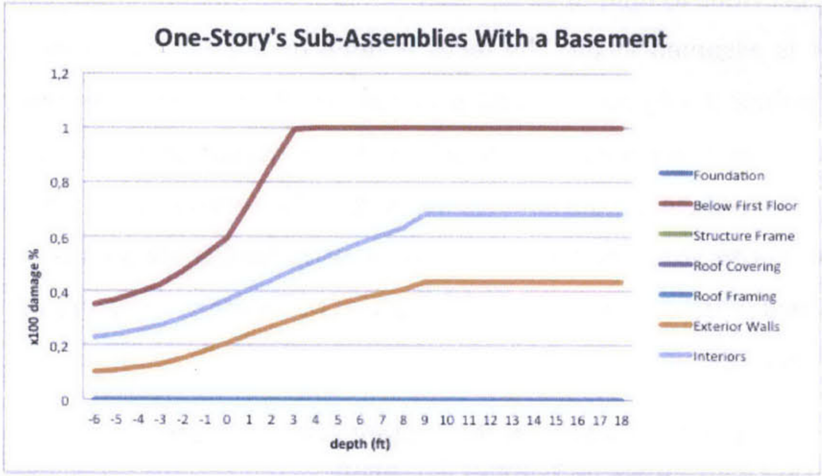


Figure 23 : Influence of the damage on the different sub-assemblies on a one-story building with a basement

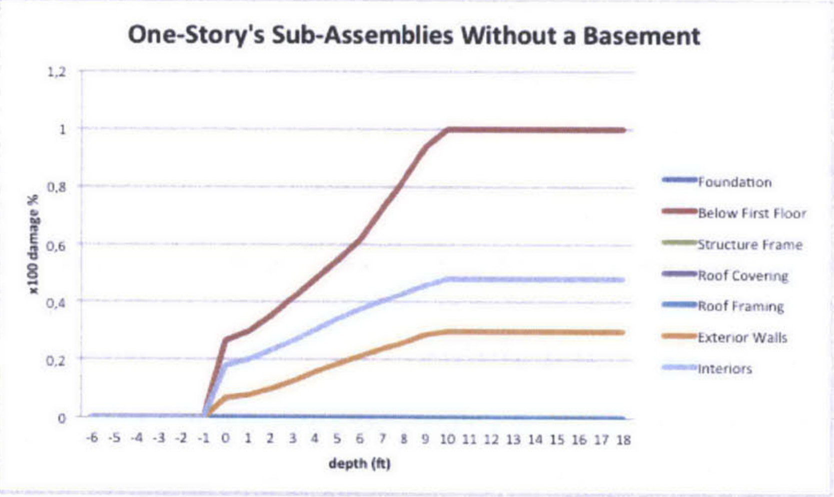


Figure 24 :Influence of the damage on the different sub-assemblies on a one-story building without a basement

4.5 Sensitivity to Frequency of Occurrence

A last parameter that needs to be studied carefully is the effect of the depth chosen for the return period. In particular, these depths are the same depth chosen to construct the *frequency function.* Figure 25 and Figure 26 both show this effect by choosing different values taken for d1 and d100 that correspond to those in Figure 15.

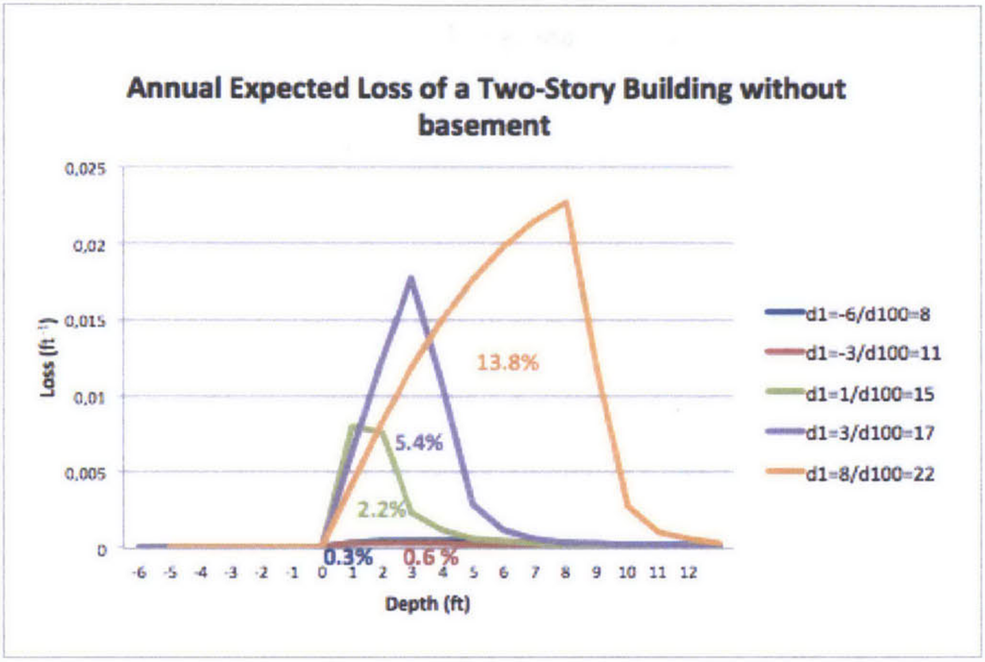


Figure 25: Annual expected loss of a two-story building without basement

On Figure 25, the absence of basement is described by a 0% loss of damage. This makes sense with the model which assumes that a building without a basement do not have any damage under 0 feet which is wrong in reality. The blue curve shows that for frequents inundation with -6 feet and very few with 8 feet depth, the expected annual loss is only 0.3%. This small resulting loss makes sense since the hypothesis means that the building will be flooded many times under at a depth less than -6 feet. Since the studied building has no basement, nothing can be damaged under less than -6 feet. On the opposite the orange curve shows that for frequent inundations of 8 feet depth, the building is expected to be damaged of 13.8%. The fact that the purple curves is at the left side of the orange one demonstrates that the majority of the damage occurs at 3 feet for the purple and 8 feet for the orange. As a result, it can be seen for what depth the damage is more important.

Figure 26 describes the same effect as before but studying a building with a basement. Except the blue curve, observe the same effects as Figure 25 are observed. The only difference is that at six feet under the ground elevation, losses have already begun in a building with a basement. This is why the curves are not beginning at 0. The model obtain 33% damage for a 1-year period depth of 8, which makes sense as it means that the first floor of the building is often impacted. The only problem is when the 1-year period depth is -6 feet. Indeed, the shape is different from the other. This is due to the density assumption. The assumption made is that after d1, the curve is constant. For the blue curve, d1 equals -6 feet, which is here the origin of the graph. So no constant can be accounted.

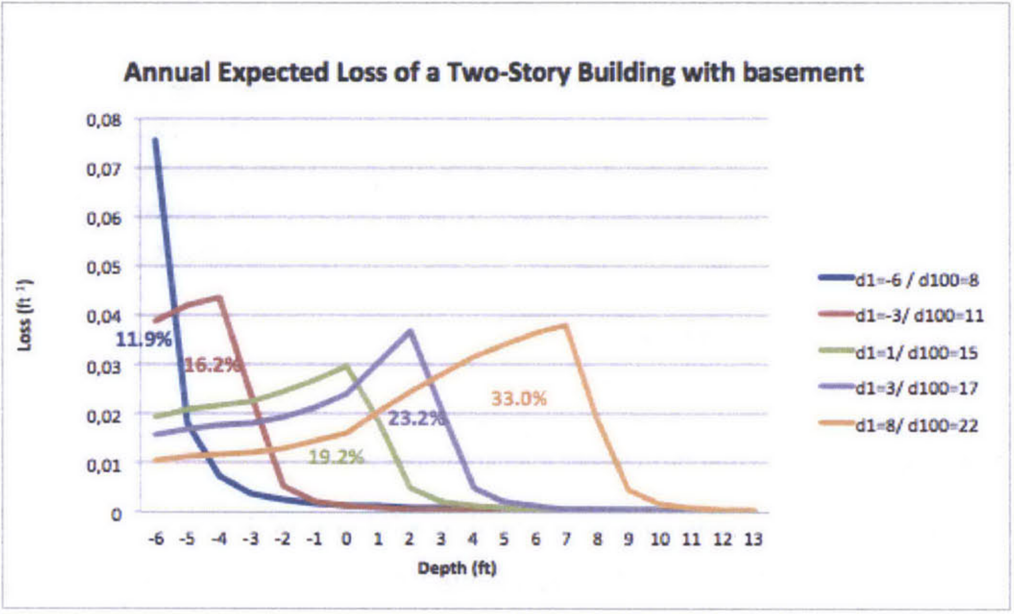


Figure 26: Annual expected loss of a two-story building with basement

5 Conclusion

Through this three-step process - overviewing of the Hazus Technical Manual, implementing an assessment method, and producing example – it has been possible to highlight the important parameters that play a crucial role in the evaluation of flood damage in buildings. Firstly, the distinction between the flood hazard analysis and the flood loss estimation analysis needs to be considered. To simplify, before starting an estimation process, flood frequency, depth and velocity need to be determined. Then, the specific building needs to be evaluated. For a start, the criteria are the square footage, the occupancy class, the construction class, the height, and the foundation and first floor elevation. What is unfortunate is that an expression of the damage function could not have been found. It would have been more rigorous to use one general function for each building that would not have been approximated. Indeed, the Hazus Technical Manual is using a broad range of damage function that varies each time a parameter is modified, such as the foundation type. A global function would have allowed us to highlight the impact of each parameter more efficiently. The sub-assembly approach is an interesting start to study each building's characteristics, but as it uses the FIA's curves as inputs that makes it less accurate.

The last chapter shows how the effect of each parameter can impact flood damage. Only a few tests are described but this part is intended to be continued. A one-story building's exterior walls are significantly damaged. It might be informative to see if the value attributed to the exterior walls is important enough so that it can eventually impact the final cost. If its value is high enough to change the damage cost then it would be worthwhile to try to decrease the exterior walls' loss. This is just a simple example of what can still be done and needs to be done, and I hope the work accomplished in this thesis will be extended and deepened.

6 Definition

- Census block is a “division of land that is based on hard geographic features that allow for the designation of territory” (Hazus-MH, Technical Manual, FEMA)

- Distinction Pre-Post firm : “Pre-Flood Insurance Rate Map (FIRM) buildings are those built before the effective date of the first Flood Insurance Rate Map (FIRM) for a community. This means they were built before detailed flood hazard data and flood elevations were provided to the community and usually before the community enacted comprehensive regulations on floodplain regulation. Pre-FIRM buildings can be insured using "subsidized" rates. These rates are designed to help people afford flood insurance even though their buildings were not built with flood protection in mind.” (National Flood Insurance Program Policy Index, FEMA)

- Flood depth is the difference between the flood and the ground surface elevation.

- Floodplain is a term to define the limit where the flood and the ground elevation are equals.

- The depth flood frequency is defined as the probability that a value is exceed in a given year.

7 References

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- R.S. Means (2002), *Means Square Foot Costs*

- R.S. Means (2006), *Means Square Foot Costs*

8 Appendix

8.1 Matlab Code: Damage Function

```
function [y]=damage(d,Vbasement,VContent,VS,material,v,t)
story=size(VContent,2); %compute the number of stories
  c=zeros(1,story+1); %create the vector of the value of the content:
  c(1)=Vbasement;    %first component is the value of the basement, then the content of the stories from the bottom to the top
  c(2:end)=VContent;
  VB=sum(c)+VS; %value of the all building (structure+content)
  if story==1 %association of the depth-damage curve related to the number of stories and basement
    if Vbasement==0
      structure='onestory_nobase';
    else
      structure='onestory_wbase';
    end
  else
    if Vbasement==0
      structure='twostory_nobase';
    else
      structure='twostory_wbase';
    end
  end % end of association function
  a=fstructure2(d,structure,VS); %computation of the structure loss
  b=fcontent(d,Vbasement,story,c);  %computation of the content loss
  if strcmp(velocity(material,story,d,v),'collapse')==1  % role of the velocity to see if the building is collapsing or if damage are only due to inundation
      y=1;
    else
      y=(a+b)/VB; %computation of the total loss
      if y~=0
        y=y+reaction(t); %consideration of the reaction
      else
        y=(a+b)/VB;
      end
      if y<=0
        y=0;
      end
  end
```

8.2 Matlab Code: Structrure Function

```
function [y]=fstructure2(d,structure,VS)

if strcmp(structure,'onestory_nobase')==1 % compute the value of the loss if the structure is a one story with no basement
  y=onestory_nobase(d)*VS;
elseif strcmp(structure,'onestory_wbase')==1
  y=onestory_wbase(d)*VS;
elseif strcmp(structure,'twostory_nobase')==1
  y=twostory_nobase(d)*VS;
elseif strcmp(structure,'twostory_wbase')==1
  y=twostory_wbase(d)*VS;
elseif strcmp(structure,'twostory_SL_nobase')==1
  y=twostory_SL_nobase(d)*VS;
else
  y=twostory_SL_wbase(d)*VS;
end
```

8.3 Matlab Code: Content Function

```
function [y]=fcontent(d,Vbasement,story,c)
% function that evaluates the content's damage for each floor, and then the total
building' content
% d=depth of the flood so depth can be negative, and if it is then only the basement's
content is damaged.
% v=vector with the value of the contents at each floor.
if Vbasement~=0
  f=zeros(1,story);
  % vector of zeros with the number of floors damaged by the flood with the basement
included in the number of flood
  % the first component of the vector is the basement
  % i=first etage
  for i=1:min(floor((d-1)/10)+2,story)  % the first story is the basement of the building
    e=d-floor((d-1)/10)*10; %computation of the depth of the flood for each floor
(works also when d is negative)
    if d<0
      if i==1
       f(i)=c(i)*fstory(e); % computation of the damage just for floor i
      else
       f(i)=0; % floors above the basement are not damaged if d<0
      end
    else
       if i==1
         f(i)=c(i)*0.9540; % if d>0 the basement is completely inundated
       elseif i<floor((d-1)/10)+2 % define the story that are totally full of water so
completely damaged.
            f(i)=c(i)*0.9540; %floors completely inundated
       else
         f(i)=c(i)*fstory(e); % floor parsely damaged because not totally full
       end
    end
  end
  if floor((d-1)/10)+2 < story % stories' content above the depth flood are not
damaged. attribute 0 damage to their story
    for i=floor((d-1)/10)+3:story
       f(i)=0;
    end
  end
   y=sum(f);
else
  f=zeros(1,story);
  %vector of zeros with the number of floods damaged without a basement.
  %the length of this vector is the same that the one with a basement. To modeled the
absence of the basement, the first component of the vector is zero.
for i=1:min(floor((d-1)/10)+2,story) % the first story is still the basement but its value
is zero
    e=d-floor((d-1)/10)*10; %computation of the depth of the flood for each floor
```

```
    if i==1
      f(i)=0; % there is no basement so no damage at the basement place
    elseif i<floor((d-1)/10)+2 % define the story that are totally full of water so
completely damaged.
       f(i)=c(i)*0.9540;
    else
      f(i)=c(i)*fstory(e); % floors are parsely damaged because not totally full
    end
  end
  if floor((d-1)/10)+2 < story % if the flood depth does not impact all the stories,
attribute 0 damage to their story
    for i=floor((d-1)/10)+3:story
       f(i)=0;
    end
  end
 y=sum(f);
end
```

8.4 Matlab Code: Sub-Assembly Function

```
function
[Foundation,Below_First_Floor,Structure_Frame,Roof_Covering,Roof_Framing,Exterior_
Walls,Interiors]=sub_assembly(d,Vbasement,VContent,VS,material,v,t,age)
g=damage(d,Vbasement,VContent,VS,material,v,t); % computation of the total loss
if strcmp(age,'Pre')==1; % choice of the sub-assembly loss table depending the age
  M=xlsread('RES1_Pre_A'); % read the excel file with th data of the sub-assembly loss
table and convert it in matrix
elseif strcmp(age,'Post')==1;
  M=xlsread('RES1_Post_A');
end
Dassembly=zeros(1,11); % vector with as many lines as the sub-assembly loss table
N=floor(10*g); %interpolation of the real percentage with the percentage from the sub-
assembly loss table
for i=1:11
  if i==N+1
    Dassembly(N+1)=((N+1)/10-g)*10; % difference between the total damage loss
compute and the closer smaller percentage od the sub-assembly loss table
  elseif i==N+2
    Dassembly(N+2)=(g-N/10)*10; % difference between the total damage loss
compute and the closer higher percentage od the sub-assembly loss table
  else
    Dassembly(i)=0; % no damage at this place
  end
end
Foundation=Dassembly*M(:,2:2); % computation of each sub-assembly 's damage
Below_First_Floor=Dassembly*M(:,3:3);
Structure_Frame=Dassembly*M(:,4:4);
Roof_Covering=Dassembly*M(:,5:5);
Roof_Framing=Dassembly*M(:,6:6);
Exterior_Walls=Dassembly*M(:,7:7);
Interiors=Dassembly*M(:,8:8);
```

8.5 Matlab Code: Annual_Loss Function

```
function [x,y]=frequency_positive(d1,d100,d,Vbasement,VContent,VS,material,v,t)

% A=(log(0.01)*log(d1))/(log(d1)-log(d100)); computation of the coefficient of the
density curve
B=log(100)/(log(d100-d1+1));
Nd1= 1/(6+d1+1); %computation of the constant at the top
n=d+7; %number of step in the square function + d must be integer
x=zeros(1,n);
for i=-6:1:d
  if i<d1
    x(i+7)=damage(i,Vbasement,VContent,VS, material,v,t)*Nd1; % area of the integral
before d1 that is constant.
  else
  %x(i-d1+1)=damage(i,Vbasement,VContent,VS, material,v,t)*(B*(i-d1+1)^(-B-1));
  x(i+7)=damage(i,Vbasement,VContent,VS, material,v,t)*((i-d1+1)^(-B) - (i-d1+2)^(-
B))*(B-1)*Nd1; % approximation of the integral L(d)*n(d)
  end
end
y=sum(x); %total damage
```