WOOD FRAME BUILDING RESPONSE TO RAPID ONSET FLOODING

by

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ABSTRACT

Floods are considered to be among of the deadliest, costliest and most common natural disasters. Rapid onset, catastrophic floods inundate the shore quickly and manifest as deep water with high velocities. The deep water and high velocities caused by these floods inflict great pressures and forces on the built and natural environments and pose a threat to human safety. Recent disasters such as Hurricane Katrina in the Southern United States and the Sumatra tsunami in the Indian Ocean have revealed that communities at risk require improved preparations for these types of dangerous events. Current building codes, design practices and disaster planning methods account for potential earthquake and wind loads on simple wood frame buildings typical of North American residential construction, however, flood impacts have not been considered in the same level of depth. The objectives of this research are to develop a theoretical model that describes flood impacts on wood frame residential buildings and relates building response to physical flood properties such as depth and velocity. This thesis provides a brief synopsis of previous approaches used to describe building response to flooding. An overview of the major loads caused by rapid onset flooding, along with a description of the structural system utilized in wood design to resist these forces is provided. The failure mechanisms considered and the model logic are described and applied to assess the response of a typical Canadian wood frame home to flood conditions that might be experienced in a rapid onset flood event like a tsunami. Building response results are discussed along with recommendations for future analysis and applications.

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CO-AUTHORSHIP STATEMENT

Chapter 2 of this thesis is a paper prepared for publication in Natural Hazards Review, co-authored with B.J. Lence and W.M. Johnstone.

Design and identification of the research proposal developed from extensive conversations with B.J. Lence and W.M. Johnstone. Literature review, data collection, model development and analysis were all carried out by A. Becker. The manuscript was prepared with guidance and editorial feedback from B.J. Lence and W.M. Johnstone.

CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW

1.1 INTRODUCTION

Floods are considered to be among of the deadliest, costliest and most common natural disasters. It is estimated that during the 1990s approximately 100 000 people were killed in floods around the world and another 1.4 billion people were affected by these serious disasters (Jonkman and Kelman, 2005). Continued global population growth is causing more development in flood prone regions, creating greater flood risks to people and communities. Canada alone has experienced 260 flood disasters since 1990 with 235 people killed and $8.7 billion in damages (Brooks, *et al.* 2001), while according to the United States Geological Survey, USGS, the United States averages $6 billion in damages and 140 deaths due to flooding each year (USGS 2006a).

Rapid onset, catastrophic floods inundate the shore quickly and manifest as deep water with high velocities. Recent disasters such as Hurricane Katrina in the Southern United States and the Sumatra tsunami in the Indian Ocean have revealed that communities at risk require improved preparations for these types of dangerous events. The deep water and high velocities caused by these floods inflict great pressures and forces on the built and natural environments and pose a threat to human safety. Simple, wood frame residential buildings are common in Canada and the United States. Current building codes, design practices and disaster planning methods account for potential earthquake and wind loads on buildings; however, flood impacts have not been considered to the same degree. The objectives of this research are to develop a theoretical model that describes the response of wood frame residential buildings to physical flood properties such as depth and velocity.

1.2 RAPID ONSET FLOOD RISKS

North American communities are often threatened by slow-rise riverine floods due to excessive rain or snowmelt that cause rivers to overtop their banks. However, Canada and the United States are also at risk from rapid onset, high velocity floods like tsunamis, dam and dike failures, and storm surges. Pressures and forces created by these types of floods can have severe impacts on buildings and infrastructure in settled areas.

1.2.1 STORM SURGE

Coastal flooding in the hurricane season is a significant threat for the Eastern United States. A storm surge is a rise in sea level due to the combination of high winds and low pressures associated with storms like hurricanes (Bowyer 2003). In 2005 Hurricane Katrina became one of the greatest disasters in American history. Storm surges reached heights of seven to eight and a half meters on the Mississippi Coast, while surges of three to six meters breached levees around New Orleans, flooding 80 percent of the city. Over 1800 fatalities directly and indirectly related to the flooding were reported. Total damages due to Hurricane Katrina are estimated to be $81 billion (USD) (Knabb *et al.* 2006).

Mississippi experienced significant damage due to the storm surge. Damage surveys revealed that light, wood frame structures generally did not survive the impacts of the storm surge, with primary failures occurring at nailed connections. Other failure mechanisms observed included wall sheathing failures and racking failures (Eamon *et al*. 2007). Structures were damaged by hydrostatic and hydrodynamic forces, as well as debris forces and scouring actions (Robertson *et al.* 2007).

Canada is also at risk of coastal storm surges. Hurricane Juan made landfall at Nova Scotia in September 2003 causing record storm surges of over one and one half meters and extensive flooding (Environment Canada 2007).

1.2.2 DAM AND DIKE FAILURE

North America has a history of using dams and dikes to control the flow of water. Many large dams impound water above settled areas. Idaho's Teton Dam failed during its first fill in June of 1976. The breach released over 200 million cubic meters of water downstream, killing eleven people. Damage estimates range from $400 million to $2 billion (Perry et al. 2005, Reisner 1986).

1.2.3 TSUNAMI

A tsunami is a series of waves generated by a significant surface impact or sudden movement of the ocean floor that displaces a large volume of water. Disturbances are usually caused by landslides, earthquakes or volcanic activity (Sorensen 1997). Tsunamis that reach the shore have been responsible for catastrophic infrastructure damage and loss of life in many coastal regions throughout the world. Landmasses throughout the Pacific Rim, including Vancouver Island, BC, Canada, are particularly vulnerable to tsunami disasters due to a high frequency of seismic activity.

North America has experienced a number of past tsunami events. In 1929 a 7.2 magnitude earthquake off the coast of Newfoundland triggered underwater landslides resulting in a tsunami that drowned 27 people and caused $2 million in damages. An earthquake and tsunami off the coast of Alaska in 1964 affected coastal communities as far south as California. Port Alberni, BC suffered the greatest impact in Canada, where a 3.6 meter wave caused $4.7 million in damages (1964 dollars) (Natural Resources Canada 2007). Homes were torn from foundations and washed away, logs and lumber became debris projectiles and hydro poles snapped. Many people opened the front and back doors of their homes to let the water wash through and reduce the impacts to the structures; still, 69 homes were heavily damaged (Obee 1989). The event also caused 110 deaths in the United States from Alaska to California (USGS 2006b).

The Sumatra Tsunami of 26 December 2004 created a newfound global awareness of tsunami risks. The tsunami caused by a 9.3 magnitude earthquake affected many countries surrounding the Indian Ocean, with waves reaching heights of up to 30 meters in some areas (Titov et al. 2005, Gibbons and Gelfenbaum 2005). Over 280 000 people lost their lives while at least five million people were affected and about one million were left homeless in at least ten different countries (USGS 2005). A reconnaissance survey of damage to the Southeast Indian Coast revealed much scouring of soils due to the tsunami actions. Infrastructure impacts showed that virtually all wood frame homes and thatched huts were destroyed, while about half of the masonry structures and almost all of the reinforced concrete structures survived the tsunami inundation (Yeh *et al*. 2007).

1.3 FLOOD IMPACTS

Environment Canada states that Canada has experienced an increased number of natural disasters over the past 15 years, much of which can be attributed to an increase in floods. Features increasing Canada's vulnerability to disasters include population growth, urbanization and urban sprawl, aging population and aging infrastructure. There has also been a decrease in community awareness about hazards that have not occurred in recent memory (Environment Canada 2003).

Floods are a serious hazard and can cause much damage to communities at risk. Potential flood impacts include loss of life and negative human health impacts; building and infrastructure damage can occur due to water forces and debris impacts; buildings and bridges may also be washed from foundations; erosion and scour can undermine foundations and compromise structural integrity; transportation lines, communication lines and electrical transmission towers may be damaged; buildings and their contents may experience water damage; pollutants carried in water, such as oil, chemicals and sewage, can damage buildings, contents and property, as well as pose a health hazard to humans; fires can be caused by shorted electrical circuits or ruptured gas lines; and sediment deposition can damage property and agricultural land (Brooks *et al.* 2001).

1.4 FLOOD PROTECTION

Several methods are used to safeguard people, buildings and property from flood hazards. Vulnerability assessments and damage estimates describe potential risks and impacts to communities in order to prepare for mitigation and recovery (Webb *et al.* 1999). Measures to reduce hazard impacts can include non-structural methods like land use policies, emergency planning and preparedness, and public education. Structural systems such as dikes, barriers, floodproofing and resistant construction can also be used to physically protect communities (Clague *et al.* 2003). Flood proofing uses adjustments to structures and building contents to reduce flood damages to a building. The Federal

Emergency Management Agency (FEMA) of the United States advocates six flood proofing methods to protect homes from flood damages: Elevation; Wet Floodproofing; Relocation; Dry Floodproofing; Levees and Floodwalls; and Demolition. These are defined as:

1. Elevation – The home is raised above a specified flood level.
2. Wet Floodproofing – Floodwaters are allowed to enter the home to equalize hydrostatic pressure and reduce the risk of structural damage. Uninhabited areas of the home are retrofitted to be resistant to water damage.
3. Relocation – The home is physically moved out of the inundation zone.
4. Dry Floodproofing – The building envelope is sealed to be water tight and prevent water from damaging the contents inside the home.
5. Levees and Flood walls – Barriers are built to prevent water from reaching the home.
6. Demolition – A flood damaged home is torn down in order to relocate or build a more flood resistant home on the same site.

Each of these floodproofing methods have advantages and disadvantages and can provide viable flood protection in certain slow-rise and small scale floods. However most are not recommended for high velocity flood flows due to the increased pressures and forces that may cause structural damage to the home (FEMA 1998).

Sudden, rapid onset flood events with high velocities like tsunamis and flash floods may provide little warning for communities to enact proper evacuation procedures. In these cases, vertical evacuation by escaping to higher levels or storeys of a building may be the best option for occupants to find safety from floodwaters (National Tsunami Hazard Mitigation Program 2001). Better understanding of how typical structures respond to flood loads is required to evaluate the feasibility of using existing (or newly designed) structures as vertical evacuation safe havens.

1.5 HUMAN SAFETY

In slow-rise flooding, people exposed to the floodwaters, as pedestrians or inside automobiles, are often at greatest risk of injury and death. Jonkman and Kelman (2005) use data from 13 small scale river- and storm-related floods in the United Kingdom and the United States to analyze the circumstances of flood fatalities. Two thirds of the casualties drowned, most of them while crossing floodwaters in a vehicle or as pedestrians. Accordingly, many models and experiments on flood impacts investigate how well pedestrians and cars can resist the forces of moving water. Abt et al. (1989) introduce flume tests on human subjects to estimate human stability in floodwaters with depths ranging from 0.49 to 1.2 meters and velocities of 0.36 to 3.05 m/s. For the RESCDAM project, the Finnish Environment Institute (2001) conducts similar laboratory experiments with human subjects in flumes with depths (*d*) ranging from 0.3 to 1.0 meters and velocities (*v*) from 0.6 to 2.75 m/s. The height and mass of the subjects are correlated with the depth and velocity of the water to identify critical *dv* (depth multiplied by velocity) thresholds that describe human stability in moving water. Cylindrical mechanical models are used by Lind et al. (2003) to represent human stability in water. Important variables identified are (*d*), (*v*), and the mass and height of the subject. Jonkman et al. (2005) question the critical *dv* factor and divide human stability into two separate mechanisms, moment instability and friction instability. They show that water velocity is a key parameter in describing human stability response to floodwaters, and that moment instability is linked to dv, while friction instability is influenced by dv^2. The effects of buoyancy are not accounted for in the model. Keller and Mitsch (1992) estimate the stability of children and cars in floodwaters by examining buoyancy, friction and drag force to produce dv threshold values for stability.

In contrast to observations of slow-rise floods, studies conducted after the Sumatra tsunami demonstrate different data patterns regarding human fatalities. Grundy et al. (2005) determine that a large proportion of deaths could be linked to structural failure of buildings since this prevented vertical evacuation from the floodwaters, and damaged buildings created dangerous debris hazards. Surveys conducted by BMC Public Health regarding Sri Lankan loss of life due to the tsunami show that 88.5% of persons killed were indoors when the tsunami hit and the level of house destruction is linearly correlated with mortality. Although there has been much study of building response to slow-rise floods to determine potential property and content damages, no studies enumerate how physical building response can impact human safety in rapid onset, high velocity flooding (Nishikiori *et al.* 2006).

1.6 BUILDING RESPONSE TO FLOODING

Currently there are limited findings related to how the wood frame residential buildings that are typical of North America react to rapid onset, catastrophic floods. Most North American flood damage research focuses on economic losses due to direct water contact, i.e., as a function of depth, for insurance purposes. However, in addition to depth, water velocity has been shown to be an important consideration with the potential to cause significant damage (Kelman 2002, Roos 2003). The relationship between the *dv* factor and flood damage to buildings is the most widely accepted predictor of the effect of water velocity. There is, nonetheless, no widely applied theoretical analysis of how swiftly moving floodwaters affect wood frame buildings, in terms of structural damage or in terms of their ability to provide for human safety. A detailed review of the literature regarding building response to floods is provided in Chapter 2.

1.7 RESEARCH OBJECTIVES

The research objectives of this thesis are to:

1. develop a theoretical model that describes flood impacts on wood frame residential buildings in terms of the ability of the building to support human safety;
2. examine the relationship between flood properties (depth and velocity) and the physical building response;
3. demonstrate application of the model to for assessing building vulnerability

1.8 THESIS FORMAT

This thesis follows a manuscript-based format. Chapter 2 is a manuscript of a journal article prepared for submission to the American Society of Civil Engineers' Natural Hazards Review. A synopsis of previous approaches used to describe building response to flooding is presented. A new computational model is developed to assess the response of a typical Canadian wood frame home to flood conditions that might be experienced in a rapid onset flood event such as a tsunami. An application of the model to typical one and two storey wood frame homes is provided along with recommendations for future analysis and applications. Overall conclusions and recommendations are summarized in Chapter 3.

BIBLIOGRAPHY CHAPTER 1

Abt, S.R., Wittier, R. J., Taylor, A., and Love, D. J. (1989). "Human Stability in a High Flood Hazard Zone." *Water Resources Bulletin*, 25(4), 881-890.

Bowyer, P. (2003). "The Storm Surge and Waves at Halifax with Hurricane Juan." Environment Canada, <http://www.atl.ec.gc.ca/weather/hurricane/juan/storm_surge_e.html> (27 July 2007).

Brooks, G.R., Evans, S.G. and Clague, J.J. (2001). "Flooding in a Synthesis of Natural Geological Hazards in Canada." *Geological Survey of Canada*, Bulletin 548, 101–143.

Clague, J.J., Munro, A., Murty, T. (2003). "Tsunami Hazard and Risk in Canada." Natural Hazards, 28, 433-461.

Eamon, C.D., Fitzpatrick, P. and Truax, D.D. (2007). "Observations of structural damage caused by Hurricane Katrina on the Mississippi Gulf Coast." *Journal of Performance of Constructed Facilities*, 21(2), 117-127.

Environment Canada (2003). "Natural Disasters on the Rise." *Science and the Environment Bulletin*, March/April 2003. <http://www.ec.gc.ca/science/sandefeb03/a3_e.html> (27 July 2007).

Environment Canada (2007). "Hurricane Juan: September 28 & 29, 2003." <http://www.atl.ec.gc.ca/weather/hurricane/juan/> (27 July 2007).

FEMA (1998). "Homeowner's Guide to Retrofitting." < http://www.fema.gov/library/viewRecord.do?id=1420> (12 March 2007).

Finnish Environment Institute (2001). "RESCDAM: Development of Rescue Actions Based on Dam-Break Flood Analysis." <http://ec.europa.eu/environment/civil/act_prog_rep/rescdam_rapportfin.pdf> (4 April 2006).

Gibbons, H. and Gelfenbaum, G. (2005). "Astonishing Wave Heights Among the Findings of an International Tsunami Survey Team on Sumatra." *USGS Soundwaves Monthly Newsletter*, March 2005.

Grundy, P., Thurairaja, A., and Walker, G. (2005). "Some reflections on the structural engineering aspects of tsunami damage." *Proc. of Earthquake Engineering in Australia Conference 2005*, Albury, New South Wales.

Jonkman, S. N. and Kelman, I. (2005). "An analysis of the causes and circumstances of flood disaster deaths." *Disasters*, 29(1), 75-97.

Jonkman, S.N., Kelman, I. and Bain, V. (2005). "A physical interpretation of human stability in flowing water." *Proc. of the International Symposium on Stochastic Hydraulics*, Nijmegen, The Netherlands.

Keller, R.J., and Mitsch, B.F. (1992). "Stability of cars and children in flooded streets." *Proc. of the International Symposium on Urban Stormwater Management*, Sydney, Australia, 264-268.

Knabb, R.D., Rhome, J.R. and Brown, D.P. (2006). "Tropical Cyclone Report Hurricane Katrina: 23-30 August 2005." National Hurricane Center, <http://www.nhc.noaa.gov/pdf/TCR-AL122005_Katrina.pdf> (27 July 2007).

Lind, N., Hartford, D. and Assaf, H. (2004). "Hydrodynamic models of human stability in a flood." Journal of the American Water Resources Association, 40(1), 89-96.

National Tsunami Hazard Mitigation Program (2001). *Designing for Tsunamis*. National Oceanic and Atmospheric Administration (NOAA), 47-50.

Natural Resources Canada (2007). "Tsunamis in Canada." *Atlas of Canada*. <http://atlas.nrcan.gc.ca/site/english/maps/environment/naturalhazards/naturalhazards1999/tsunamis/tsunamis_stats_new.html> (16 July 2007).

Nishikiori, N., Abe, T., Costa, D.G.M., Dharmaratne, S.D., Kunii, O. and Moji, K. (2006). "Who died as a result of the tsunami? – Risk factors of mortality among internally displaced persons in Sri Lanka: a retrospective cohort analysis." *BMC Public Health 2006*, 6(73).

Obee, B. (1989). "Tsunami!" *Canadian Geographic*, February/March 1989.

Perry, C.A., Aldridge, B.N. and Ross, H.C. (2005). "Summary of Significant Floods in the United States, Puerto Rico, and the Virgin Islands, 1970 Through 1989." USGS Water Supply Paper 2502, <http://ks.water.usgs.gov/Kansas/pubs/reports/wsp.2502.html> (21 July 2007).

Robertson, I.N., Riggs, R.H., Yim, S.C.S. and Young, Y.L. (2007). "Lessons from Hurricane Katrina storm surge on bridges and buildings." Journal of Waterway, Port, Coastal and Ocean Engineering, 133(6), 463-483.

Reisner, M. (1986). "Cadillac Desert: The American West and Its Disappearing Water." Viking Penguin, Inc., New York, 407.

Sorensen, R.M. (1997). *Basic Coastal Engineering*. Chapman and Hall, New York, 119-122.

Titov, V., Rabinovich, A.B., Mofjeld, H.O., Thomson, R.E. and González, F.I. (2005). "The Global Reach of the 26 December 2004 Sumatra Tsunami." *Science*, 309 (5743), 2045-2048.

United States Geological Survey (2005). "News Release: Magnitude 9.1 Off the West Coast of Northern Sumatra." <http://neic.usgs.gov/neis/eq_depot/2004/eq_041226/neic_slav_nr.html> (12 March 2007).

United States Geological Survey (2006a). "Flood Hazards - A National Threat." *USGS Science for a Changing World Factsheet*, January 2006 <http://pubs.usgs.gov/fs/2006/3026/2006-3026.pdf> (27 July 2007).

United States Geological Survey (2006b). "Tsunami Hazards – A National Threat." USGS Factsheet 2006-3023. < http://ga.water.usgs.gov/edu/tsunamishazards.html> (27 July 2007).

Webb, T., Sharpe, A., Hoffman, T., LaMorte, J., Waterman, J. (1999). "NHEMATIS User's Guide Version 0.4." Emergency Preparedness Canada.

Yeh, H., Francis, M., Peterson, C., Katada, T., Latha, G., Chadha, R.K., Singh, J.P. and Raghuraman, G. (2007). "Effects of the 2004 Great Sumatra Tsunami: Southeast Indian Coast." *Journal of Waterway, Port, Coastal and Ocean Engineering*, 133(6), 382-400.

CHAPTER 2: MODEL DEVELOPMENT AND ANALYSIS[1]

[1] A version of this chapter will be submitted for publication.
Becker, A., Lence, B.J., and Johnstone W.M. Wood frame response to rapid onset flooding.

2.1 INTRODUCTION

Rapid onset, catastrophic floods, while less common than slow-rise riverine floods, have the potential to cause significant damage to communities and infrastructure. Here, rapid onset, catastrophic floods refer to those that inundate the shore quickly and manifest as deep water with high velocities, including tsunamis, dam or dike failures and powerful storm surges. Recent disasters such as Hurricane Katrina in the Southern United States and the Sumatra tsunami in the Indian Ocean, with casualties in the hundreds and hundreds of thousands, respectively, have shown that communities at risk require improved preparations for these types of dangerous events (Knabb *et al.* 2006, USGS 2005). The deep water and high velocities caused by these floods inflict great pressures and forces on the built and natural environments.

Natural hazard damage predictions are important factors in emergency planning, response and mitigation which aim to protect communities at risk. The Federal Emergency Management Agency of the United States of America (FEMA) uses a software system called *Hazards U. S. Multi-Hazard* (HAZUS-MH) to analyze natural hazard dangers to American communities due to earthquakes, wind and floods (FEMA, 2007). Hurricane wind damage assessments are estimated using structural analysis and building response dynamics to predict the loads caused by high velocity winds. However, HAZUS-MH flood damage estimates focus on slow-rise flooding and water damage and do not address the potential structural impacts of fast moving floodwaters on buildings. Recent European studies of rapid onset floods have begun to focus more on the structural vulnerabilities due to flooding, but commonly investigate unreinforced masonry and brick buildings. To date there has been little investigation of catastrophic flood impacts on wood frame residential buildings typical of North America. Therefore, the objectives of this research are to develop a theoretical model that describes flood impacts on wood frame residential buildings and relates building response to physical flood properties such as depth and velocity to inform community and building vulnerability assessments.

Human safety is a major concern when estimating the impacts of rapid onset, catastrophic flooding. People directly exposed to the floodwaters are usually at greatest risk of injury and death. Evacuation and escape are important in these quickly arriving floods; however some people may still be in their homes when the event occurs, especially if there is little or no warning. Studies conducted after the Sumatra tsunami determined that a large portion of the fatalities could be linked to structural failure of buildings since this prevents vertical evacuation, causes injury and adds dangerous debris to the water (Grundy *et al.* 2005). Analyzing the response of wood frame homes to catastrophic flooding will provide greater understanding of how buildings may or may not protect occupants during this type of event.

Wood frame construction common to Canada and the United States results in a very complex and redundant system that requires more than one component failure to cause the structure to fail completely (Rosowsky *et al.* 2005). A load versus resistance model to assess wood-frame building response to flooding related to the physical and quantifiable flood properties, water depth and velocity, is developed herein. The model uses a spreadsheet based methodology to evaluate the major failure mechanisms for low-rise residential buildings under rapid onset flood loading. A timber frame home in fast moving flood waters has the potential to fill with water, collapse or float. The model describes whether a typical wood frame building will be safe for occupants, or whether it will fail by one of the aforementioned failure mechanisms, while under flood conditions specified by depth (*d*) and velocity (*v*).

This paper provides a brief synopsis of previous approaches used to describe building response to flooding. An overview of the major loads caused by rapid onset flooding, along with a description of the structural system utilized in wood design that acts to resist these forces is provided. The failure mechanisms and the model logic are described and applied to assess the response of a typical Canadian wood frame home to flood conditions that might be experienced in a rapid onset flood event like a tsunami. Building response results are discussed along with recommendations for future analysis and applications.

2.2 BUILDING RESPONSE TO FLOOD EVENTS

Currently there is limited research related to how typical wood frame residential buildings in North America would react to a rapid onset, catastrophic flooding event. Most North American flood damage research focuses on economic losses due to direct water contact and damage to the contents of the buildings for insurance purposes. Stage-damage or depth-damage loss functions are developed by White (1945, 1964, as provided in Smith, 1994) as the basis for flood damage assessments related solely to the depth of the water. Depth-damage models developed by the United States Army Corps of Engineers, USACE, and the United States Federal Insurance Administration, FIA, are used in the United States Federal Emergency Management Agency, FEMA, HAZUS-MH

Flood Model to estimate monetary damages to buildings due to flooding. Regression analysis of flood damage case studies are used to develop over 900 highly specific depth-damage curves for different structure types, contents and facilities to describe the damage to the building in monetary terms (Scathorn *et al.* 2006).

After Tropical Storm Agnes hit the Northeastern United States in 1972, several studies were undertaken to investigate the impacts on buildings. Here, flood depths reached approximately four meters and the maximum velocity was about 1.5 m/s. Lorenzen *et al.* (1975) find that variation in the quality of construction and materials, building type and anchorage cause considerable variance in the response of wood frame homes to the flood event.

The tropical storm also prompted a study by Black (1975) examining how wood frame rural homes resist floodwaters with the intention of furthering design practices. Buoyant actions are investigated and hydrostatic and dynamic forces are considered. Conclusions obtained indicate that homes will float when the depth outside reaches about three quarters the height of the house, but well-built homes designed for the common wind load of 70 miles per hour (~113 km/h) "should experience little structural damage in flooding." Interestingly, an increased chance of structural damage is acknowledged due to increased hydrostatic pressures when dry-floodproofing is enacted to keep water out of the building.

Sangrey *et al.* (1975) utilize Black's evaluation of buoyancy and introduce a non-dimensional analysis of the vertical and horizontal forces on wood buildings. The horizontal drag force and vertical buoyant force are normalized by the weight and height of the building, respectively. The structural resistance to horizontal flood forces is calculated using a frictional model representing the friction between the house and foundation with no foundation anchors. The non-dimensionalized forces are correlated with empirical damage data from the flood to estimate a damage function. The structural response analysis is based on the frictional model only and does not consider structural component failure or collapse. The results show a greater reliance on depth than on velocity.

More recent studies conducted in Europe have begun to incorporate the impacts of high velocity floods in damage and loss estimations. England's Dale Dike failure in 1864 flooded a downstream community with depths up to three meters and velocity of about 1.5 m/s, resulting in extensive damage and 245 deaths. Clausen and Clark (1990) use inundation and damage reports from the flood to estimate potential flood damage to brick and masonry homes. Peak flood conditions are extracted from a numerical model of the flood based on inundation reports. Various functions of maximum depth and maximum velocity are compared with the damage data to assess any possible correlation, with the relationship relating the depth multiplied the velocity (*dv)* to damage providing the best correlation. It is suggested that damage states are bounded by threshold curves of constant *dv*. Inundation occurs at *dv* values less than three m^2/s. Partial damage occurs between *dv* values of three m^2/s and seven m^2/s, above which the building is totally destroyed. A lack of damage at velocities below two m/s is also noted.

Since then, the *dv* factor has been the most widely accepted relationship to estimate potential flood damage to buildings. The Finnish Environment Institute (2001) uses data from Black (1975), Clausen and Clark (1990), Lorenzen et al. (1975), Sangrey et al. (1975) and Smith (1994) to apply the *dv* factor to all types of Finnish homes, including wood construction. Based on the results from these investigations, it is estimated that unanchored timber frame homes experience partial damage at *dv* values greater than two m^2/s and total damage above three m^2/s; anchored homes are partially damaged when the *dv* factor is greater than three m^2/s and are totally destroyed at values over seven m^2/s.

Kelman (2002) studies the damage to unreinforced masonry buildings in England at risk to storm surges. Masonry block wall failure and glass failure are identified as the most significant damage modes. Twelve vulnerability matrices are developed to describe damage to twelve typical masonry buildings as a result of different velocities and depth differentials (i.e., the difference between the inside and outside of the building that describes the degree of hydrostatic pressure). The building types range from one to four storeys and 38 to 84 m^2 in footprint area. The vulnerability matrices assign the expected flood impacts to a building using a five point damage scale.

Britain's Environment Agency and Department for Environment Food and Rural Affairs, DEFRA (2003, 2005), conclude that velocity is the critical factor for building damages in high velocity floods. An average of Kelman's twelve depth differential-velocity matrices is used as a preliminary estimate of general building response to floods. Accordingly, DEFRA is currently investigating alternatives to the *dv* factor that place a greater emphasis on velocity such as dv^2 or $d(v + 1.5\text{m/s})$ (DEFRA 2005).

While the previously mentioned studies are largely based on empirical flood data, Roos (2003) uses structural theory to investigate the failure of modern masonry walls due to flood loads, including hydrostatic and hydrodynamic pressures, and potential debris impacts. He compares the bending moments and shear forces created in the walls with the strength of construction. The results suggest that there is no linear correlation between damage to masonry walls and the *dv* factor previously introduced. The analysis indicates that debris impacts are a significant factor in flood damage to masonry walls.

Water velocity, in addition to depth, has been shown to be an important consideration with the potential to cause significant damage. There is, however, no strong theoretical analysis of how swiftly moving floodwaters impact wood frame buildings, in terms of structural damage or in the context of human safety.

2.3 LOADING DUE TO FLOODS

The interaction of water with objects in the flooded area can result in several actions, including hydrostatic pressure, hydrodynamic pressure, buoyant force, debris impacts, soil erosion around foundations and water damage. The actions that present the most potential for damage and the least uncertainty are chosen to describe the effects of flooding on residential buildings in the preliminary model developed herein. They result in the direct forces that act on the building at risk in the flood shown in Figure 2.1. Hydrostatic and hydrodynamic pressures and forces act on the walls and frame of a structure. Water displaced by a home in its path also causes buoyant uplift of the building and can potentially shift the building from its foundation.

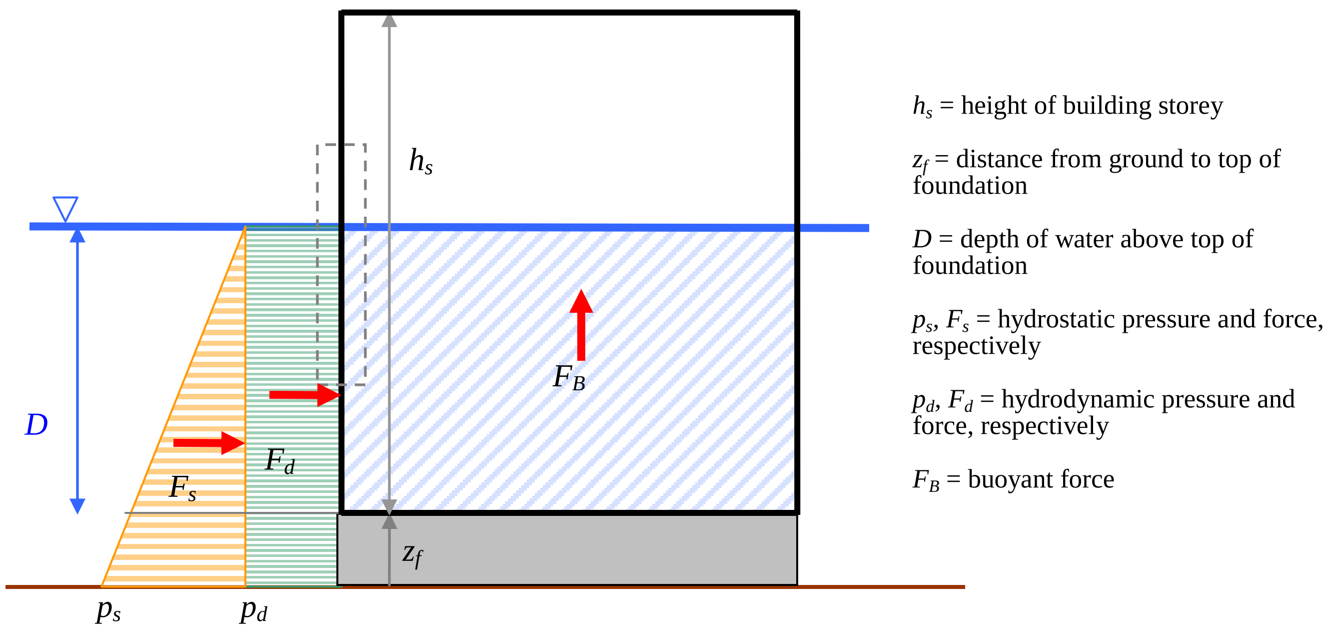

Figure 2.1: External hydraulic forces on low-rise building due to floodwaters

2.3.1 HYDROSTATIC PRESSURE

Hydrostatic pressure is exerted directly on the building due to the contact of fluid against a wall. It is a linearly distributed pressure that increases with the depth of the water. However, if water enters the building, it should be noted that the pressures on both sides of the wall become equal and the effective external static pressure is cancelled.

2.3.2 HYDRODYNAMIC PRESSURE

The velocity of moving water against a structure causes a constant hydrodynamic pressure on the external surface. This pressure is very similar to the pressure exerted on a building due to high velocity winds. However, the relative density of water to air (about 1000 to 1) causes much greater pressures to develop due to water at much lower velocities compared with winds of the same speed.

Hydrostatic and hydrodynamic actions are both lateral pressures causing horizontal forces which act on the building. The forces act directly on a wall of the building that is assumed to be perpendicular to the flow. The two walls parallel to the flow, in a simple rectangular building must also resist the force. The response of the wall on the leeward, sheltered side of the building is not examined for response to the major hydraulic forces.

2.3.3 BUOYANT FORCE

Water displaced by a building causes a vertical buoyant force upwards on the building. This upward force effectively reduces the weight of the building acting in the downward direction. The effective weight and the foundation anchors act to hold the building on the foundation. There is a risk that the buoyant force may overcome the resistance of the building and lift it from the foundation. As well, the reduced weight of the building and reduced friction at the foundation combined with the lateral velocity of the water create the potential for the building to move from its foundation.

2.3.4 OTHER IMPACTS

Especially in high velocity floods, water has the potential to collect and carry objects that become floating debris including soil, rocks, branches, trees and even cars and parts of damaged buildings. As Roos (2003) has shown, large, heavy objects carried at the velocity of the floodwaters can cause significant damage to buildings. Debris action is not enumerated in the model developed herein due to the great uncertainties regarding debris onset and accumulation in flooding, but may be added to the model in the future with no loss of generality.

Other actions that are not considered in the present analysis include water damage due to floodwaters inside and outside a building, and scour of foundation soil by the erosive actions of moving water. Scour is largely dependent on the soil conditions and slope stability at the site, which are highly localized and are not considered here due to the significant uncertainties associated with estimating these effects. However, these may also be added to the model in the future with no loss of generality.

2.4 RESISTANCE OF WOOD FRAME STRUCTURES

Building response to the external actions described above depends on the structural components of the building and how they interact. Low-rise residential buildings in Canada and the United States are most commonly built using simple timber construction. Lateral force response of wood frame structures is well documented in terms of wind and earthquake loading. Building codes and design manuals have explicit guidelines in place for designing structures to withstand specified wind and earthquake lateral loads. Wind loads are treated as uniform lateral pressures acting along the entire height of the building with a magnitude determined by wind velocity. Loads due to moving water can be likened to the pressures due to winds. However, in calculating floodwater loads, the varying depth of the water is an added variable that affects the load, along with the velocity of the water.

Figure 2.2 shows a representation of the structural configuration used for analysis of the lateral load resistance portion of the model. Platform frame homes consist of four main components: foundation, floor, walls, and roof. The goal of the structural frame is to transfer the external loads safely to the foundation and the ground. The loads are conveyed along the load path (i through vi in Figure 2.2) through various components of the structure including the sheathing, studs, floors, roofs, nailed connections, shearwalls and foundation anchors. Each of the components along this path must resist the forces imposed on them so the load can be transferred safely to the foundation and the ground. Flow direction is assumed to be perpendicular to a wall of the building (i). Sheathing is an important component in the structural resistance of lateral forces on a building. *Structural use panels* are most commonly plywood, but can also include waferboard, oriented strand board, particleboard or composite panels. The panels are nailed to the frame members as sheathing and comprise the surfaces of floors and walls; the sheathing also forms horizontal diaphragms and shearwalls that resist lateral loading. Flood water contacts the exterior sheathing which distributes the load to the studs. Studs transfer the load to the lumber at the top and bottom of the wall, i.e. the top plate and sill plate, respectively (ii). The sill plate transfers its portion of the load to the foundation (iii), while the top plate transfers its portion of the load to the roof diaphragm (iv). The roof diaphragm behaves as a beam under uniform loading and must resist the shear forces and bending moments created in order to transfer the lateral load to the shearwalls parallel to flow direction (v). The components of the shearwall work together to resist the shear forces from the roof so the load can be safely transferred to the foundation and the ground (vi). Anchor bolts are used to connect the stud walls to the foundation, and are important aspects of the lateral resistance system.

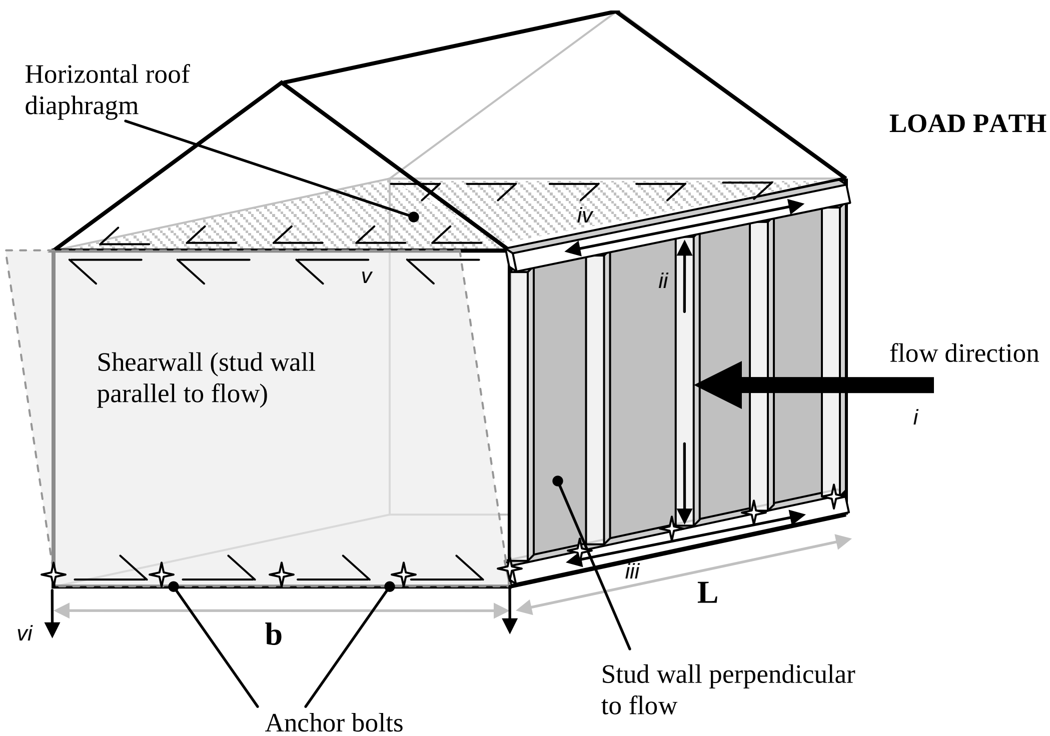

Figure 2.2: Simple timber frame home configuration

2.5 FAILURE MECHANISMS IN RAPID ONSET FLOODING

Depending on the perspective from which a building is viewed, different failure mechanisms for a structure may be defined. From the viewpoint of an insurance company, failure may be represented as any damage to the building, property and contents quantified in monetary terms. From an engineering perspective, failure of the building may be defined as structural damage rendering the building unsafe for reoccupation. During a high velocity flood, such as a tsunami or dam breach event, one of the key concerns is the safety of the population at risk in the community. From the viewpoint of an emergency planner, the building may be considered to have failed when the occupants are no longer safe inside. During a catastrophic flood event, there are three major failure mechanisms that can occur that would make the home unsafe: (1) the building could fill with water to a depth that is unsafe for people inside; (2) floodwaters may cause structural damage that could lead to collapse and injury to occupants, or even death; (3) the buoyant and lateral force of the water may overcome the strength of the anchors and weight of the building holding it to the foundation. We refer to these three failure mechanisms as fill, collapse and float, respectively.

2.6 COMPUTATIONAL MODEL DEVELOPMENT

The model developed herein assesses whether the three separate failure mechanisms in the context of supporting human safety – fill, collapse, float – will occur under specified velocity and depth values. The model is spreadsheet based and evaluates each failure mechanism individually, although whether a building may collapse or float is also dependent on the fill mechanism.

The flowchart in Figure 2.3 illustrates the logic used to create the computational model. Each failure mode is evaluated using simple load versus resistance concepts adapted from reliability analysis and load and resistance factor design techniques (Canadian Wood

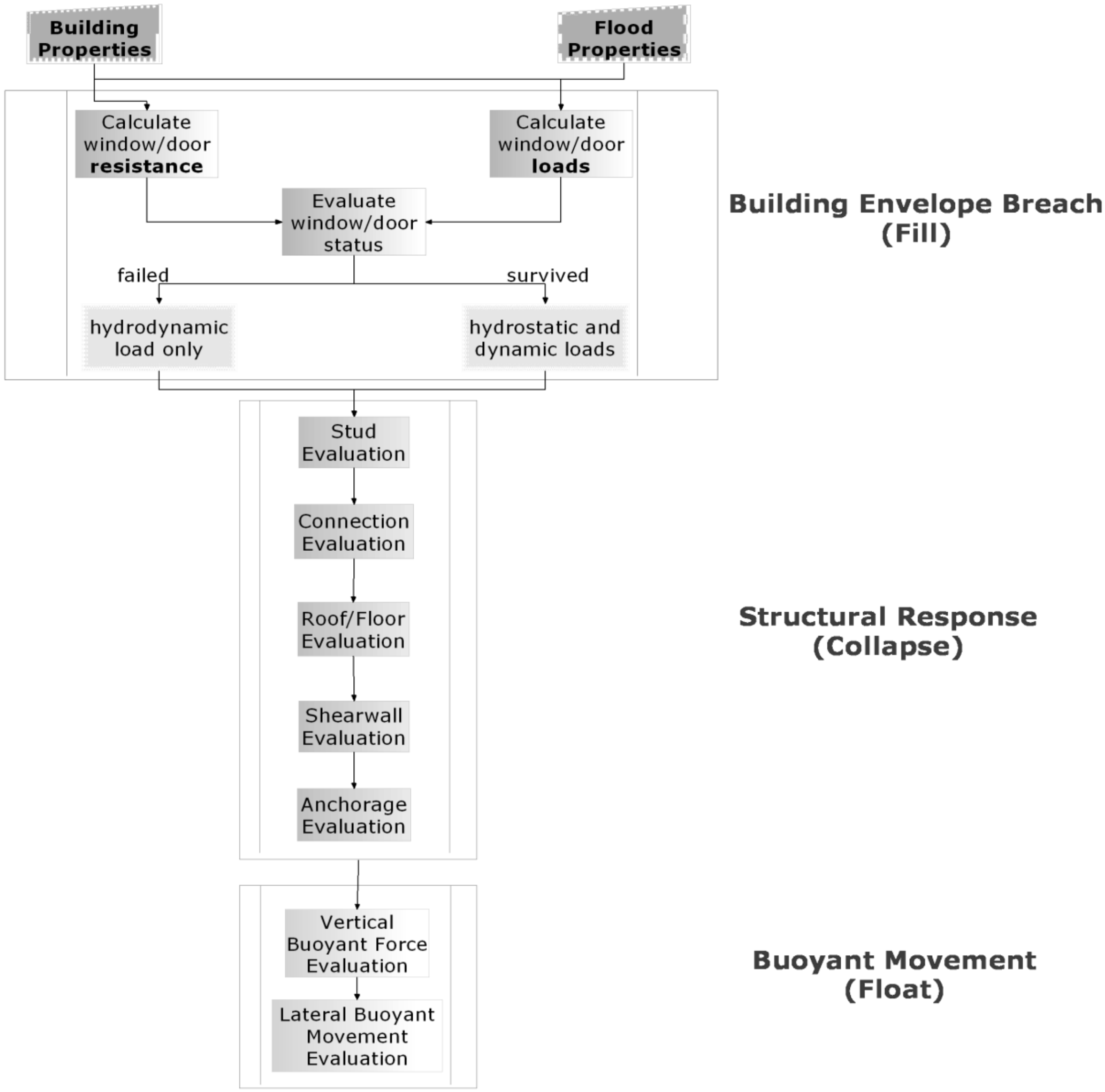

Figure 2.3: Model logic flowchart

Council 1990, 2001; American Forest & Paper Association/American Wood Council 1996). The functions evaluated for each failure mode are described in detail in the Appendix to Chapter 2. Input parameters describe the initial state of the building, indicating size, weight, number of storeys, size of windows and doors, along with resistance parameters that describe the strength of various building components. Flood forces on the building are described using the input parameters depth, d, and velocity, v.

Fill – Floodwaters initially contact the exterior of the home, the building envelope. Windows and doors are assumed to be the weakest elements of the envelope and are most likely to be damaged by floodwaters. External hydraulic pressures, as calculated in Section A1. of the Appendix to Chapter 2, are compared with the strength of the windows and doors to determine whether the building envelope is breached. If the pressure exceeds the specified resistance of the window or door, it is assumed that water instantaneously fills the home to the external level, d. The building is considered unsafe if the depth of water inside reaches 1.5 m above the floor of the top storey.

Collapse – The load versus resistance method for breach evaluation is also used to analyze structural response to flood loads. Horizontal flood forces are calculated based on the depth and velocity. Figure 2.3 shows that there are two potential flood inputs for the collapse failure mechanism. If the building envelope is intact, no water enters and both hydrostatic and dynamic pressures act on the building. On the other hand, when a breach occurs and the building fills with water and hydrostatic pressures inside and out are equalized and only hydrodynamic pressure is used in the analysis.

Loads imposed on the building follow the load path through various structural components including studs, connections, roof sheathing, roof struts and chords, shearwall sheathing, tension chords and wall anchors, as calculated in Sections A2.1., A2.2., A2.3., A2.4., A2.5., A2.6. and A2.7. of the Appendix to Chapter 2, respectively. Loads and resistances are compared to determine whether the various structural components of the frame survive the loading.

Float – Wood frame homes are relatively lightweight structures. The buoyant force of the water is proportional to the volume of water displaced by the house, and ultimately the flood depth. Again, the load versus resistance analysis is used to determine if the building fails by floating or by moving off the foundation. The loads are the buoyant force, A3.1, plus lateral pressures and forces, A3.2 (refer to the Appendix to Chapter 2). The resistance to buoyancy is provided by the weight of the house and the strength of bolts anchoring it to the foundation. Lateral movement of the building is also resisted by the anchor bolts, as well as the friction between the lumber sill plate and concrete foundation.

2.7 AN APPLICATION TO ONE AND TWO STOREY WOOD FRAME BUILDINGS IN CANADA

The model developed herein is applied to typical one and two storey wood frame buildings to evaluate building response to depth and velocity values that might be experienced in a rapid onset flood like a tsunami, dam failure or storm surge. Typical building parameters are used and a range of structural resistance characteristics are applied to evaluate the best and worst case responses to the flood waters. The flood waters are characterized by depth and velocity values taken from a numerical model of the potential tsunami wave that would result from a Cascadia Subduction Zone earthquake on the west coast of British Columbia. The results of the numerical model show that for an important tourist area in the region, the water depths could reach over ten meters, and the velocities up to six m/s (Alexander *et al.*, 2008).

Part 9 of the National Building Code of Canada (2005) provides guidelines for proper construction of residential buildings. The Canadian Wood Council (1990, 2001) also publishes a Wood Design Manual for engineers to design homes to withstand common external loads like wind and earthquake; this includes the National Standards Association specified strengths for various components of a typical Canadian wood frame home. Using these guides, the building parameters in Table 2.1 were selected to describe a typical one or two storey home in Canada.

Table 2.1: Building parameters of a typical wood frame home

Building Properties	Value	Source
Number of storeys, n_s	1,2	Assumed value
Length of home, L (m)	10.0	Assumed value
Width of home, b (m)	10.0	Assumed value
Height of storey, h_s (m)	2.5	Estimated based on 2.4 m studs
Distance to bottom of window, z_w (m)	1.0	Assumed value
Height of window, h_w (m)	1.0	Assumed value
Distance to bottom of door, z_d (m)	0.3	Assumed value
Height of door, h_d (m)	2.0	Assumed value
Width of door, b_d (m)	1.0	Assumed value
Number of nails per connection	5.0	Assumed value
Roof pitch angle, a (rad)	0.3	Assumed value
Height of roof gable, h_{gable} (m)	1.8	Assumed value
Mass of house, m (kg/m^2)	244.0	EPA530-R-98-010
Height of foundation above ground, z_f (m)	0.3	Based on British Columbia Building Code 2006 (9.15.4.6)
Stud spacing (m)	0.4	British Columbia Building Code 2006 (9.23.10.1)
Anchor bolt spacing (m)	2.4	British Columbia Building Code 2006 (9.23.6.1)
Constant Parameters		
Density of water, ρ (kg/m^3)	1000	
Gravitational constant, g (m/s^2)	9.81	
Drag coefficient, C_D	2.0	coefficient for drag around a cube
Coefficient of friction, μ	0.6	friction coefficient between wood and concrete

The model was run for an array of 2500 flood condition combinations using flood depths from zero to five meters and velocities up to five m/s; preliminary estimates indicate high levels of damage occur beyond these values. Although it should be noted that there is no consideration of the correlation of depth and velocity during flooding, the array allows the development of a pattern that describes the response of a single, typical wood frame residential building to flooding using various depth and velocity combinations. Each failure mechanism was investigated individually, as well as in combination.

Wood frame homes in North America are built using a variety of woods, nails, connections and construction techniques that affect building properties. The overall strength, and therefore response, of the building is dependent on each of these factors. Nominal strengths for various building elements have a range based on the material and construction technique used. For example, the specified bending strength for stud grade lumber provided by the Canadian Standards Association (2001) is different for different types of wood: Pacific Coast Hemlock and Amabilis Fir are the strongest, while Northern Canadian species are the weakest. Table 2.2 provides the ranges of building properties used to describe best and worst case response scenarios. As previous flooding disasters have demonstrated, hydrostatic and buoyant forces can cause severe damage to light-frame wood structures, with reports of homes floating off foundations (Robertson *et al.* 2007, Yeh *et al*. 2007, FEMA 1998). Therefore, for this investigation, the best case response scenario occurs when the windows and doors have low resistance to allow water inside more easily, and thereby reduce loading by the hydrostatic pressure (see Black, 1975 and Roos, 2003), and all resistance parameters for the structural components of the building are strong. Conversely, the worst case scenario is comprised of the maximum window and door resistance and the minimum structural resistance values. The best case response scenario is the combination of high resistance and lower external loads, while the worst case scenario combines low structural resistance with higher external loads.

Table 2.2: Building Parameters that Comprise the Worst and Best Case Resistance Scenarios

	Mean Values (or 50th percentile)				
Building Properties	**Low**	**High**	**Best**	**Worst**	**Source**
$n_{storeys}$	1	2	2	1	
m_{house} (kg)	24400	48800	48800	24400	based on per square foot estimate, 50lb/ft^2
W_{house} (N)	239364	478728	478728	239364	conversion from mass
r_{window} (N/m^2)	1000	10000	1000	10000	Kelman
r_{door} (N/m^2)	1000	10000	1000	10000	Kelman
$r_{sheathing}$ (N/m^2)	1000	10000	1000	10000	Kelman
Mr_{stud} (N-m)	348	1277	1277	348	CSA*
r_{nail} (N)	1188	3550	3550	1188	CSA, for 2.5-3.5 inch nails (8d - 16d)
roof sheathing shear resistance (N/m)	4630	30558	30558	4630	CSA
strut/chord tensile resistance (N)	10439	55327	55327	10439	CSA
shearwall sheathing shear resistance (N/m)	5294	32256	32256	5294	CSA
anchor bolt lateral resistance (N)	1389	46300	46300	1389	CSA

*Canadian Standards Association

Complete structural collapse requires the failure of more than just a single building element. The model defines structural failure as the failure of three or more of the structural frame elements that are analyzed in the model (studs, connections, roof, floor, shearwall sheathing, struts/chords or anchor bolts). For example, it may not be significant if only floor connections fail, but if other elements fail as well, such as shearwall sheathing and anchor bolts, the overall structural integrity and safety may be significantly compromised.

Figure 2.4 shows the building response space for each of the failure mechanisms under the best (Figure 2.4 a, b, c) and worst (Figure 2.4 e, f, g) case scenarios for a typical one storey Canadian home. Also shown is a composite diagram of the building response to

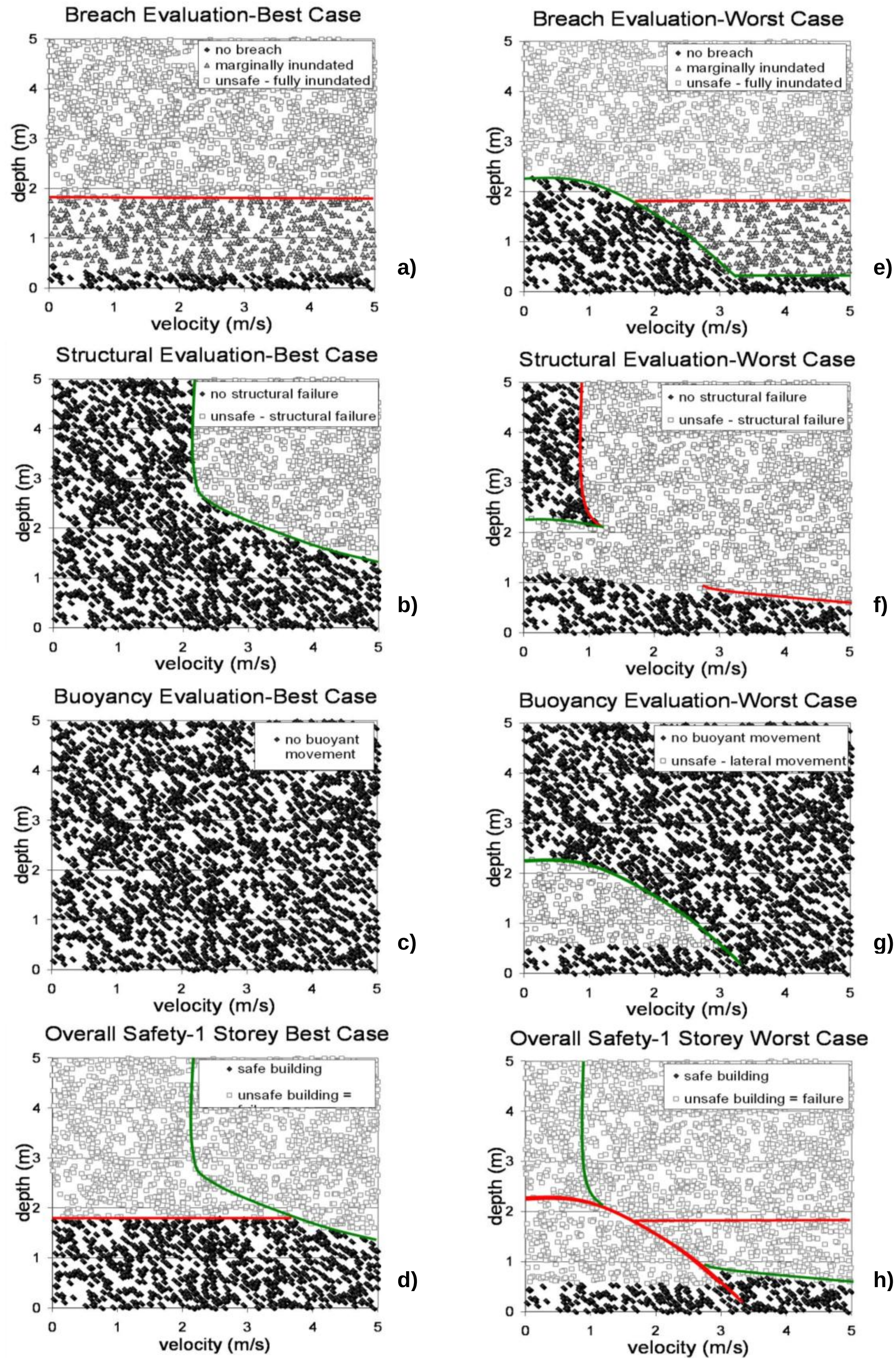

Figure 2.4: Model output plots for one storey home under best and worst case conditions

all failure mechanisms for the best and worst case (Figure 2.4 d and h). In the composite diagrams, the darkly shaded area shows velocity and depth combinations for which the building is safe, and the remaining areas represent flood conditions for which the building is unsafe. These composite diagrams confirm predictions that deep water combined with high velocity can cause severe building damage and pose a danger to the community. The demarcated areas in the composite diagrams show the type of failures that make the building unsafe for these velocity and depth combinations. Each of the other diagrams in the figure show the nature of the individual failure mechanisms (breach, structural and buoyant) at different velocity and depth combinations.

If the depth and velocity of flood waters are not sufficient to enter the building, no breach occurs. The building becomes marginally inundated when water enters, but depth does not rise above 1.5 meters inside on the highest storey; once this depth is surpassed, the building is described as fully inundated. Under the best case scenario windows and doors are weaker (to allow for equilibrium of static pressures); water enters the building at low depths, regardless of its velocity (see Figure 2.4a). Since complete structural collapse would require the failure of more than a single building element, the model defines structural failure as the failure of three or more structural frame elements. Under the best conditions (see Figure 2.4b), where hydrostatic pressure has been equalized and the structural frame elements are stronger, the building is shown to withstand many of the depth and velocity combinations. Finally, when the building easily fills with water, the vertical resistance is large enough to withstand the buoyant uplift forces and the building will not float at all (Figure 2.4c).

In contrast, the influence of the high window and door strength is apparent from the results of the worst case resistance scenario (Figures 2.4e, f, g). In the worst case, water is kept out of the building at higher depths and velocities (up to 2.3 meters of still water) compared with the best case scenario. While those inside the building are safe from breach failure, the building is more susceptible to structural and buoyant failure due to the build up of hydrostatic pressure outside the building, as demonstrated in the remaining plots. Figure 2.4f shows that at depths below approximately one meter, no structural failure occurs, however, at depths of one to two meters, hydrostatic pressure on the face of the building leads to structural failure. At greater depths, the building is completely submerged and inundated due to breach failure which causes the hydrostatic forces to be equalized on all sides. At these depths combined with low velocities no structural failure occurs. However, hydrodynamic forces due to large velocities can cause structural failures beyond a velocity of approximately 1.25 m/s. A similar phenomenon is observed in the buoyant response. When the building remains sealed (no breach), it is more buoyant and can float at low depths and may be shifted by low velocity flows. If the depths and velocities are high enough for breach to occur, the building will not float. The lines drawn in Figure 2.4e, f and g, highlight the impacts of hydrostatic and hydrodynamic forces in breach-resistant buildings.

The model is also applied to a typical two storey home. Figure 2.5 shows the composite failure actions of all failure mechanisms for both one and two storey wood frame homes. The two storey model considers only first floor components in the structural failure analysis. It is assumed that the components on the first floor will experience greater

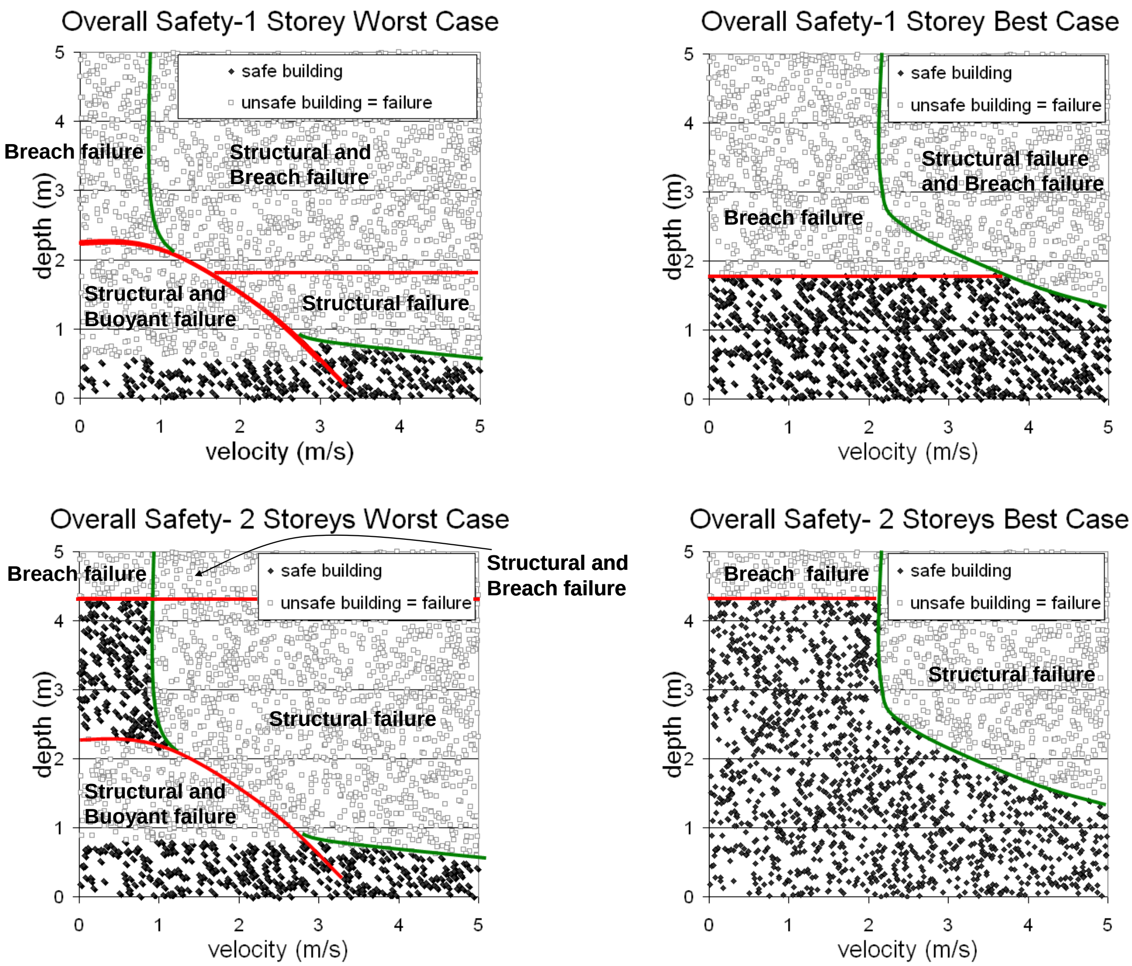

Figure 2.5: Composite flood response of one and two storey wood frame homes

depths and velocities, and thus exposure to damage, before water reaches the second storey during flood progression. The results demonstrate the significant opportunity for vertical evacuation in a two storey home since there is more height than a one storey wood frame building. Furthermore, the weight of the two storey building serves to resist greater buoyant forces than for a one storey home. There are larger regions of “safe” flood conditions for a two storey home, especially under the best case scenario when water is allowed to enter the building and equalize some of the external flood forces. The difference in safe zones between the best and worst case scenarios for both types of buildings also demonstrates that the strength of windows and doors significantly affects the buildings response to flooding.

From the results in Figure 2.5, it is clear that fairly low flood depths can be dangerous. A one storey home can be unsafe at depths less than one meter for the worst case scenario and just under two meters for the best case. Under the best case scenario, for both one and two storey wood frame homes, there is no risk of buoyant failure because water is allowed to enter the building at low depths and acts against the buoyant uplift. On the other hand, the worst case scenario reveals a more complex response space that includes depth and velocity regions where all failure mechanisms are working together, including buoyant failure, to cause the building to be unsafe for occupants during a flood.

A similar analysis was also conducted to investigate the details of structural response to flood loading in order to determine the limiting components of structural failure. For a one storey building under best and worst case flood response scenarios, each of the structural components significant to the load path are evaluated individually and the failures of these are combined to define the overall structural response. For all velocity and depth combinations, the load and resistance for each structural component was determined; the response space output plots are illustrated in Figure 2.6. The lines shown on the figures correspond to the bounds of overall structural failure representing the lightly shaded area in Figures 2.4 b and f in order to visually identify the limiting structural components for the failure response.

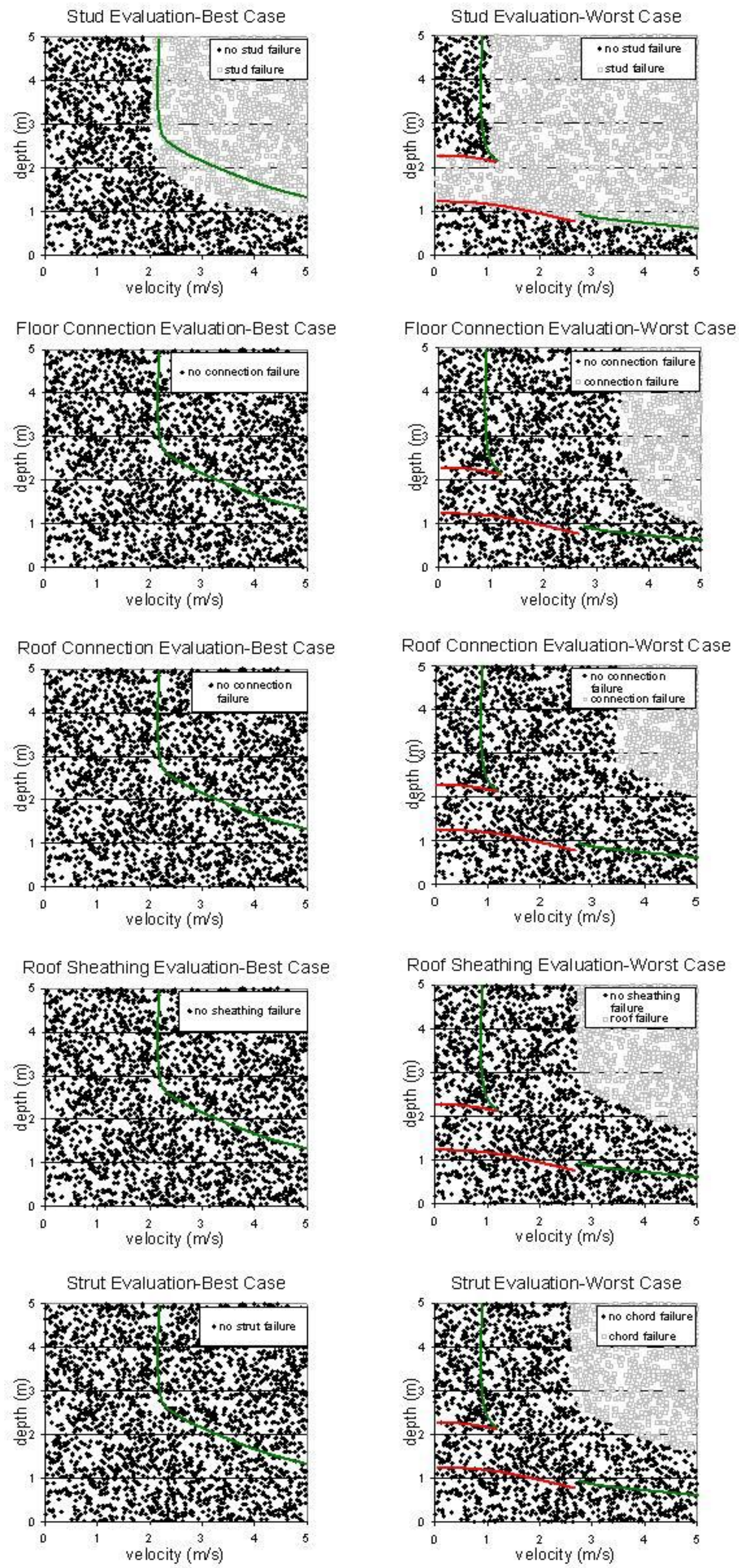

Figure 2.6: Individual structural element analysis

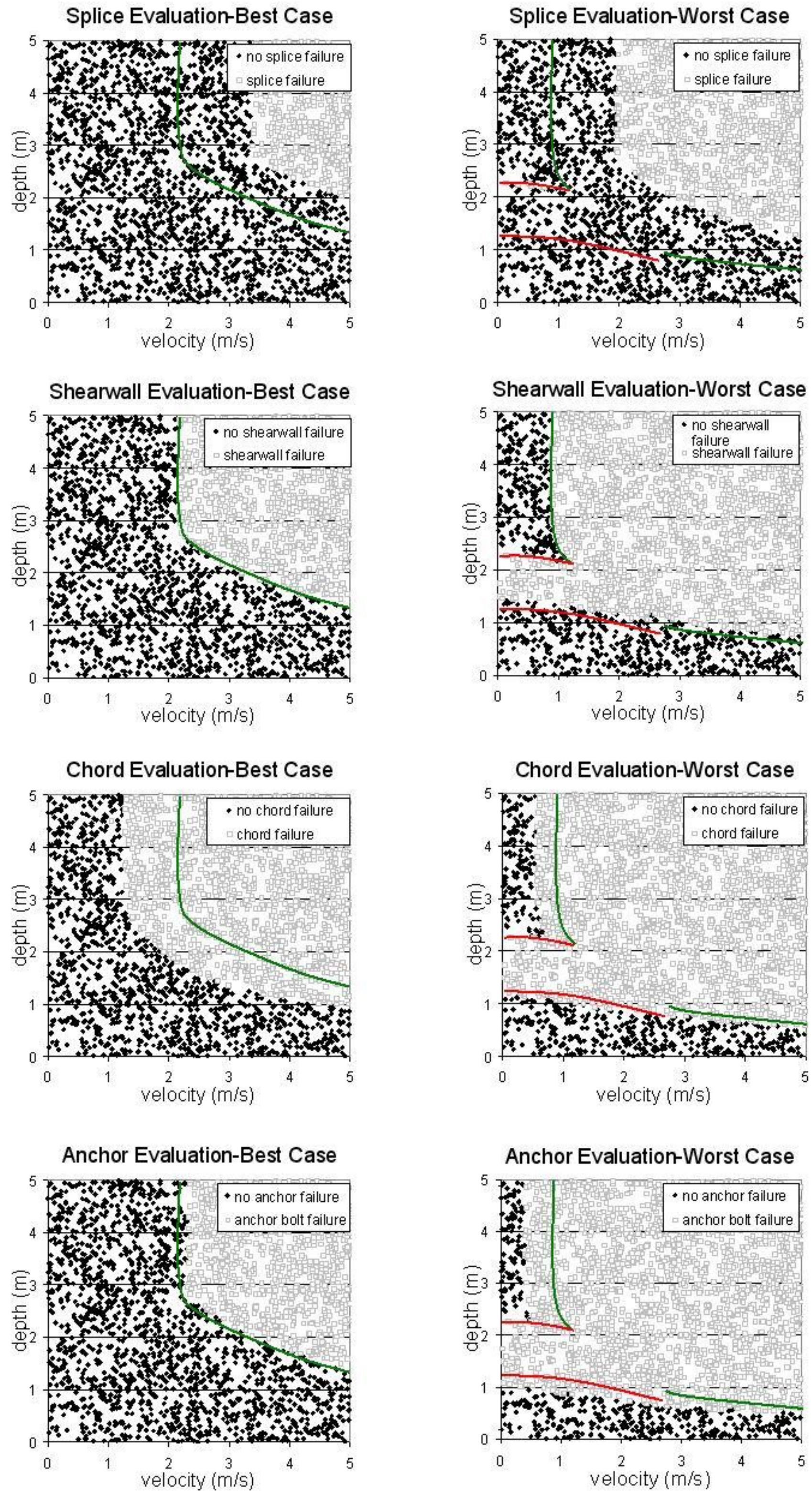

Figure 2.6 Continued: Individual structural element analysis

For both the best and worst case scenarios, the studs, shearwall, shearwall chords and anchor bolts are the most vulnerable structural elements under flood loading conditions, as the plots for each of these components have the largest response spaces of failure under flood conditions, and most closely match the overall structural failure space shown in Figure 2.4 b and f. Other structural elements, such as connections, roof sheathing, and struts can still be affected by external flood forces, but failures occur at higher depth and velocity combinations.

2.8 CONCLUSIONS

The results of this model application do not immediately reveal a simple, all-encompassing relationship or factor, such as the popular *dv* factor, for describing wood frame building response to flood loading. Rather, a number of complex responses are revealed by assessing the results from the best and worst case resistance parameter combinations. The contrast between the best and worst case scenarios highlights the influence of individual building elements on the overall response of a wood frame home to flood forces. Lateral pressures and buoyancy are highly dependent on whether the building envelope fails and water enters. Keeping water out of the building with stronger windows and doors will protect finishes from water damage. However, this also causes the building to be more susceptible to greater lateral forces acting on the structures. Also, the building will be much lighter since it is full of air, not water, and will float off the foundation more easily. There is also a significant variation in responses between one and two storey homes. An increased number of storeys gives occupants a chance to vertically escape rising water inside the home, while the weight of the building, as a function of floor area and number of storeys, adds to the buoyancy resistance.

Structural failure makes up a large portion of the response space for higher depth and velocity combinations under both the best and worst case flood response scenarios. Anchor bolts were shown to be very important flood response elements that connect the house to the foundation, which is one of the most important structural elements of a building. Similar findings are noted in wind and earthquake engineering (National Building Code of Canada 2005). The strength of shearwall components is also demonstrated to have a significant impact on the structural response of a wood frame home to flooding.

It is well known in the structural and wood engineering communities that common wood frame construction results in a very complex structural system. A system factor approach has been developed to describe the interdependent response and resistances of the building components. It is also observed to be a highly redundant system that requires more than one component malfunction to initiate a full system (building) failure (Rosowsky *et al.* 2005). A rapid onset flood event is also very a complex phenomenon – turbulence, velocity, drag, buoyancy, orientation, volume, debris, sediments and other aspects of flood response can be very localized and dependent on a wide range of factors. More precise details regarding the specific structures in question and the flood event in question will be required to more finely predict potential damages and losses to a community.

The work presented here acknowledges these complexities, while identifying characteristic building responses and areas for further study so as to better understand and describe the plight of timber frame homes in flooding and to develop reliable damage predictions. The structural analysis used to identify wood frame flood responses is a simplified approximation of the dynamics of a wood frame structure, and although a simple relationship between building damage and the "*dv* factor" is not observed, the model application undertaken demonstrates the potential for this type of behaviour modelling and investigation to contribute to flood vulnerability assessments for wood frame buildings.

2.9 RECOMMENDATIONS/FUTURE WORK

Application of uncertainty analyses is recommended to gain further insights into how building and flood parameters influence response. This requires the identification of the range and probability distributions of parameter estimates. Also, the current model configuration evaluates randomly chosen array of instantaneous flood conditions. It may be helpful to analyze the cumulative effects of a flood flow time series provided by hydrodynamic models of such events.

There are other potentially damaging flood actions, such as debris impacts, that were not considered in the initial response investigation presented here. Debris can be modelled as a direct force at the point of impact. The impact of debris on a wood frame structure can be simulated by spring behaviour describing the response of each component of the collision (Haehnel and Daly 2004). This type of impact will directly influence envelope breach analysis and structural response, and indirectly affect buoyancy. In order to adequately account for debris, a probabilistic estimate of debris onset and accumulation will be required. Scour of soil around the building foundation can undermine the structural integrity of a building and can be described using the threshold velocities for various types of soil (Roos 2003, FEMA 1988). Slope stability issues accompanying earthquake or flood events could also affect buildings in flood and earthquake zones. Native soil and fill data are required to obtain a reliable estimate of erosion damage caused by high velocity flows around a building.

Tsunami events are often preceded by large offshore earthquakes that will have their own effects on the infrastructure of nearby communities; dam and dike failure may result from seismic activity as well. Pre-softening by earthquake shaking can undermine the structural integrity of the building, decreasing its ability to resist the later flood forces. This type of impact could also be incorporated into the model developed herein by reducing the building strength parameters by an appropriate factor to indicate pre-softening. Hurricane winds that accompany storm surges and coastal flooding events could be addressed in a similar manner.

The applications of this type of analysis go beyond emergency planning and mitigation. By developing a greater understanding of building response to high velocity floodwaters, actions could be investigated that may improve resistance of buildings in flood prone regions. In the future, building and design code recommendations may further develop in response to such events and the design of safe haven structures that can protect people from dangers floodwaters may be advanced. The modelling framework presented herein, and developed by others, including Roos (2003) and Kelman (2002), may contribute to such advances. Failure response spaces shown in the model output plots identify ranges of flood conditions where wood frame homes are vulnerable to the various failure mechanisms identified (breach failure, structural failure, buoyant failure), and also when combinations of these mechanisms may be responsible for building failure. The structural building elements identified in this analysis as particularly vulnerable and significant in structural failure under flood loading (including anchor bolts and shearwall elements) can provide direction for future investigation and development of more flood-resistant structures. The combination of this type of modelling result with flood prediction tools could be used to identify significant areas to target in developing a plan to make community infrastructure more resistant to the specific flood events to which it is at risk.

BIBLIOGRAPHY CHAPTER 2

Alexander, D., George, D. and Johnstone, W.M. (2008). *Hydraulic model of Cascadia Subduction Zone tsunami.* Document in preparation.

American Forest & Paper Association/American Wood Council (1996). *Load and Resistance Factor Design: Manual for Engineered Wood Construction.* Washington, DC, USA.

Black, R.D. (1975). "Flood proofing rural residences – A Project Agnes report." US Department of Commerce, Economic Development Administration, EDA 77-088.

British Columbia Building Code 2006. Ministry of Forests and Range and Minister Responsible for Housing, Victoria, BC, Canada.

Canadian Standards Association (2001). Engineering Design in Wood (Limit States Design). CAN/CSA-O86.1, Toronto, Canada.

Canadian Wood Council (1990). *Wood Design Manual: The complete reference for wood design in Canada.* Ottawa, Canada.

Canadian Wood Council (2001). *Wood Design Manual: The complete reference for wood design in Canada*. Ottawa, Canada.

Clausen, L. and Clark, P.B. (1990). "The development of criteria for predicting dambreak flood damages using modelling of historical dam failures." *Proc. of the International Conference on River Flood Hydraulics,* Surrey, UK.

DEFRA (2003). "Flood Risks to People Phase 1." R&D Technical Report FD2317/TR, London, UK.

DEFRA (2005). "Flood Risk Assessment Guidance for New Development Phase 2: Framework and Guidance for Assessing and Managing Flood Risk for New Development." R&D Technical Report FD2320/TR2, London, UK.

Environmental Protection Agency Municipal and Industrial Solid Waste Division (1998). "Characterization of Building-Related Construction and Demolition Debris in the United States." Report No. EPA530-R-98-010, Prairie Village, KS, USA.

FEMA (1988). *Design Manual for Retrofitting Flood-prone Residential Structures*. Washington, DC, USA.

FEMA (1998). "Homeowner's Guide to Retrofitting." < http://www.fema.gov/library/viewRecord.do?id=1420> (12 March 2007).

FEMA (2007). “HAZUS: FEMA’s Software Program for Estimating Potential Losses from Disasters.” < http://www.fema.gov/plan/prevent/hazus/index.shtm> (23 July 2007).

Finnish Environment Institute (2001). “RESCDAM: Development of Rescue Actions Based on Dam-Break Flood Analysis.” <http://ec.europa.eu/environment/civil/act_prog_rep/rescdam_rapportfin.pdf> (4 April 2006).

Grundy, P., Thurairaja, A., and Walker, G. (2005). “Some reflections on the structural engineering aspects of tsunami damage.” *Proc. of Earthquake Engineering in Australia Conference 2005*, Albury, New South Wales.

Haehnel, R.B. and Daly, S.F. (2004). “Maximum impact force of woody debris on floodplain structures.” *Journal of Hydraulic Engineering*, 130(2), 112-120.

Kelman, I. (2002). “Physical flood vulnerabilities of residential properties in coastal, eastern England.” Ph.D. Thesis, University of Cambridge, UK.

Knabb, R.D., Rhome, J.R. and Brown, D.P. (2006). “Tropical Cyclone Report Hurricane Katrina: 23-30 August 2005.” National Hurricane Center, <http://www.nhc.noaa.gov/pdf/TCR-AL122005_Katrina.pdf> (27 July 2007).

Lorenzen, R.T., Black, R.D. and Nieber, J.L. (1975). “Design aspects of buildings for flood plain locations.” *American Society of Agricultural Engineers Annual Meeting*, Paper 75-4037.

National Building Code of Canada 2005. Canadian Commission on Building and Fire Codes, National Research Council of Canada, Institute for Research in Construction, Ottawa, Canada.

Robertson, I.N., Riggs, R.H., Yim, S.C.S. and Young, Y.L. (2007). “Lessons from Hurricane Katrina storm surge on bridges and buildings.” Journal of Waterway, Port, Coastal and Ocean Engineering, 133(6), 463-483.

Roos, W. (2003). “Damage to Buildings.” TNO Built Environment and Geosciences, Delft Cluster: No. DC1-233-9, The Netherlands.

Rosowsky, D.V., Guangren, Y. and Bulleit, W.M. (2005). “Reliability of light-frame wall systems subject to combined axial and transverse loads.” *Journal of Structural Engineering*, 131(9), 1444-1455.

Sangrey, D.A., Murphy, P.J. and Nieber, J.L. (1975). “Evaluating the impact of structurally interrupted flood plain flows.” The Office of Water Research and Technology, U.S. Department of the Interior, Project A-059-NY, Technical Report 98.

Scawthorn, C., Flores, P., Blais, N., Seligson, H., Tate, E., Chang, S., Mifflin, E., Thomas, W., Murphy, J., Jones, C. and Lawrence, M. (2006). "HAZUS-MH flood loss estimation methodology II: Damage and loss assessment." Natural Hazard Review, 7(2), 72-81.

Smith, D.I. (1994). "Flood damage estimation – A review of urban stage-damage curves and loss functions." *Water South Africa*, 20(3), 231-238.

United States Geological Survey (2005). "News Release: Magnitude 9.1 Off the West Coast of Northern Sumatra." <http://neic.usgs.gov/neis/eq_depot/2004/eq_041226/neic_slav_nr.html> (12 March 2007).

Yeh, H., Francis, M., Peterson, C., Katada, T., Latha, G., Chadha, R.K., Singh, J.P. and Raghuraman, G. (2007). "Effects of the 2004 Great Sumatra Tsunami: Southeast Indian Coast." *Journal of Waterway, Port, Coastal and Ocean Engineering*, 133(6), 382-400.

APPENDIX A

<u>Model Logic</u>

The load versus resistance model assesses wood-frame building response to flooding related to the physical and quantifiable flood properties, water depth and velocity. The model uses a spreadsheet based methodology to evaluate major failure mechanisms for low-rise residential buildings under rapid onset flood loading, namely, fill, collapse and float. The model describes whether a typical wood frame building will be safe for occupants by comparing flood loads due to specified depths and velocities with the resistance of building components. The equations that make up the model logic are described below.

<u>A1. Breach</u> – Building envelope breach failure is evaluated based on lateral pressures (hydrostatic and hydrodynamic) exerted on window and door components. There are three possible loading cases. The first case is trivial and the second and third cases are shown in Figure A1:

Case 1: Flood depth, d, is below the window or door level (z_w or z_d), so no hydraulic pressure acts on the window/door.

Case 2: Flood depth reaches the window/door, but is not higher than the top of the window/door. Both hydrostatic and hydrodynamic pressures act on the window/door.

Case 3: Flood depth is higher than the top of the window or door. Hydrostatic and hydrodynamic pressures act on the window/door.

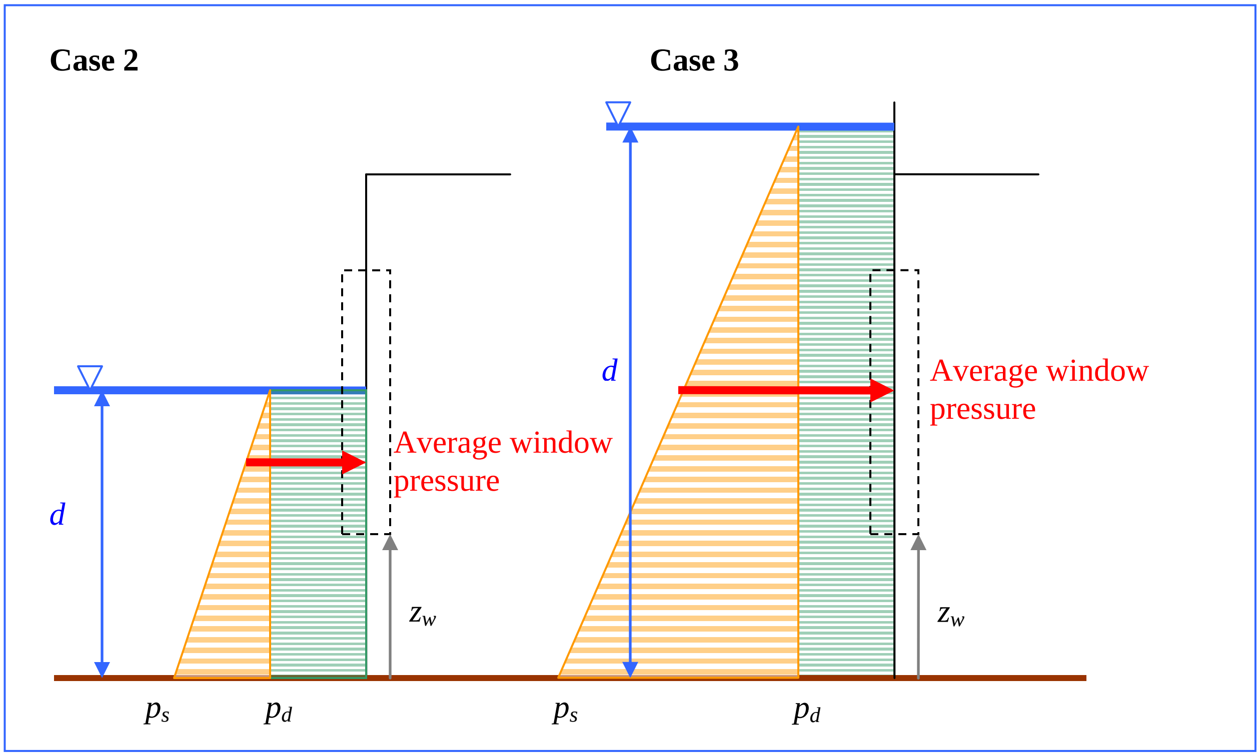

Figure A1. Breach evaluation

Load on the window is the average hydrostatic and hydrodynamic pressures on window due to floodwaters, and is calculated as follows.

Case 1. $d < z_w$

$$p_{avg} = 0 \tag{1}$$

Case 2. $z_w < d \le (z_w + h_w)$

$$p_{avg} = \frac{1}{2}\left[\rho g(d - z_w)\right] + \frac{1}{2}C_D \rho v^2 \tag{2}$$

Case 3. $d > (z_w + h_w)$

$$p_{avg} = \rho g(d - h_w - z_w) + \frac{1}{2}\rho g h_w + \frac{1}{2}C_D \rho v^2 \tag{3}$$

where d = depth of flood water outside building, m
z_w = vertical distance from ground to bottom of window, m
p_{avg} = average pressure exerted on window, Pa
h_w = height of window, m
ρ = density of water (1000 kg/m^3)
g = gravitational constant (9.81 m/s^2)
C_D = drag coefficient (assumed to be 2.0 for a cube home)
v = water flow velocity, m/s
p_s = hydrostatic pressure, Pa
p_d = hydrodynamic pressure, Pa.

The same logic is used for loads on a door with z_d and h_d substituted for z_w and h_w,
where z_d = vertical distance to bottom of door, m
h_d = height of door, m

Window resistance is calculated based on the work of Kelman (2002) where glass window panes are estimated to break under average pressures between 1 kPa and 10 kPa and smaller panes (<1 m^2) may withstand pressures of greater than 10 kPa.

Door resistance is assumed to be equal to that of windows (Kelman 2002).

A2. Collapse – Structural response of the wood frame building is evaluated by adapting lateral resistance design techniques for lateral wind pressures from the Canadian Wood Council's Wood Design Manual (1990, 2001). The external pressures and forces acting on a building are resisted by several components of the structural frame. The loads are transferred through various components along the load path to safely reach the foundation and the ground.
The load is carried through the following components:

1. Stud wall
2. Floor connection and roof connection
3. Roof sheathing
4. Roof struts/chords (also splice connections)
5. Shearwall sheathing
6. Shearwall tension chords
7. Wall anchors

The first floor wall experiences the greatest pressures, therefore, only the first floor is examined for stud wall response. If a breach has occurred, it is assumed that water has entered the home and reaches a depth, *d*, equalizing the hydrostatic pressure on each side of the exterior wall and in this case, only hydrodynamic forces are considered.

Specified nominal resistance values provided by the National Standards of Canada, Engineering Design in Wood represent the 5th percentile strength properties of the structural materials for use in conservative design calculations. The Weibull distribution was used to obtain the median (50th percentile) resistance values to use as model inputs to represent the average range of structural resistance values.

Weibull Distribution

$$f(x) = k\lambda^k x^{k-1} e^{-(\lambda x)^k}$$

$$F(X) = 1 - e^{-(\lambda x)^k}$$

$$p\text{th quantile} = \frac{\left[-\ln(1-p)\right]^{\frac{1}{k}}}{\lambda}$$

$$\text{Coefficient of Variation} = 0.2 \quad \text{for wood frame strength properties}$$

$$k = \frac{1.2}{\text{CoV}} = 6$$

$$\text{median value} = \frac{(0.05\ \text{quantile})\left[-\ln(0.5)\right]^{\frac{1}{6}}}{\left[-\ln(0.95)\right]^{\frac{1}{6}}}$$

The median of the Weibull distribution was used as an approximation to develop the range of average resistance values for the structural frame elements evaluated in the model, where

$f(x)$ = probability distribution function

F(X) = cumulative distribution function

k = shape parameter

λ = scale parameter

A2.1. Stud wall evaluation

- Assumptions
    - Flood flow is perpendicular to the external stud wall of the building.
    - The moment resistance of one stud in transferring the tributary load is evaluated. The tributary load carried by each stud is calculated based on stud spacing of 406 mm on centre.
    - Studs are standard 38 mm by 89 mm (2x4) stud grade lumber 2.44 m (8 ft) long, spaced 406 mm (16 inches) on centre.

There are three cases to be considered. The first case is trivial, while the second and third cases are shown in Figure A2:

Case 1: Flood depth, *d*, is below the first floor level, z_f, so no hydraulic pressures act on the wall.

Case 2: Flood depth reaches the stud wall, but is not higher than the top of the first storey.

Case 3: Flood depth is higher than the top of the first storey.

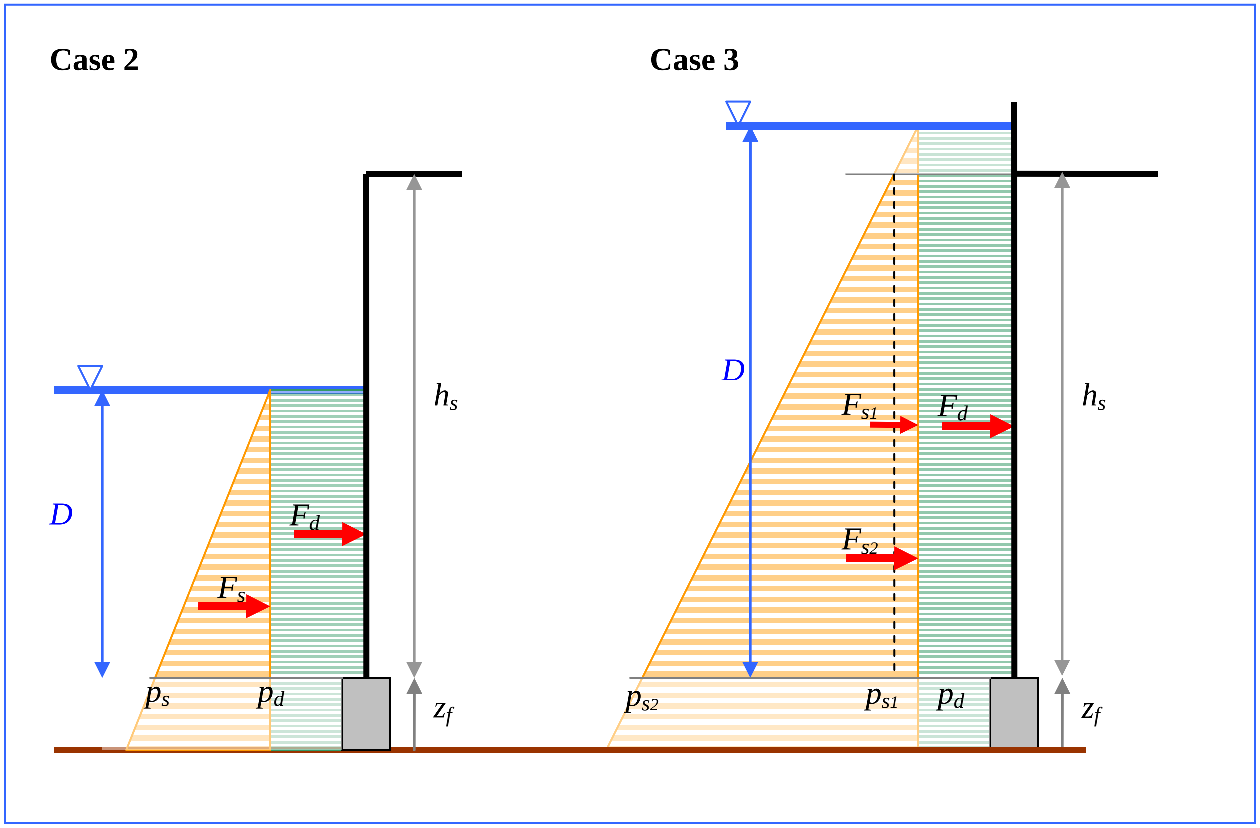

Figure A2. Stud wall evaluation

The load on the stud wall is assessed by the moment created in the stud by applied hydraulic forces, and is calculated as follows:

Case 1. $d \le z_f$

$$M_{\max} = 0 \tag{4}$$

Case 2. $z_f \le d \le h_s$

$$q(x) = p_d + p_s(1 - \frac{x}{D}) \tag{5}$$

$$V(x) = \int q(x)\partial x \quad (6a)$$

$$V(x) = p_d x + p_s x - \frac{p_s}{2D} x^2 + R_A \quad (6b)$$

$$M(x) = \int V(x)\partial x \quad (7a)$$

$$M(x) = \frac{1}{2} p_d x^2 + \frac{1}{2} p_s x^2 - \frac{p_s}{6D} x^3 + R_A x \quad (7b)$$

$$M_{\max} = M(x_0) \quad (8)$$

$$x_0 = x \text{ where } V(x) \text{ is zero} \quad (9a)$$

$$x_0 = \frac{-p_d - p_s \pm \sqrt{(p_d + p_s)^2 + \frac{2 p_s R_A}{D}}}{-\frac{p_s}{D}} \quad (9b)$$

Case 3. $D > h_s$

$$q(x) = p_d + p_{s1} + \rho g h_s - \rho g x \quad (10)$$

$$V(x) = \int q(x)\partial x \quad (11a)$$

$$V(x) = (p_d + p_{s1} + \rho g h_s)x - \frac{1}{2}\rho g x^2 + R_A \quad (11b)$$

$$M(x) = \int V(x)\partial x \quad (12a)$$

$$M(x) = \frac{1}{2}(p_d + p_{s1} + \rho g h_s)x^2 - \frac{1}{6}\rho g x^3 + R_A x \quad (12b)$$

$$M_{\max} = M(x_0) \quad (13)$$

$$x_0 = x \text{ where } V(x) \text{ is zero} \quad (14a)$$

$$x_0 = \frac{-(p_d + p_{s1} + \rho g h_s) \pm \sqrt{(p_d + p_{s1} + \rho g h_s)^2 + 2\rho g R_A}}{-\rho g} \quad (14b)$$

where, z_f = height of foundation above ground, m

M_{max}	=	maximum moment created in stud, N-m
D	=	d-z_f
x	=	vertical position of interest
$q(x)$	=	pressure at point x, Pa
$V(x)$	=	shear at point x, N
$M(x)$	=	moment at point x, N-m
R_A	=	reaction at connection of stud to floor, N
R_B	=	reaction at connection of stud to roof, N
x_0	=	point where shear is zero, m

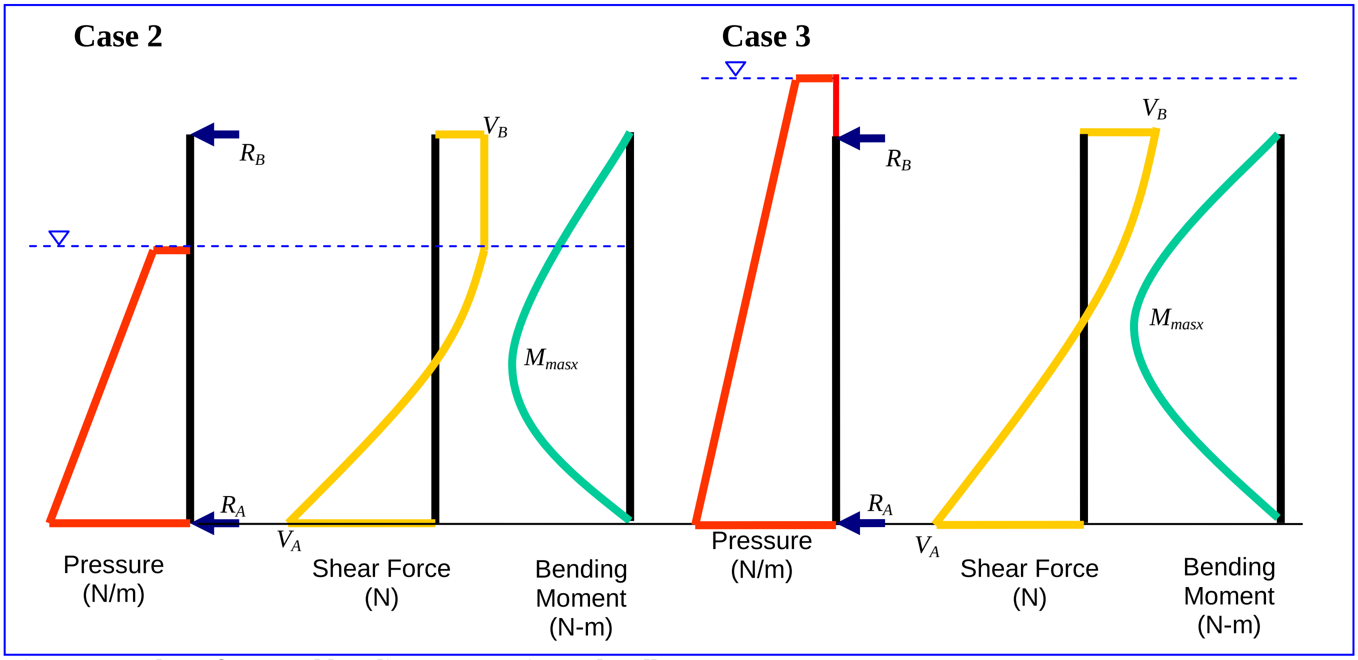

Figure A3. Shear force and bending moment in stud wall

The resistance of the stud wall is based on the specified moment resistance of studs (N-m) provided by National Standards of Canada, Engineering Design in Wood, where:

$$M_r = f_b S \qquad (15)$$

and

M_r	=	specified moment resistance, N-m
f_b	=	specified bending strength, Pa
S	=	section modulus, mm^2
S	=	$\frac{wl^2}{6}$ = 50166 mm^2 for a "2x4" stud
w	=	stud dimension – width (38 mm)
l	=	stud dimension – height (89 mm)

A2.2. Connections (wall-to-roof and wall-to-floor)

The stud transfers the lateral load to the roof and floor as depicted in Figure A3.

The load on the wall-to-roof and the wall-to-floor connections are defined as the shear transferred from the studs to floor and roof and is evaluated as follows

= V_A for floor [N/m]*tributary area [m]

= V_B for roof [N/m]*tributary area [m]

The resistance is provided by the nailed connections [N/nail] (CSA-O86).

A2.3. Roof sheathing

The top plate transfers the load from the studs to the horizontal roof diaphragm. The diaphragm behaves as a beam under uniform loading, as shown in Figure A4.

The load on the roof sheathing is the shear transferred from studs along entire length of roof parallel to force, where,

V_r = roof shear, and

$$V_r = \frac{R_B}{2} \tag{16}$$

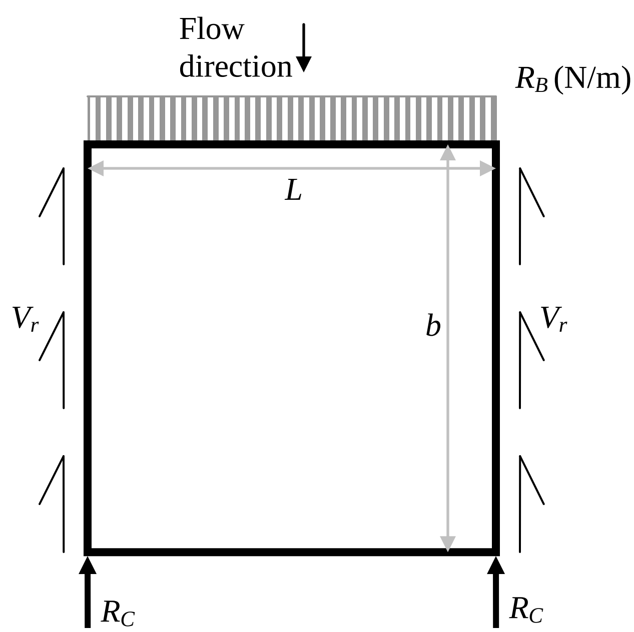

Figure A4. Response of horizontal roof diaphragm

The resistance is defined as the shear resistance of roof sheathing (kN/m) provided in CSA-O86.

A2.4. Roof struts/chords

The horizontal roof diaphragm behaves as a simple beam with fixed ends, under uniform loading. The load on the roof struts and chords are tensile loads resulting from the moment couple due to lateral roof loading, as shown in Figure A5, where

$$T_r = \frac{M_{max}}{L} = \frac{R_B L}{8} \quad (17)$$

where, T_r = tension in roof members, N
L = length of member, m

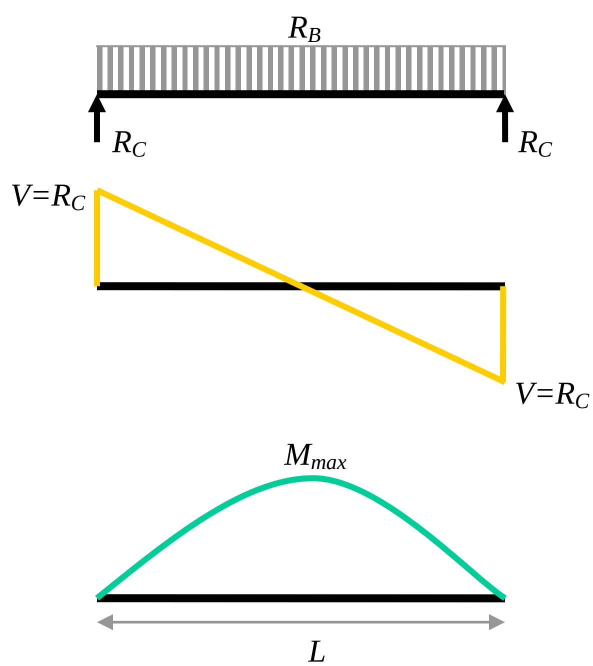

Figure A5. Response of roof struts and chords

The resistance of roof struts and chords is defined by the tensile resistance of visually graded lumber provided in CSA-O86.

A2.5. Shearwall sheathing

The load on the walls that are parallel to the flow is the shear due to lateral load transferred from roof, V_{sw}, as calculated below. As a conservative estimate, it is assumed the shearwall contains a door opening of width b_{door}. See Figure 6.

$$V_{sw} = \frac{R_C b}{(b - b_{door})} \quad (18)$$

Where, V_{sw} = R_C distributed along the wall, N/m
R_C = roof connection reaction, N
b = width of shearwall, m
b_{door} = width of door, m

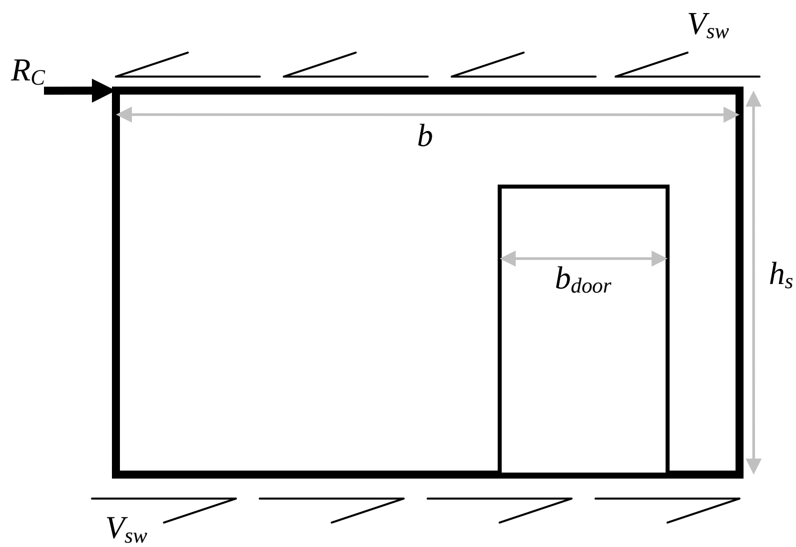

Figure A6. Shearwall response

The shear load is resisted primarily by the sheathing (usually plywood) based on resistance values provided in CSA-O86.

A2.6. Shearwall tension chords

The load on the shearwall tension chords is the force due to overturning moment, T_{chord}, calculated as follows,

$$b_{chord} = \frac{b - b_{door}}{2} \quad (19)$$

$$T_{chord} = \frac{V_{sw}(b - b_{door})h_s}{\left(\frac{b - b_{door}}{2}\right)} \quad (20a)$$

$$T_{chord} = 2V_{sw}h_s \quad (20b)$$

where, b_{chord} = effective length of the shearwall chord, m
T_{chord} = tension in shearwall chord, N

h_s = height of storey, m

The resistance is the specified tensile strength of lumber (2x6) as described in CSA-O86.

A2.7. Wall anchors

The load on the wall anchors is the lateral force transferred from the shearwall chords, T_{chord}.

The resistance is bolt lateral resistance (kN/shear plane) provided in CSA-O86.

A3. Float – Wood frame buildings may float if the buoyant force of the water is greater than forces acting in the downward direction to hold the building on the foundation. Lateral forces, combined with buoyancy may be able to push the building off the foundation.

A3.1. Buoyancy

Case 1. If a breach has not occurred, the building envelope is intact and the structure is treated as a prism filled with air.

$$V_{submerged} = LbD \qquad (21)$$

where, $V_{submerged}$ = the volume of the building submerged by water, m^3
L = length of the building, m
b = width of the building, m
D = depth of water higher than the foundation, m

The resistance is provided by the weight of the house, W, and the vertical anchor resistance, F_A, as estimated from values provided by CSA-O86.

Case 2. If the building envelope has been breached, water enters the home. It is assumed that the buoyant force acts on the wood frame of the building only.

$$V_{submerged} = (\text{cross-sectional area of frame})D \qquad (22)$$

The cross-sectional area of the frame is based on the following assumptions:

- Floors – 2x6 lumber, floor sheathing
- Walls – 2x4 studs, interior and exterior sheathing
- Roof/ceiling – 2x6 joist horizontal ceiling, sheathing
  – 2x6 sloped roof, roofing shingles

The resistance is provided by the weight of building, W, the weight of water inside the building, W_w and the anchor resistive force, F_A, as estimated from values provided by CSA-O86.

For both cases the vertical upward load on the building is the buoyant force of the water, F_B, where

$$F_B = \rho_{water} g V_{submerged} \tag{23}$$

A3.2. Lateral Movement

The horizontal drag force of the water can also move the building laterally off its foundation.

Case 1. $D > n_s h_s$

$$F_d = p_d n_s h_s L \tag{24}$$

Case 2. $D \leq n_s h_s$

$$F_d = p_d DL \tag{25}$$

where,
F_d = horizontal drag force, N
p_d = horizontal drag pressure, Pa
D = d-z_f
d = depth of water, m
z_f = height of foundation above ground, m
L = length of wall perpendicular to flood flow, m

The resistance is provided by the frictional force between the lumber sill and the concrete foundation. The weight of the house is effectively reduced by the vertical buoyant force, which also reduces the friction.

$$F_f = \mu N \tag{26a}$$

$$F_f = \mu \left| W - F_B \right| \tag{26b}$$

where,
F_f = frictional force between sill and foundation, N
μ = coefficient of friction
N = normal force, N
W = weight of the building, N
F_B = buoyant force, N

CHAPTER 3: CONCLUSIONS AND RECOMMENDATIONS

3.1 CONCLUSIONS

It is well known in the structural and wood engineering communities that common wood frame construction results in a very complex structural system. The numerous components of the structural frame work together to resist external loads applied to the system. System factors are developed for the design process to account for the interdependent response, load-sharing and system effects of the building elements. Common practices in wood frame construction are also observed to produce highly redundant systems that require more than one component malfunction to initiate a full system (building) failure (Rosowsky *et al.* 2005). A rapid onset flood event is also a very complex phenomenon; turbulence, velocity, drag, buoyancy, orientation, volume, debris, sediments and other aspects of flood response can be very localized and dependent on a wide range of factors. Therefore, the analysis of wood frame building response to rapid onset flooding is a complicated endeavour.

Quickly moving floodwaters can affect a wood frame building in a number of ways. A model was developed to investigate the response of a simple wood frame residential building to a randomly selected array of flood conditions, represented by uncorrelated combinations of depth and velocity. The modes of failure considered in this study are based on the role of the building to act as protection for the occupants from the flood. The outputs from the model show the relationship between the flood parameters, depth and velocity, and the physical building response. The building fails if it fills with water beyond a depth that is safe for people inside, or structural damage occurs causing the building to be unsafe, or the force of the water causes the building to move off its foundation. Each of these three major failure mechanisms are evaluated individually in the model developed in this thesis. However, there are also interdependencies between the failure mechanisms. For example, whether the building floats off the foundation is highly dependent on whether water has breached the building envelope and filled the building. These complexities and interdependencies contribute to the complicated relationships between predicted building response and flood properties presented in the results. Although a simple relationship between building damage and the "*dv* factor" is not observed, the model application undertaken demonstrates the potential for this type of behaviour modelling and investigation to contribute to flood vulnerability assessments for wood frame buildings.

3.2 STRENGTHS AND WEAKNESSES

The work presented herein directs new emphasis on the structural response of the building to flood impacts, as well as the focus on human safety impacts, rather than solely economic water damage predictions. The analysis is grounded in the physical interactions between the built environment and rapid onset floodwaters. The model foundation adapts existing building response techniques, and effectively updates flood damage prediction methods to the level of analysis common in wind response analysis.

However, many uncertainties in the analysis remain. Building response parameters have been significantly generalized for the current analysis. Many building properties are related to the date of construction, the region, or materials used, and are specific to each individual building. More accurate and reliable damage estimates could be provided by acquiring more accurate estimations of building strength and response properties.

The model as currently developed addresses the direct physical impacts of water forces on a residential wood frame building and potential consequences for occupants inside. However, in a rapid onset flood event there are additional impacts which may affect the safety of the home. Debris impacts and soil scour around the foundation are examples of serious flood actions that can have detrimental impacts on the structural safety of a home. These impacts are not currently assessed in the model. Debris can be modelled as a direct force at the point of impact. A debris impact to a wood frame structure can be simulated using spring behaviour to describe the response of each component of the collision (i.e., the debris and the wall) (Haehnel and Daly 2004). This type of impact will directly influence envelope breach analysis and structural response, and indirectly affect buoyancy. In order to adequately account for debris, a probabilistic estimate of debris onset and accumulation will need to be developed. Scour of soil around the building foundation can undermine the structural integrity of a building and can be described using the threshold velocities for various types of soil (Roos 2003, FEMA 1988). Native soil and fill data are required to obtain a reliable estimate of erosion damage caused by high velocity flows around a building. The computational model is designed to allow the addition of these types of actions in future model developments.

There are also significant external factors related to rapid onset flood waves that are not addressed with the current model. Tsunamis, and often large dam failures, can be triggered by earthquakes. While this model predicts the interactions of the built environment with the rapid onset flood that follows, the earthquake itself has the potential to initially cause great structural damage before the flood wave arrives. Similarly, damaging hurricane winds often accompany rapid onset floods caused by storm surges. Future extensions of the model may incorporate earthquake and hurricane ‘pre-softening’ damages that can cause the building to be less resistant to the ensuing flood forces.

3.3 OVERALL CONTRIBUTIONS

The applications of this type of analysis go beyond emergency planning and mitigation. By developing a greater understanding of building response to high velocity floodwaters, actions could be investigated that may improve resistance for buildings in flood prone regions or to relocate structures if they cannot be hardened sufficiently. Improved depth, accuracy and reliability of flood damage estimates through the application of building response principles will be beneficial to emergency planning, insurance estimates, building code recommendations, land use planning and safe haven design.

BIBLIOGRAPHY CHAPTER 3

FEMA (1988). *Design Manual for Retrofitting Flood-prone Residential Structures*. Washington, DC, USA.

FEMA (2007). "HAZUS: FEMA's Software Program for Estimating Potential Losses from Disasters." < http://www.fema.gov/plan/prevent/hazus/index.shtm> (23 July 2007).

Haehnel, R.B. and Daly, S.F. (2004). "Maximum impact force of woody debris on floodplain structures." *Journal of Hydraulic Engineering*, 130(2), 112-120.

Roos, W. (2003). "Damage to Buildings." TNO Built Environment and Geosciences, Delft Cluster: No. DC1-233-9, The Netherlands.

Rosowsky, D.V., Guangren, Y. and Bulleit, W.M. (2005). "Reliability of light-frame wall systems subject to combined axial and transverse loads." *Journal of Structural Engineering*, 131(9), 1444-1455.