FLOOD LOSS AND RETROFIT ANALYSES FOR RESIDENTIAL BUILDINGS

A Thesis

by

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FLOOD LOSS AND RETROFIT ANALYSES FOR RESIDENTIAL BUILDINGS

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Dedicated To

My Parents

"To avoid any possible disaster we must first think of preventive means to meet it. When the disaster has happened it is no good to complain"

M. Kemal Atatürk

ABSTRACT

Flooding events are the most frequent natural disasters that cause significant physical damage on the built-infrastructure, leading to severe economic losses and social disruptions on communities. To measure and increase disaster resilience of communities, reliable assessment of direct physical losses (i.e., repair cost and time associated with flood damage) of building structures under the hazard actions is the first main and essential ingredient. To mitigate disasters effectively, sophisticated approaches are also needed to support citizens to give risk-based decisions on disaster retrofit actions.

This study presents an assembly-based framework that first develops models to estimate physical flood losses for typical single-family and multi-family residential buildings in Europe, with a focus on houses in UK. Considering several residential building types with or without basement, flood damage potential of each nonstructural and content components of the buildings were examined for various flood depths. Relative losses associated with flood-repair cost and time for each damaged component were obtained considering the individual failure limit of the component. Next, all components were assembled to estimate the total losses on houses in terms of both repair cost and time. Furthermore, this study performed benefit analyses on flood-retrofit approaches to find the optimal solutions minimizing the associated losses.

Results show that water-contact can give severe damage and losses on non-structural building items and building content items. Also, retrofit actions are found to give more effective reductions in losses and repair times if the key ones are applied together, comparing to their effectiveness as an individual action.

ÖZETÇE

Sel olayları, inşa yapılarında önemli fiziksel hasara neden olan ve topluluklar üzerinde ciddi ekonomik kayıplara ve sosyal bozulmalara yol açan en sık görülen doğal afetlerdir. Toplulukların afet direncini ölçmek ve artırmak için, afet eylemleri altında bina yapılarının doğrudan fiziksel kayıplarının (yani, sel hasarı ile ilişkili onarım maliyeti ve süresi) güvenilir bir şekilde değerlendirilmesi ilk ana ve gerekli bileşendir. Ayrıca, afetleri etkili bir şekilde azaltmak için, vatandaşların afet güçlendirme eylemleri hakkında riske dayalı kararlar vermelerini destekleyen sofistike yaklaşımlara ihtiyaç vardır.

Bu çalışma, ilk olarak, İngiltere'deki evlere odaklanarak, Avrupa'daki tipik tek aileli ve çok aileli konut binaları için fiziksel sel kayıplarını tahmin eden modeller geliştiren birleştirme tabanlı bir çerçeve sunmaktadır. Bodrumlu veya bodrumsuz birçok konut bina tipleri göz önüne alınarak, binaların her bir yapısal olmayan ve içerik bileşeninin sel hasar potansiyeli çeşitli sel derinliklerinde incelenmiştir. Her hasarlı bileşen için sel onarım maliyeti ve süresi ile ilişkili göreceli kayıplar, bileşenin bireysel hasar limiti dikkate alınarak elde edilmiştir. Daha sonra, tüm bileşenler hem onarım maliyeti hem de onarım zamanı açısından konutlardaki toplam kayıpları tahmin etmek için birleştirilmiştir. Ayrıca, bu çalışma, ilgili kayıpları en aza indirgeyen en uygun çözümleri bulmak için sele karşı güçlendirme yaklaşımları üzerinde fayda analizleri yapmıştır.

Sonuçlar, sel suyu temasının yapısal olmayan konut binası elemanları ve konut içerisindeki eşyalar üzerinde ciddi hasar ve kayıplar verebileceğini göstermektedir. Ayrıca, güçlendirme eylemlerinin, önemli olanları birlikte uygulanırsa, bireysel bir eylem olarak etkinliklerine kıyasla, kayıplarda ve onarım sürelerinde daha etkili azalmalar sağladığı bulunmuştur.

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CHAPTER 1

INTRODUCTION

1.1 Motivation

Flooding events are the most frequent natural disasters that cause serious physical damage on infrastructure and economic losses and social disruptions on communities. Floods affect approximately 250 million people annually on average [1]. In the past few years, annual average losses from floods have reached an average of 40 billion dollars per year [2].

In the world, 44% of disasters and 31% of economic losses are associated with floods. Between 1970 and 2019, there were 4,886 flood-related disasters reported in the world. For the same period, a total of 322,514 deaths and a total economic loss of 1145.8 billion dollars were reported due to flood-related disasters [3]. Moreover, the frequency of flood disasters increases with changing climate. The number of flood disasters experienced last decade was reported as twice the total number of floods occurred in the previous decade [4].

Flooding is also one of the significant disasters that occurs frequently in Turkey. The total number of floods in Turkey between 1975 and 2002 is 487, and the total loss of life is 493. Between 2003 and 2015, the total number of floods is 722 and the total loss of life is 227. In recent years, a serious increase can be seen in the number of flood disasters in Turkey according to these data. The economic losses due to floods between 1975 and 2015 are approximately 300 million TL [5].

One of the recent flooding in Turkey, the 2021 Kastamonu flooding caused loss of 71 people and enormous damage on buildings and infrastructure. Pictures of buildings affected by this disaster are shown in the Figure 1-1 to Figure 1-3. When these pictures are investigated, it is understood that most engineered buildings do not get any serious structural flood damage, but flooding can give significant damage on the non-structural and content items in the affected buildings. Especially contact with dirty flood water, as shown in the example pictures below (Figure 1-1 to Figure 1-3), can lead to need of full replacement for most items due to hygienic conditions.

Figure 1-1 Interior damage on a residential building after the 2021 Kastamonu flooding [6]

Figure 1-2 Content damage on a residential building after the 2021 Kastamonu

flooding [6]

Figure 1-3 Interior damage on a residential building after the 2021 Kastamonu flooding [6]

Recent flooding events show that it is very significant to understand the flood risk facing communities and take appropriate mitigation decisions. Therefore, this study develops flood loss and retrofit models for residential buildings, considering the potential flood damage that mostly occurs on the nonstructural and content items.

1.2 Literature Reviews on Existing Flood Studies

1.2.1 Flood Losses and Restoration Times

In this section, general information about flood loss models and flood restoration (including repair) time models in the literature is first provided. Flood loss models are generally divided into two main groups: losses due to tangible damage and losses due to intangible damage. If the damage can be stated in monetary terms, this type of damage is called tangible damage. On the contrary, if the damage cannot be directly stated in monetary terms, this type of damage is called intangible damage. In addition, tangible damage is divided into two different groups as direct and indirect tangible damage. Direct tangible damage is the damage caused by the physical contact of flood water with property, or any other objects, for example, the damage of structural and non-structural building items and content items due to water contact. Indirect tangible damage is induced by the indirect impacts and occurs in space or time outside the flood event such as, business interruptions, loss of income of people, etc. Likewise, intangible damage is divided into two subgroups as direct and indirect intangible damage. Effects such as direct loss of life, injuries, psychological distress of people because of flood disaster can be given as examples of intangible direct damage. Effects such as loss of trust in authorities and post-disaster trauma can be examples of intangible indirect damage [7], [8], and [9]. Table 1-1 shows examples of types of flood damage.

Table 1-1 Type of flood losses

Type of Losses Due To:	Direct Damage	Indirect Damage
Tangible Damage	Structural, non-structural, and content damages	Business interruption and loss of income
Intangible Damage	Loss of life, injuries, diseases and psychological distress	Loss of education, trauma

Also, flood losses can be assessed at various spatial scales, such as micro-scale, meso-scale and macro-scale, considering damage assessment details at the level of individual building, region, and nation respectively [7].

In the literature, there are several flood intensity measures reported affecting damage potential of houses. These measures are flood depth, flood duration, flood velocity, flood debris loads, and flood contaminants [10]. However, most of the loss models in the literature mainly use flood depth to describe direct damage potential of buildings in absolute losses (i.e., repair cost values associated with direct flood damage) or in relative ratios with respect to building replacement values [7]. Also, mostly these models are deterministic for some specific regions, ignoring significant uncertainties existed in flood losses [11], [12], [13], and [14].

There are two main approaches in creating direct flood loss models for buildings: empirical and synthetic approaches. While the empirical approach establishes models based on the damage information collected after the flood events, the synthetic approach depends on some scenarios and assumptions to build models analytically [7]. One obvious advantage of the empirical loss model is its use of real damage information, but this requires detailed damage survey after flooding, which is usually rare. On the other hand, the main advantage of the synthetic loss model is that damage information can be analytically obtained at various water heights inside any building, but this also requires reasonable assumptions and takes a lot of effort and time to create such models. Depending on the availability and reliability of previous real flood case data, empirical approach or synthetic approach or even a mixed approach can be chosen [11], [12], [13], and [14].

Another important issue for flood loss models is estimating the repair time. How long it takes for a home to recover after a flood is an important issue for homeowners. However, there is a lack of literature on repair time models, except a few studies. One of these few studies is the US-based HAZUS study [15]. HAZUS presents time data for certain depth intervals according to various building occupancy classifications in US [15]. HAZUS gives more detailed information about physical restoration time and dry-out and clean up times in this study. If the flood height is between 0 and 120 cm in single-family houses without a basement, the total of physical restoration period, dry-out and clean up period are specified between 4 and 7 months. If the flood height is between 120 cm and 245 cm, the total duration is specified between 7 and 10 months. It states that if the house is flooded with a flood depth of more than 245 cm, this period becomes 13 months for single-family without basement houses. Time information on other house typologies is presented in Chapter 3.6.2.

In another study on flood restoration times by Lamond et., al. [16], the average time for clean-up and drying is given as 115 days. Lamond et al. [16] also stated that under normal conditions, a period of 3 months is reasonable for drying. However, there is not any time-depth relation given as in the HAZUS study [15].

Since there is a deficiency in the literature on flood repair time models, more diverse and detailed studies on this topic are needed.

1.2.2 Flood Losses on Content Items

In residential buildings, there are content elements as well as non-structural elements that are sensitive to water-contact. Furniture, equipment, computers, and other supplies are all considered as building contents. The repair or replacement values of the damaged content items can be very costly so they cannot be ignored in flood loss assessment models [17], [18], [19], [20], and [21].

In flood loss assessment models, it is necessary to determine the repair or replacement cost values of the content elements. In the literature, this value for content elements is specified as a percentage of the building structure replacement value. This ratio is called content-to-structure value ratio [15] [17]. In HAZUS [15], this ratio is defaultly defined as 0.50 (i.e., the default replacement value of the content elements as 50% of the value of the whole structure). The same ratio is used for single-family and multi-family houses in HAZUS [15].

The USACE study [17] describes the replacement value for content items in residential buildings by surveying homeowners and using expert opinions. In addition, in this study, the flood height that can give damage for each content items is also stated. The loss on content items is presented separately for freshwater and saltwater flooding conditions. The damage is more in saltwater floods because the saltwater causes more corrosion and deterioration on the household content items due to the intense salt content. In this study, the content-to-structure ratios for 1-storey and 2-storey residential buildings for a freshwater flooding are specified as 0.71 and 0.43, respectively.

1.2.3 Flood Retrofit Analyses

Flood damage has significantly increased in Europe and across the world in recent decades, mostly due to the continuous growth of population and financial resources in high-risk areas [22] [23]. Flood-damage-reducing measures are thus used to mitigate this increased flood damage. These measures can be at different levels: individual flood damage mitigation actions on a building basis or collective mitigation actions on a residential neighborhood [24], [25], [26], [27], [28], and [29].

Flood damage reduction actions applied on building basis are generally divided into three types in the literature: elevation of buildings, dry floodproofing (e.g., wall tanking to resist outside water) and wet floodproofing (e.g., using water resistant floor finishes) [24]. The measure of raising buildings is usually applied to new buildings in flood-prone zones but can also be applied to existing buildings. Due to the high cost of this retrofit measure, it is not practical for existing buildings, so it is not considered in this study. More details on different mitigation actions are described in Section 4.2.

Benefit-cost analyses (BCA) calculations are usually performed to investigate the economic benefit of flood retrofit actions [30], [31], [32], [33]. BCA is defined as a formal approach used for logical, systematic, and unbiased decision-making, particularly when dealing with complicated choices or questionable facts [30] [31]. BCA has also become mandatory in European countries for any flood risk management measures that is planned to be applied [34].

In the literature, there are some studies on flood retrofit actions and BCA analyses. For example, Linham et al. [35] assess the costs of flood adaptation for worldwide cities, whereas Jonkman et al. [36] present an overview of coastal flood protection for three case studies in the Netherlands, Vietnam, and the United States. Also, Aerts et al. [37] and Lasage et al. [38] present extensive cost estimates for flood protections in New York City, Los Angeles, and Ho Chi Minh City. Most of these studies consider flood retrofit actions individually but not in combinations. They did not thoroughly consider the efficiency of combined retrofit actions. Moreover, these studies in the literature generally considered the costs of retrofit actions and the reduction of the flood economic losses but not the flood repairing times or restoration times.

1.2.4 Research Needs

The list below summarizes the research needs identified from the literature reviews:

- There is a lack of information in the literature to find out how soon after the floods the houses will become normal. Models that can estimate flood repair and restoration times are needed for houses.
- There is a lack of loss models that can estimate of damage on common areas in the flat buildings (garden, mechanical equipment, lobby cleaning etc.).
- Detailed and reliable flood loss models are needed that can give full control to the users on easily performing the benefit-cost calculations of retrofit actions by connecting them with the flood loss model.
- Most of the flood studies did not thoroughly consider the efficiency of combined retrofit actions. More studies are needed that can consider both individual and combined flood retrofit actions.
- Moreover, most flood studies in the literature generally consider the costs of retrofit actions and the reduction of the flood economic losses but not the flood repairing times or restoration times. Approaches are needed that can measure the cost-effectiveness of the retrofit packages and evaluate not only the associated repair cost reduction but also the restoration time it takes after the flooding.
- Uncertainties related flood loss estimates are significant and should be considered in the flood loss assessment. Their effects should be investigated by using approaches like sensitivity analyses.

1.3 Research Objectives

The main objective of this study is to create flood loss models for residential buildings and examine the effects of retrofit actions on flood damage and losses.

Moreover, this study investigates which of these retrofit actions are the best cost effective and beneficial options. While creating flood loss models, the repair cost and the repair time associated with flood damage are considered to get flood loss estimates in terms of monetary and time. Establishing repair cost and time models are important for estimating the required fund/aid to get back to normal and especially predicting the answer to the question "how many days later the house can become habitable". The main objectives of this thesis are as follows:

1. Creating comprehensive building typologies for residential buildings, considering both single and multi-family buildings.
2. Creating flood loss models for these building typologies in terms of repair cost and repair time.
3. Understanding efficiency of damage-reducing retrofit actions for residential buildings and deciding which of these retrofit actions are the most cost effective and beneficial.
4. Performing sensitivity analyses on loss models and retrofit results to understand effects of uncertainties in key parameters, such as building type (single or multifamily houses), foundation, number of stories, building dimensions (floor area), and construction quality.

1.4 Organization of the Thesis

This thesis consists of five chapters:

- This chapter (Chapter 1) briefly summarizes the motivation of the thesis and the literature review on flood loss models and retrofit actions, and then it presents the research objectives.

- Chapter 2 summarizes the typologies of residential buildings found in Europe and the UK and shows the typical residential building case studies created in this study. It also explains the characteristics for the created case study set of the residential buildings.
- Chapter 3 describes the development of flood loss models for residential buildings. The proposed repair cost and repair time models associated with potential flood damage on residential houses are demonstrated in this chapter.
- Chapter 4 describes the retrofit actions, which are the damage reduction strategies before or after the flood, and the benefit-cost analyses of the retrofit packages are also performed.
- Chapter 5 summarizes this thesis in general and interprets the overall results and states limitations of the study.

CHAPTER II

THE CASE STUDIES

The purpose of this study is to create flood loss and retrofit models for typical EU residential buildings. Since the construction cost database for UK is more practical to understand and use (in terms of language and information available), UK houses are used in creating the loss and retrofit models. This chapter first summarizes the general characteristics of the UK residential buildings in comparison to European residential buildings, and then shows the typical model houses selected for different building typologies using the UK residential characteristics.

2.1 Residential Building Properties in UK and Europe

In a study of Building Performance Institute Europe (BPIE) [39], building stocks are generally classified into two different categories: residential and non-residential buildings, corresponding to 75% and 25% of the building stocks of European countries, respectively. Most of the residential buildings in Europe consist of single-family houses (64%), including detached, semi-detached, and terraced houses. Greece, Ireland, and the UK have the smallest apartment building ratio in residential building stocks [39], with %12 ratio for UK apartments.

According to the BPIE study [39], the five major countries (France, Germany, Italy, Spain, and the UK) account for 65% of the total floor area for all residential buildings in Europe, as general floor area per person in Europe is reported as 48 m^2. There are considerable variances between countries within Europe. Also, the average floor area per person for single-family and multi-family houses in Europe are found to be 35.3 m^2 and 29.3 m^2 respectively.

To further analyze building characteristics such as floor area, BPIE study [39] also separates buildings stocks in European countries into three regions based on their similarities in climate, building types, and domestic market: North and West regions (UK, France, Germany, etc.), Central and East regions (Poland, Belgium, Romania, etc.), and South regions (Greece, Italy, Spain, etc.). BPIE study indicates that the floor area per person for the countries in the Eastern, Central and North, and Southern regions are 25 m^2, 39 m^2 and 42 m^2 respectively. Similarly, considering only single-family houses, per capita floor area is found to be 26 m^2 in the Central and East regions, 41 m^2 in the North and West regions, and 50 m^2 in the Southern part. Also, it is noted that the North and West regions have the largest values for residential floor area per capita.

Based on the English Housing Survey study for UK (2011 and 2018) [40] and [41], which is usually conducted every five years, 54% of the houses in the UK are terraced or semi-detached houses, 17% of them are detached houses, and 9% of them are bungalow houses. The remaining 20% of the stock is flat buildings, generally low-rise flat buildings for construction purposes. The average residential useable floor area is 91 m^2 and 103 m^2 based on the 2011 and 2018 English Housing Surveys, respectively [40] [41]. Mean useable floor areas based on different building typologies are shown in Table 2-1, changing from 58 m^2 (low rise-flat) to 149 m^2 (detached) [41].

Table 2-1 Useable floor areas for UK residential buildings [41]

Dwelling Type	Mean Useable Floor Area (m^2)
All Terraced Houses	88 m^2
Semi-detached	97 m^2
Detached	149 m^2
Bungalow	77 m^2
Converted Flat	65 m^2
Purpose Built Flat	58 m^2

Old buildings in the EU are usually traditional masonry structures where the exterior walls are often unreinforced masonry walls [42]. For example, the UK is among the countries with the highest ratio of old buildings, with 55% of the total residential building stocks in pre-1960, 33% in the 1961-1990 period, and 12% in 1991-2010 [39]. The BPIE study presents the ages of residential buildings for three regions of Europe: In the South region, 37% of residential buildings are in pre-1960, 40% in 1961-1990, and 14% in 1991-2010. For the residential buildings in the North and West area, 42% of them are in pre-1960, 39% in 1961-1990, and 19% in 1991-2010. In the Central and East regions, 35% of the residential buildings were built before 1960, 48% in 1961-1990, and 17% in 1991-2010 [39].

Again, for the UK, based on the English Housing Survey (2011), 95% of the total building stock was traditionally built using masonry or wood, primarily load-bearing walls (i.e., supporting vertical load in addition to their own weight) [40]. While 64% of these homes were built using traditional cavity walls, 27% were constructed with solid masonry walls using brick, block, stone, or flint [39].

2.2 *Typical Residential Buildings Considered in the Study*

This study focuses on typical single-family homes and multi-family homes in Europe to model flood losses and recovery times for residential buildings. To create a set of typical case studies for flood loss and time models, the building parameters such as construction age, construction type, construction quality, number of storey, floor area, foundation type of residences are found to be the most key parameters significantly affecting the repair cost and time calculations associated with flood damage on homes.

Kelman [8] noted in his study that the age of the building would give information about the materials used in the buildings and how they were constructed. He emphasized that the old well-maintained building was less vulnerable than the new poor-maintenance building. Assuming, there is enough building maintenance, the age of the building is not taken into account in this study.

Using the findings of the literature review summarized above, the set of building typologies in Table 2-1 – Table 2-3 are selected in this study. Totally, 30 different building typologies are selected, considering different building type (single family detached house and multi-family flat building), construction quality (low, average, and high), number of storeys (one storey or two storeys for single family, and three storeys and four or more storeys for flats) and foundation type (finished or unfinished basement, slab on grade).

Table 2-2 The case studies for single-family houses with basement

Case No	Single-family House with Basement Case Studies
1	One storey, single family detached house, low quality, with finished basement, with an average floor area of 100 m^2
2	One storey, single family detached house, average quality, with finished basement, with an average floor area of 100 m^2
3	One storey, single family detached house, high quality, with finished basement, with an average floor area of 100 m^2
4	One storey, single family detached house, low quality, with unfinished basement, with an average floor area of 100 m^2
5	One storey, single family detached house, average quality, with unfinished basement, with an average floor area of 100 m^2
6	One storey, single family detached house, high quality, with unfinished basement, with an average floor area of 100 m^2
7	Two storey, single family detached house, low quality, with finished basement, with an average floor area of 100 m^2
8	Two storey, single family detached house, average quality, with finished basement, with an average floor area of 100 m^2
9	Two storey, single family detached house, high quality, with finished basement, with an average floor area of 100 m^2
10	Two storey, single family detached house, low quality, with unfinished basement, with an average floor area of 100 m^2
11	Two storey, single family detached house, average quality, with unfinished basement, with an average floor area of 100 m^2
12	Two storey, single family detached house, high quality, with unfinished basement, with an average floor area of 100 m^2

Table 2-3 The case studies for single-family slab-on grade houses

Case No	Single-family House with Slab-on Grade Case Studies
13	One storey, single family slab-on grade house, low quality, with an average floor area of 100 m^2
14	One storey, single family slab-on grade, average quality, with an average floor area of 100 m^2
15	One storey, single family slab-on grade, high quality, with an average floor area of 100 m^2
16	Two storey, single family slab-on grade, low quality, with an average floor area of 100 m^2
17	Two storey, single family slab-on grade house, average quality, with an average floor area of 100 m^2
18	Two storey, single family slab-on grade house, high quality, with an average floor area of 100 m^2

Table 2-4 The case studies for multi-family flat buildings

Case No	Multi-Family Flat Buildings Case Studies
19	Low-rise flat building (3-storey), low quality, with unfinished basement with an average flat floor area of 60 m^2
20	Low-rise flat building (3-storey), average quality, with unfinished basement with an average flat floor area of 60 m^2
21	Low-rise flat building (3-storey), high quality, with unfinished basement with an average flat floor area of 60 m^2
22	Low-rise flat building (3-storey), low quality, slab-on grade with an average flat floor area of 60 m^2
23	Low-rise flat building (3-storey), average quality, slab-on grade with an average flat floor area of 60 m^2
24	Low-rise flat building (3-storey), high quality, slab-on grade with an average flat floor area of 60 m^2
25	Mid-rise or more flat building flat (4+ storey), low quality, with unfinished basement with an average flat floor area of 60 m^2
26	Mid-rise or more flat building flat (4+ storey), average quality, with unfinished basement with an average flat floor area of 60 m^2
27	Mid-rise or more flat building flat (4+ storey), high quality, with unfinished basement with an average flat floor area of 60 m^2
28	Mid-rise or more flat building flat (4+ storey), low quality, slab-on grade with an average flat floor area of 60 m^2
29	Mid-rise or more flat building flat (4+ storey), average quality, slab-on grade with an average flat floor area of 60 m^2
30	Mid-rise or more flat building flat (4+ storey), high quality, slab-on grade with an average flat floor area of 60 m^2

Typical EU case studies for selected single-family home and multi-family home are created. A floor area of 11 m by 9.1m is considered for single-family homes (see Figure 2.1- 2.3). Also, a floor area of 6.6 m by 9.1 m is considered for multi-family homes (see Figure 2.4). The minimum clear inner height (floor-to-ceiling height) in European buildings varies between 2.20 m and 2.70 m [43]. In this study, the mean value for clear inner height is thus assumed to be 2.5 m. The mean storey height (floor to floor height) is taken as 2.75 m for all house typologies, considering the slab thickness and floor covering thickness.

The selected residential buildings are considered with two different types of foundations: basements and slab-on-grades. The most common foundation types in Central Europe are slab-on grade and strip footing foundation types (basement type) [44]. In the UK, 2% of all homes (340,000 dwellings) have at least one of their rooms in the basement storey [45]. Moreover, two different types of basements are considered as finished or unfinished basements. The basement foundation walls, and floor slab of the building are assumed to be masonry and concrete, respectively.

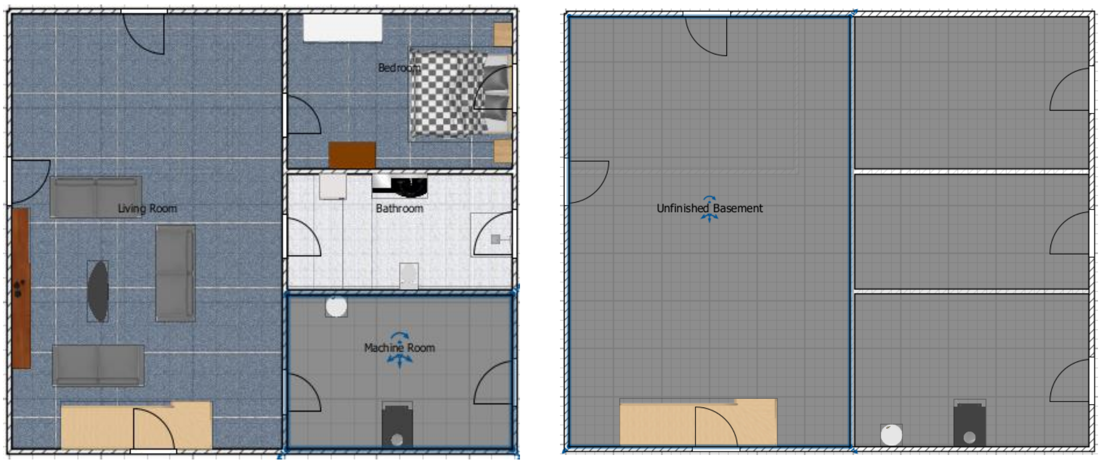

Figure 2-1 Floor plans of a finished basement (left) and unfinished basement (right) for one or two-storey single-family detached houses

Figure 2-2 Floor plans of the 1st storey for single-family detached houses with basement (left) and with slab-on-grade (right)

Figure 2-3 Floor plan of the 2nd storey for two-storey single-family detached houses with basements or slabs

Figure 2-4 Floor plan of a multi-family dwelling (flat)

All of the assumed single and multi-family house properties are shown in Table 2-2 – 2-4 according to their number of floors and the type of foundation. An example of the elevation plan of low-rise flat buildings is also shown in Figure 2-5. In addition, the elevation plan of the two-storey single-family house with slab-on grade is shown in Figure 2-6.

All created house plans for single-family houses have a bedroom, bathroom, and living room on each floor plan. The room areas according to the building typologies are presented in Table 2-5. In single family houses with finished basements, there is an unfinished mechanical/machine room (or storage room for hot water and heater etc.) in addition to other finished rooms (bedroom, bathroom, and living room). If the basement is unfinished, there is no room or items but only mechanical items in the basement. If the single-family house does not have any basement (slab-on-grade houses), the mechanical room is located on the ground floor (see Figure 2-3 right). The kitchen is considered only for the first (ground) floor plan of all single-family houses. Lastly, a boiler heating type is assumed since boiler is commonly used (90%) in the UK houses [46].

Multi-family buildings are divided into two groups: low-rise flats and medium-rise flats. Flat buildings with at least three floors are mostly defined as low-rise flats, and flat buildings with four floors and above are defined as medium-rise flats in some UK-based studies [47]. Similarly, most studies indicate low-rise as 3-storey buildings and they cover most of the flat building stock in UK [46]. So this study assumes 3-storey for low-rise flats, and 4 or more stories for medium or high rise flats. The multi-family building properties are shown in Tables 2.6-2.7. Apartment (flat) buildings are assumed to have lobby space of one-third of a resident's floor area. Therefore, this area is considered to be 20 m^2. In the study by Kelman [8], residence surveys were done for specific regions in the UK, and it was reported that there was generally no basement in any flat building. However, to understand the differences, this study assumes either unfinished basement (assuming nobody lives in there) or slab-on-grade for flat buildings. 75% of the flat buildings in UK have central heating [48]. Therefore, it is thought that there is a central heating in the low-rise and medium/high rise flat buildings. Also, it is assumed that there is an elevator in medium/high rise buildings. In the UK, the rate of having an elevator in flat buildings with 6 storeys or more is 98% [45].

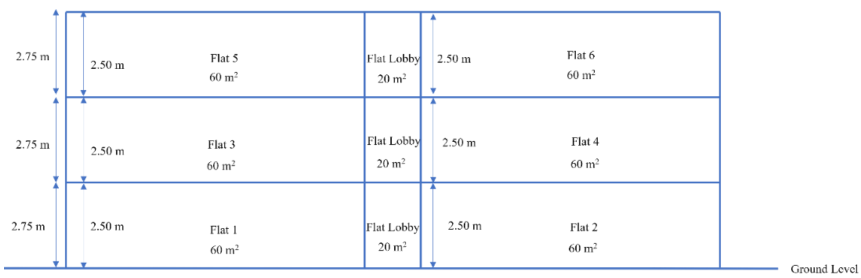

Figure 2-5 Low-rise flat building elevation plan

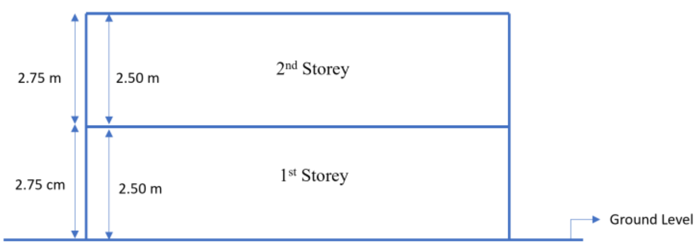

Figure 2-6 Elevation plan of two storey single-family with slab on grade house

Table 2-5 Single-family building properties [41] [43]

General Single-Family Buildings Properties	Structural Type	Floor Area (m^2)	Number of Storey	Total Floor Area (m^2)	Inner Storey Height (m)	Floor to Floor Height (m)
	1 Storey Detached Single-family House with Basement	100 m^2 [41]	2 (1+1)	200 m^2	2.5 m [43]	2.75 m [43]
	2 Storey Detached Single-family House with Basement	100 m^2 [41]	3 (1+2)	300 m^2	2.5 m [43]	2.75 m [43]
	1 Storey Slab-on Grade Detached Single-family House	100 m^2 [41]	1	100 m^2	2.5 m [43]	2.75 m [43]
	2 Storey Slab-on Grade Detached Single-family House	100 m^2 [41]	2	200 m^2	2.5 m [43]	2.75 m [43]

.

Table 2-6 Multi-family building properties [41] [43] [47]

General Multi-Family Buildings Properties	Structural Type	1 Flat Floor Area (m^2)	Number of Storey	Number of Flats	Inner Storey Height (m)	Floor to Floor Height (m)
	Low-Rise Flats	60 m^2 [41]	3 [47]	6	2.5 m [43]	2.75 m [43]
	Medium Rise Flats	60 m^2 [41]	4+ [47]	8	2.5 m [43]	2.75 m [43]

Table 2-7 Room dimensions for single-family and multi-family buildings

	Single-family homes			Multi-family buildings (flats)
Name of Room	**Basement's Room Area (m^2)**	**1st Storey's Room Area (m^2)**	**2nd Storey's Room Area (m^2)**	**Flat's Room Area (m^2)**
Living Room	54.6 m^2	38.65 m^2	54.6 m^2	25.8 m^2
Bedroom	16.5 m^2	16.5 m^2	16.5 m^2	8.6 m^2
Bathroom	12.5 m^2	12.5 m^2	12.5 m^2	6.5 m^2
Storage Room (if it exists)	16.5 m^2	16.5 m^2	-	-
Kitchen (if there exists)	-	15.85 m^2	-	10.5 m^2
2nd Bedroom (if there exists)	-	16.5 m^2	16.5 m^2	8.6 m^2
Total	100 m^2	100 m^2	100 m^2	60 m^2

2.3 Non-structural Items and Contents

In flooding events, mostly nonstructural building items and contents are damaged, while structural frame or components stay stable [11] and [12]. There are many non-structural items in the houses that may get damaged when in contact with water. Therefore, a list of standard non-structural items vulnerable to water contact is created and used for all building types considered in the study. The list is presented in Table 2-8.

Most dwellings in the UK use gas central heating. Approximately 83% of dwellings use gas central heating [49]. Therefore, the elements used in this heating system are considered in creating the list of nonstructural mechanical items.

Non-structural items related to wall cleaning, plasterboard, painting, and staircase are considered in four parts along the wall height. Insulation is considered in two parts along the wall because these items can be removed and replaced partially with new ones as the flood water level increases along the wall height.

Non-structural items are almost common in all building typologies. Only main differences exist in the common areas for flat buildings, where their mechanical items significantly differ, using elevators (for medium-rise) and central based higher capacity boilers.

In addition to the non-structural items, there are also content items in the houses. These content items can also get damage from flood waters. Therefore, in this study, a content list that can be found in an ordinary single or multi-family house is created. In this list, separate content item lists are created for each room. The content list is shown on the floor plan (see Figure 2-7).

In next chapter, non-structural items and contents shown in Table 2-8 and Figure 2-7 will be examined in more detail to perform flood analyses for each 30 building case studies mentioned in Table 2-2 to Table 2-4.

Table 2-8 Non-structural items list

Flooring	Floor Cleaning and Decontamination	Floor Covering and Skirting				
Along Walls	Doors and Door's Frames	Plasterboard and Insulation	Painting	Electrical Items (outlets, wiring, etc.)	Staircase	Bottom and Upper Cabinet, Counter
Along Walls Cont'd	Windows	Breaker Box				
Ceiling	Lighting	Coving	Plasterboard for Ceiling	Smoke Detector	Insulation	Ductwork
Ext. Walls and Garden Cleaning	Exterior Wall Painting	Cleaning Site Vegetation				
Extra Items for Kitchen	Floor Covering	Bottom and Upper Cabinet, Counter	Ceramic Wall Tiles			
Lobby for Flats	Staircase Cleaning	Wall Cleaning, Decontamination and Painting				
Mechanical Items for Single Family	Hot Water Heater	Boiler	Drying	Room Thermostat	Pump for Basement (if any)	
Mechanical Items for Multi Family (Flats)	Elevator (only in med and high rise)	Central Boiler	Central Hot Water Heater	Water Softener	Pump for Basement (if any)	Drying
Mechanical Items for Multi Family (Flats) Cont'd	Water Pressure Booster (only in med and high rise)	Circulator (only in med and high rise)	Electrical Equipment			

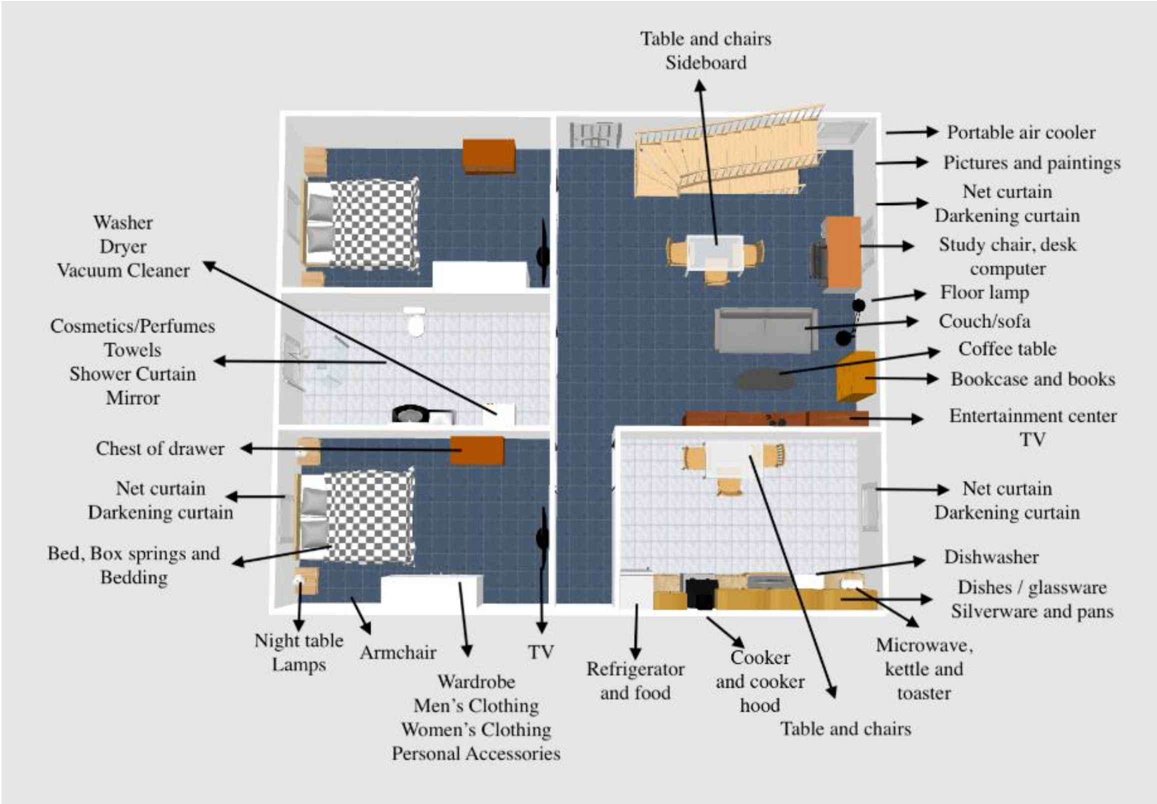

Figure 2-7 Content items

CHAPTER 3

FLOOD LOSS AND TIME MODELS

3.1 Methodology

Most of flood damage occur in the interior of homes on non-structural items due to water-contact, and rarely structural damage occur. To construct flood loss models, this study thus focuses on non-structural building components (e.g., infill walls, electrical cables, doors, …etc.) and content components (fridge, oven, table etc.). Assembly-based vulnerability (ABV) approach has been considered for loss estimation calculations, as this approach can be easily used together with analytical (synthetic) flood loss method [11] [50]. ABV approach calculates detailed losses associated on each damaged component item by item, then assembles all item losses into a total loss. As it requires detailed item loss analyses, it takes time and efforts but give more reliable results. Spons's Architect and Builders Price Book (2020) and Spon's Mechanical and Electrical Services Price Book (2020) are used to calculate repair or replacement cost for each damaged item [51] [52]. Lastly, all repair actions are assumed to be cascading events to assess the total repair time models.

Generally, flood loss models are obtained in terms of flood depth-loss curves in the literature. Similarly, this study assesses loss curves and repair time curves depending on the flood depth. The flood depth is taken with respect to finished floor level in the developed models below.

Multi-coloured manual is one of the sources that provides flood depth-loss models for UK, divided into two groups as financial and economic losses. For example, financial losses consider the price of the 10-year-old television in the house based on present day's price, without considering any depreciation in the price [19]. On the contrary, economic losses consider the price of the 10-year-old television in the house as a loss based on 10 years ago price [19]. In this study, while determining the flood damage in household, unit prices are considered as financial damages, therefore it is assumed there is not any depreciation with age.

3.2 Non-structural Flood Analyses

Flood analyses are performed on the non-structural items for the different house typologies. A flood capacity depth is assumed for the water level at which each of the non-structural elements given in Table 2-8 gets damaged. The flood depth ranges for non-structural elements are listed in groups in Table 3-1. While deciding on these flood depths, pictures of various houses damaged by flooding and our engineering judgement are used. In this study, the worst-case scenario is considered. It is assumed that muddy and unhygienic flood water enters the house, and a deep cleaning and a complete replacement of all vulnerable non-structural items are needed.

Some assumptions are made while creating the non-structural flood loss and time models. These assumptions are:

- Spon's Architect and Builders Price Book (2020) and Spon's Mechanical and Electrical Services Price Book (2020) are used for price and time data. For some missing removal items, other construction database sources such as 2013 RS Means unit price US-dollar values are used by converting them to 2013 GDB prices, then to 2020 GDB prices.

- Prices and labor rates come from Outer London based on Spons' Architect and Builder's Price book 2020.
- 3% overhead and profit are already included in the unit prices.
- Debris removal is included inside the unit prices.
- The low construction quality home is based on the lowest unit prices found on Spon’s, likewise the high one depends on the logical maximum values found on the book.
- Carpet tile is considered as floor covering in low quality and average quality houses, but wood block is considered as floor covering in high quality houses.
- There could be some cleaning on the garden or pavement, but fence if any is assumed to be okay. The area related to cleaning garden is assumed to be half of floor area for single family and multi family buildings.
- The worst scenario is considered: muddy flood and not hygiene so it requires deep cleaning and full replacement for all items.
- Pump sump is only considered for single family houses or multi family flat buildings with basements.
- The kitchen is only on the first floor of the single-family houses and in each of resident apartments of the flat buildings.
- Houses with basements also have windows in the basement.
- It is thought that there is a gypsum plasterboard and insulation on the interior side of the brick walls of the house or resident apartment.
- It is assumed that the mechanical items (hot water heater, boiler etc.) are in the mechanical room on the basement for the houses with basements, or

the mechanical items are in the mechanical room on the 1st floor for the slab-on grade houses.

- Losses for residents in flat buildings are assumed to be losses in their own apartments plus any shared losses that might occur in common areas or on common items such as unoccupied basements, mechanical items, and lobbies.

While creating the flood loss model, the non-structural elements in the house are grouped according to their location in the house. For example, floor coverings and skirtings are classified in the floor category; items such as doors, gypsum plasterboard, insulation, and staircase are classified in the wall category; items such as lightning, coving, smoke detector are classified in the ceiling category; extra materials for kitchen such as kitchen cabinets, worktop ceramic tile are classified in the kitchen category. Exterior wall cleaning and painting for exterior walls are also grouped as one. The cleaning of the common stairs and floors and the cleaning and painting of the walls in the common area are classified as lobby items for apartment buildings. Machine elements in single family houses and apartments are classified separately (see Table 3-1).

Table 3-1 Assumed damage heights (flood depth capacities) for non-structural items

Non-structural Items Location	**Damage Height (cm)**
Single Family Houses and Apartments in Flat Buildings:	
Flooring Items (Floor finishes, skirtings etc.)	2.5 cm – 5 cm
Wall Items (Doors, insulation, gypsum plasterboard etc.)	10 cm – 220 cm
Ceiling Items (Lightning, coving, insulation etc.)	240 cm – 250 cm
Ext. Walls and Garden Cleaning	15 cm – 195 cm
Extra Items for Kitchen	2.5 cm – 180 cm
Mechanical Items	5 cm – 120 cm
Common Areas in Flat Buildings:	
Lobby Items for Flats	15 cm – 240 cm
Central (Common) Mechanical Items for Flats	5 cm – 185 cm

Non-structural synthetic flood loss models created by considering an average of 100 m^2 floor area houses are created separately for different house typologies and three different non-structural component quality. Figures 3-1 to Figure 3-12 show the repair loss and repair time models associated with flood losses at each water depth.

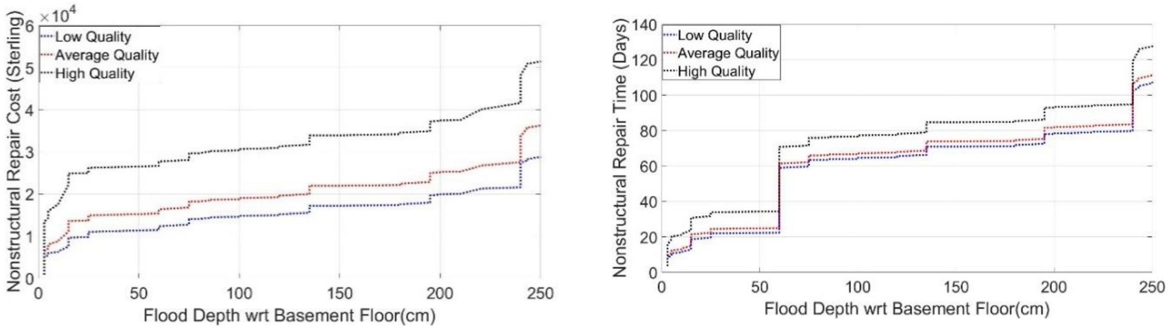

Figure 3-1 Non-structural flood repair cost and time for the finished basement storey of one or two storey single family detached house, with an average floor area of 100 m^2

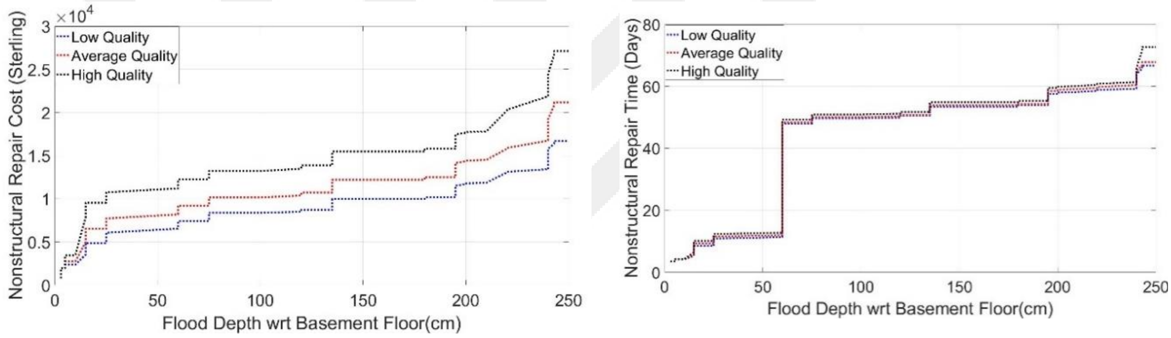

Figure 3-2 Non-structural flood repair cost and time for the unfinished basement storey of one or two storey single family detached house, with an average floor area of 100 m^2

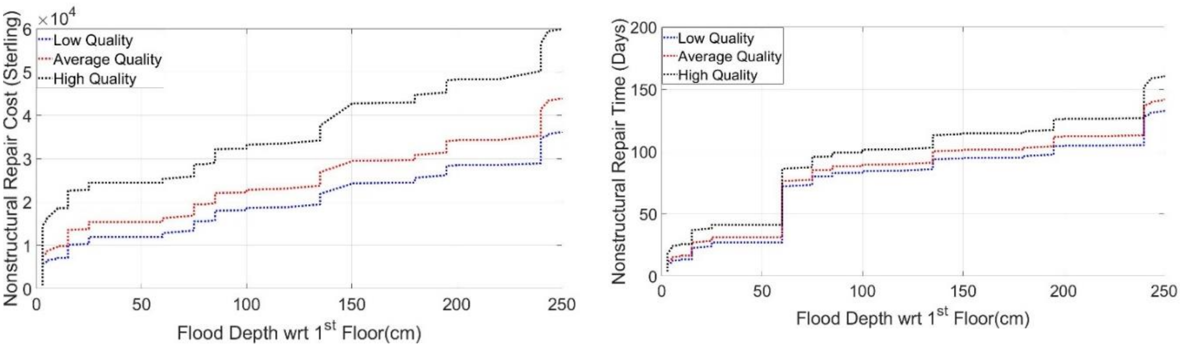

Figure 3-3 Non-structural flood repair cost and time for the 1st storey of one storey single family detached house, with an average floor area of 100 m²

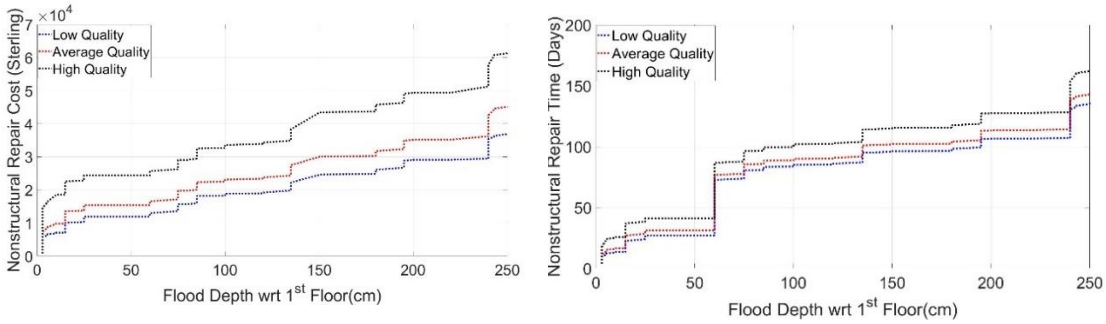

Figure 3-4 Non-structural flood repair cost and time for the 1st storey of two storey single family detached house, with an average floor area of 100 m²

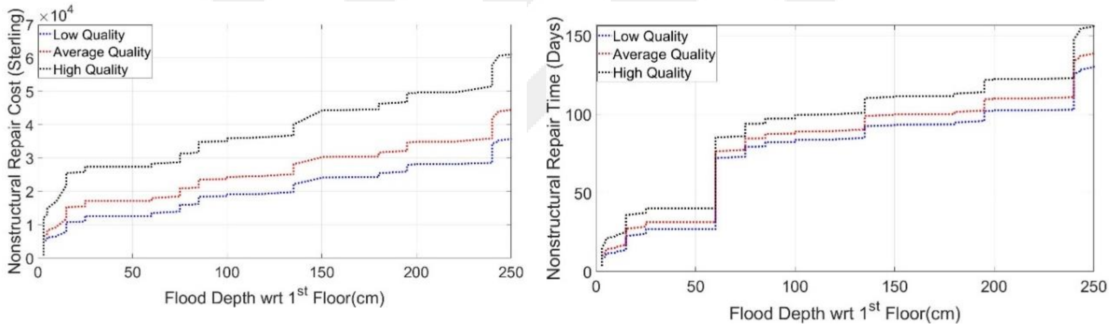

Figure 3-5 Non-structural flood repair cost and time for the 1st storey of one storey single family slab-on grade house, with an average floor area of 100 m²

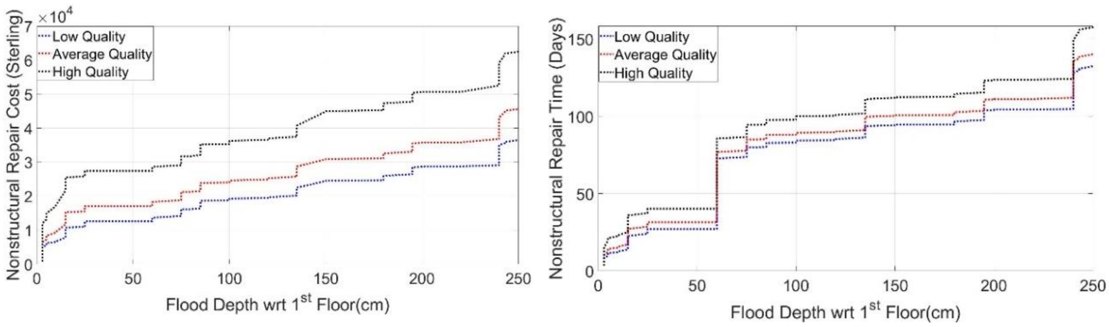

Figure 3-6 Non-structural flood repair cost and time for the 1st storey of two storey single family slab-on grade house, with an average floor area of 100 m^2

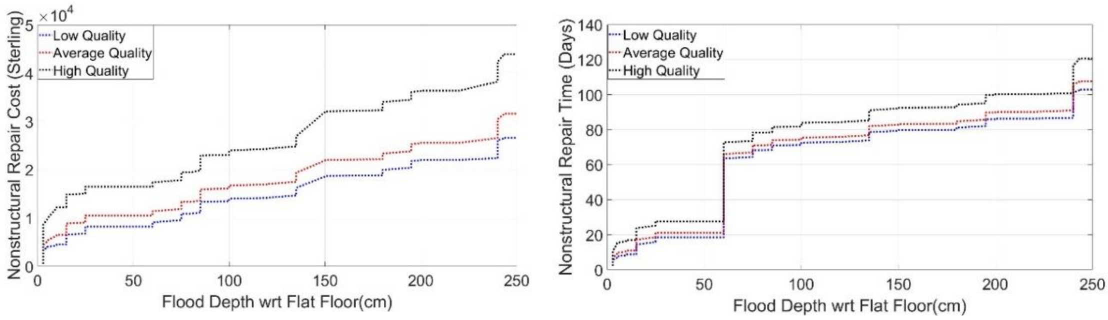

Figure 3-7 Non-structural flood repair cost and time for a resident apartment at low-rise or mid-high rise flat building with an average flat floor area of 60 m^2

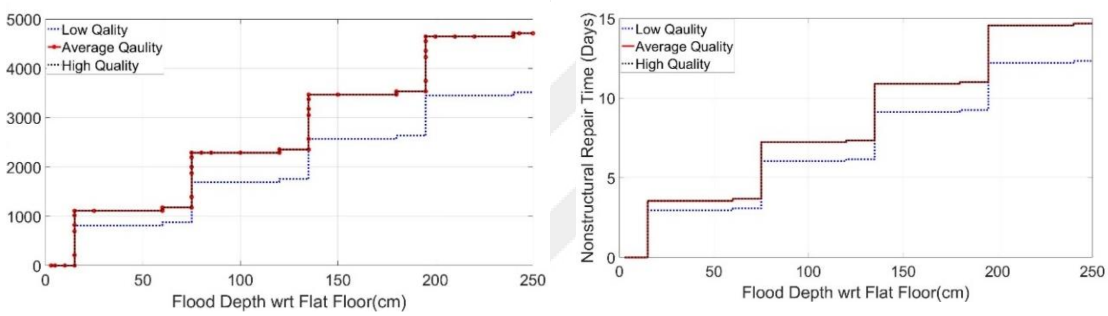

Figure 3-8 Non-structural flood repair cost and time for lobby area of low or med/high rise flat buildings with unfinished basement (note: the depth is with respect to basement floor)

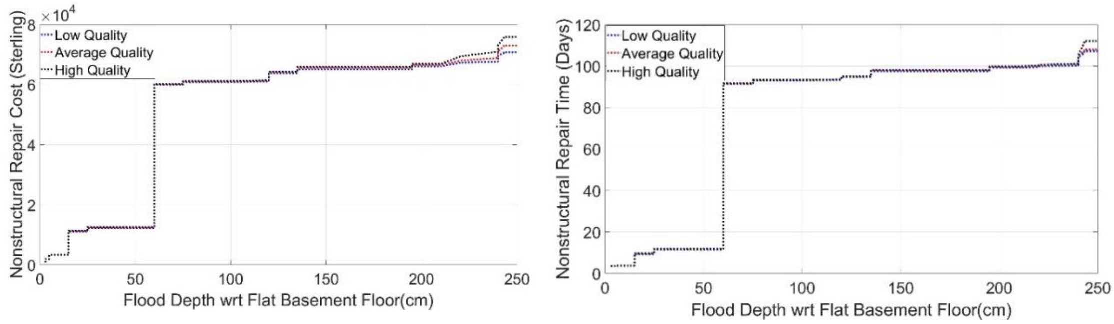

Figure 3-9 Non-structural flood repair cost and time for unfinished basement area (for low rise flat buildings)

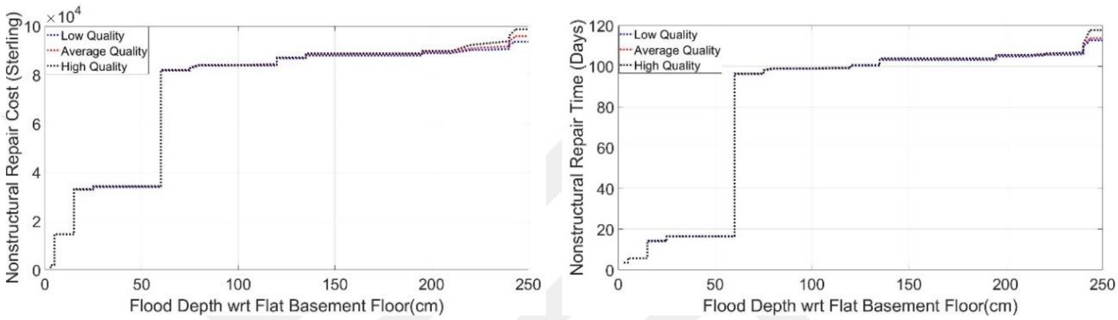

Figure 3-10 Non-structural flood repair cost and time for unfinished basement area (for medium-high rise flat buildings)

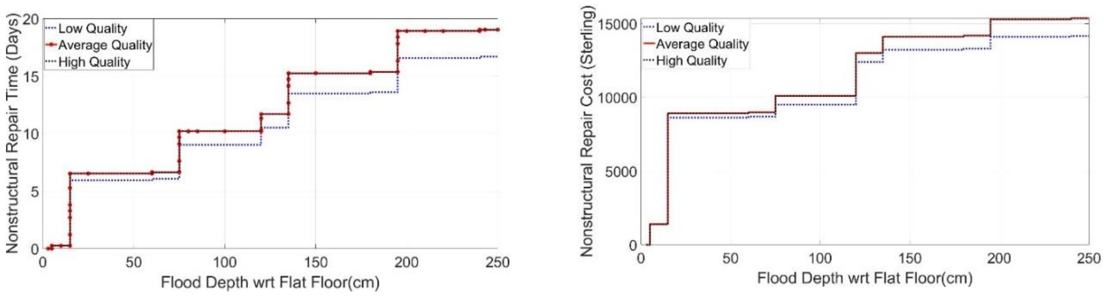

Figure 3-11 Non-structural flood repair cost and time for lobby area for low rise flat buildings with slab-on grade (note: the depth is with respect to ground level)

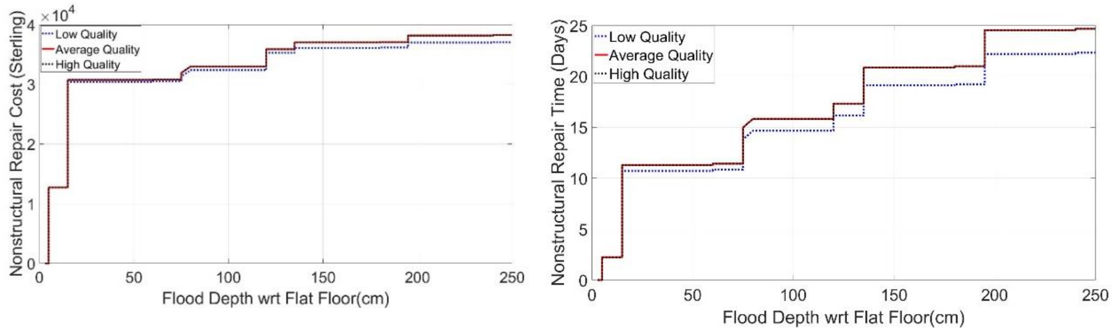

Figure 3-12 Non-structural flood repair cost and time for lobby area for med/high rise flat buildings with slab-on grade (note: the depth is with respect to ground level)

As seen from Figures 3-1 to Figure 3-12, there is usually a sudden increase in cost estimates at initial values of water depth inside the home. As the household material quality increases, the total repair cost increases as expected, since household material quality is a key parameter significantly affecting repair cost and time estimates. All loss and time models increase as the water height increases. This is due to large repair costs associated with damage on the flooring and equipment. Electrical items, such as water heater and furnace, are usually located just on the floor, and they are highly valuable and sensitive to water-touch comparing to other interior items.

Table 3-2 compares flood loss and time models for different building typologies for a fully flooded floor up to 3 m. If the basement flood loss models are compared, the house with the finished basement has more repair costs than the house with the unfinished basement. In houses with finished basements, the basement has more non-structural items because the rooms are habitable. Therefore, both repair time and repair costs are higher in houses with finished basements.

Table 3-2 Maximum (at 3 m) non-structural loss and time values for every building type (note: all floor areas for single family houses and flat apartments are assumed to be 100 m^2 for comparison)

Building Typologies	**Fully Flooded Floor (up to 3 m)**	**Max. Value for Nonstructural Loss (£)**			**Max. Value for Nonstructural Time (Days)**		
		Low	**Ave**	**High**	**Low**	**Ave**	**High**
Single family detached house	Finished basement storey	28825	36278	51449	108	112	128
Single family detached house	Unfinished basement storey	16701	21172	27107	67	68	73
One storey single family detached house with basement	1st storey	36206	43949	59937	133	142	161
Two storey single family detached house	1st storey	36908	45128	61289	136	144	163
One storey single family slab-on grade house	1st storey	35786	44474	61145	131	139	157
Two storey single family slab-on grade house	1st storey	36488	45653	62498	133	141	158
Low or med/high rise flat buildings	Flat resident	33968	40512	56500	123	130	149
Low or med/high rise flat buildings with unfinished basement	Lobby area	3512	4712	4712	12	15	15
Low rise flat buildings with unfinished basement	Unfinished basement (including mech. area)	70723	72982	75842	107	108	112
Medium-high rise flat buildings with unfinished basement	Unfinished basement (including mech. area)	93593	95852	98712	113	114	118
Low rise flat buildings with slab-on grade	Lobby area and mech. area	14171	15370	15370	17	19	19
Med/high rise flat buildings with slab-on grade	Lobby area and mech. area	37040	38240	38240	22	25	25

Regardless of whether the houses have a basement or not, when 1-storey and 2-storey houses are compared, it is understood that the first floor of 2-storey houses has little more repair costs and repair time. Since there exists staircase on the first floor to go up to second floor in two storey houses, the damage to this staircase has increased the repair cost, slightly.

In Table 3-2 , when the 1st floor repair cost and repair time of slab-on grade houses and houses with basements are compared, there is more repair cost and repair time on the 1st floor in slab-on grade houses. Because in slab-on grade houses, the mechanical tools are on the 1st floor, but in the houses with a basement, the mechanical tools are in the basement. Therefore, the 1st floor of slab-on grade houses has more repair costs and repair time.

In Table 3-2, the losses for flat building are also given, considering the floor area of 100 m^2 for a flat resident for comparison purpose. Non-structural losses of the lobby areas and mechanical equipment losses are presented for flat buildings. When looking at the lobby area of flat buildings, non-structural losses for the lobby is higher in flat buildings with slab-on grade compared to flat building with basements. Because mechanical equipment are located in the lobby area in slab-on grade flat buildings. However, in flat buildings with unfinished basements, mechanical equipment are located in the unfinished basement. Therefore, non-structural loss is higher in slab-on grade flat buildings.

As expected, when looking at the lobby areas of slab-on grade flat buildings, the lobby non-structural damages of medium/high rise flat buildings are more. Due to the presence of elevators and mechanical devices with high capacity in medium/high rise flat buildings, non-structural loss is higher in such buildings.

3.3 Non-structural Relative Flood Analyses

In this study, relative loss values (damage ratios) are calculated instead of absolute repair costs. The damage ratio is found by dividing the repair cost by the building replacement value of the building. Each building replacement value is found from the European Construction Cost database [53]. These building replacement values are shown in the Table 3-4. Since the building replacement values in the database belong to 2021, these values have been converted to 2020 in damage ratio calculations.

Table 3-3 All building replacement values for all typologies (note: SF and MF stand for single family house and multi family building, respectively) based on 2021 year

Building Typologies	Eurocost Values [53] (£/m^2)		
	Low Quality	**Average Quality**	**High Quality**
SF, One Storey with Finished Basement	1595	1775	2088
SF, Two Storey with Finished Basement	1595	1775	2088
SF, One Storey with Unfinished Basement	1595	1775	2088
SF, Two Storey with Unfinished Basement	1595	1775	2088
SF, One Storey with Slab on Grade	1595	1775	2088
SF, Two Storey with Slab on Grade	1595	1775	2088
MF, Low rise Flat with Slab on Grade	1694	1841	2122
MF, Low rise Flat with Basement	1694	1841	2122
MF, Medium/High Rise Flat with Slab on Grade	1816	1998	2327
MF, Medium/High Rise Flat with Basement	1816	1998	2327

The depth-damage ratio models for all building typologies are presented in Figure 3-13. When calculating the building replacement value of the basement in houses with unfinished basements, 33% of the building replacement value of the finished basement is accepted. The results in Figure 3-13 show that the building with the highest damage ratio is the low rise flat building with unfinished basement. It gives more damage ratios than the flat building with slab on grade. This is expected since buildings with basements are more vulnerable. When comparing the results in Figure 3-13, the building with the least damage ratio cones from the two storey single-family house with slab-on grade. It is even lesser than the results for flat building with slab on grade, since the mechanical elements in flat buildings are more valuable than the mechanical elements in single family houses.

In Figure 3-14, damage ratios are calculated for a building typology by considering different construction qualities. Considering different building replacement values for different construction qualities (see Table 3-3), the higher construction quality model gives higher damage ratios for a single family house. Therefore, it can be deduced that construction quality is an important parameter for flood loss models.

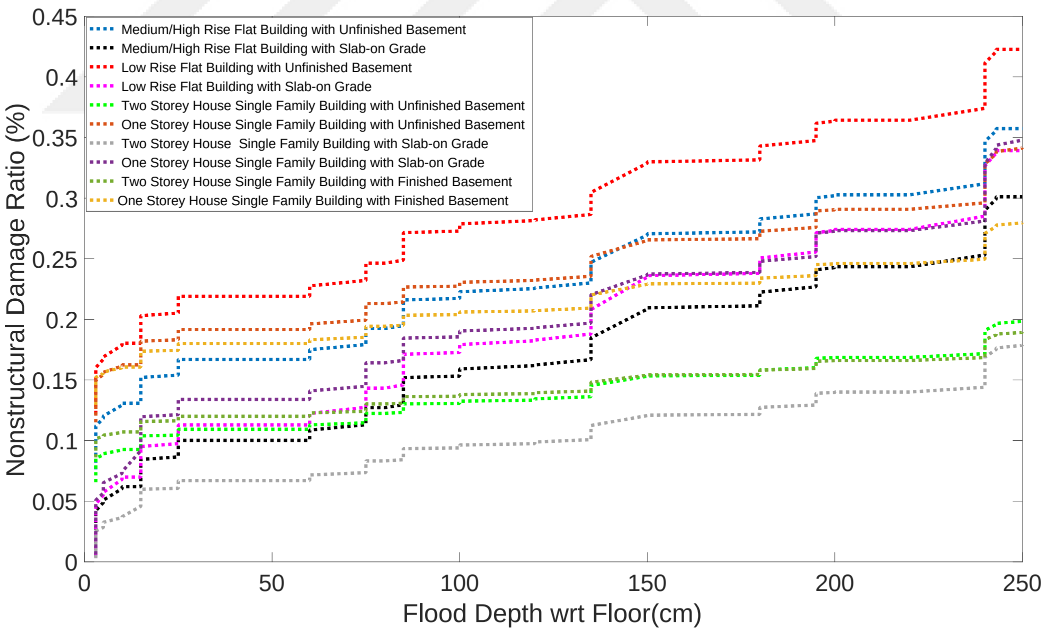

Figure 3-13 Non-structural depth-damage models ratio for all building typologies for average quality (note: for the flats, the cost on resident apartment is considered in the plots)

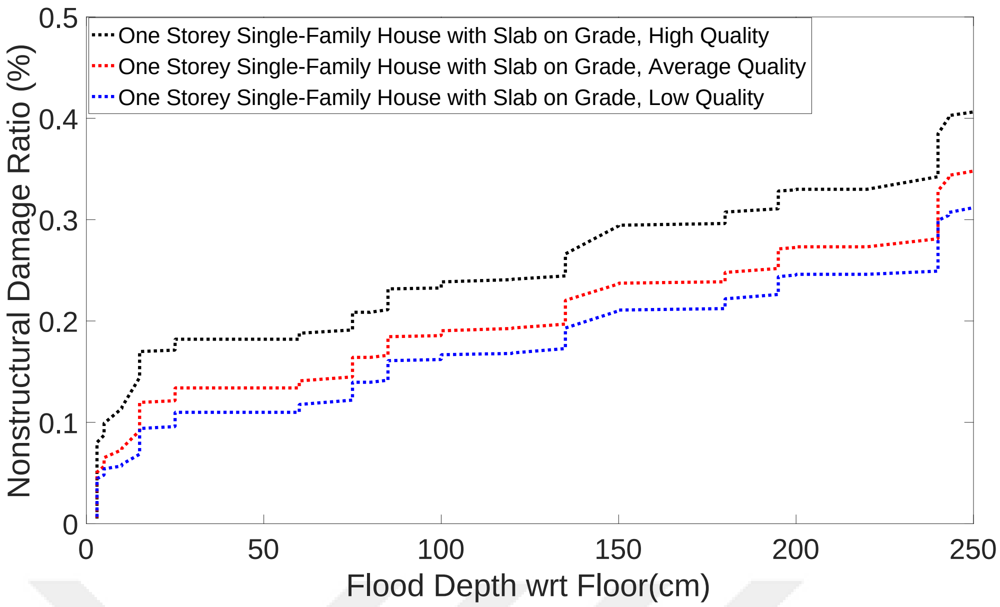

Figure 3-14 Non-structural damage ratio for one storey single family house with slab-on grade

3.4 Content Flood Loss Models

In this section, a flood loss model of typical content items that can be found in houses or apartments is created. While creating this flood loss model, a separate item list is created for each room in the house (kitchen, living room, bathroom, and bedroom; see Table 3-4 – Table 3-9). It is assumed that each item in the rooms gets damaged at a specific water level and it requires full replacement due to hygienic conditions. In the USACE document [17], the flood water depths were created for each item by taking the survey of the homeowners and the expert opinions. Using USACE document as an example and our own engineering judgement, the flood water depth at which each content in the house gets damaged was decided.

As in the non-structural flood loss model, three different qualities (low, average and high) are also considered in the content flood loss model. The prices of household content are determined by looking at the IKEA (UK) online shopping site and the

CURRYS (UK) online shopping site [54] [55]. While deciding the prices of the items, the items with extreme values (very low and very high prices) are ignored, and reasonable priced items in three different qualities are used in the model.

About the miscellaneous items listed in each room in Table 3-5 to Table 3-10, it is assumed that there may be miscellaneous items worth 15% of the total of the content items in that room.

Table 3-4 Content item list for living room

Living Room	
Damage Height (cm)	**Content Items**
100	Bookcase/Entertainment Center
100	Bookcase
100	Books
15	Coffee Table
15	Couch/Sofa
15	Chairs (study chair)
80	Tables (study desk)
5	Lamps (floor lamp)
65	Net Curtains/Drapes
65	Darkening Curtain
120	Pictures/Paintings
2,5	Carpet
50	TV/VCR/DVD
80	Computer
10	Portable Air Cooler
100	Misc.

Table 3-5 Content item list for dining room (inside living room)

Dining Room (inside living room)	
Damage Height (cm)	**Content Items**
60	Table/Chairs
35	Sideboard (similiar to China Cabinet)
2,5	Carpet
120	Pictures/Paintings
100	Misc.

Table 3-6 Content item list for kitchen room

Kitchen	
Damage Height (cm)	**Content Items**
15	Food
15	Refrigerator
15	Range/Stove/cooker
85	Microwave
60	Tables/Chairs
180	Dishes/Glassware (upper cabinet)
40	Silverware/Utensils (lower cabinet)
40	Pans/Cookware
85	Small Appliances/Kettle
85	Small Appliances/Toaster
170	Cooker Hood
25	Dishwasher
65	Net Curtains/Drapes
65	Darkening Curtain
50	Misc.

Table 3-7 Content item list for bedroom

Bedroom	
Damage Height (cm)	**Content Items**
20	Beds
40	Box Springs/Mattresses
40	Bedding
30	Chest of Drawers
15	Night Tables
5	Lamps
15	Armchair
65	Net Curtains/Drapes
65	Darkening Curtain
120	Pictures/Paintings
50	TV/VCR/DVD
100	Shelf (bookcase)
2,5	Carpet
20	Wardrobe
10	Portable Air Cooler
20	Men's Clothing
20	Women's Clothing
100	2 Personal accessories (jewelry, handwatches..)
50	Misc.

Table 3-8 Content item list for bathroom

Bathroom	
Damage Height (cm)	**Content Items**
170	Cosmetics/Perfumes/Medication/Hygiene Items
60	Towels/Linens
100	Curtains/Drapes/Rugs
120	Pictures/Decorations/Mirror
100	Misc.

Table 3-9 Content item list for storage room

Storage Room	
Damage Height (cm)	**Content Items**
10	Washer
10	Dryer
10	Vacuum Cleaner
15	Misc. (Laundry equipment, detergent etc.)

The content flood loss models for the building typologies created are shown in the Figure 3-15 to 3-21. For content flood losses, the repair time for a fully flooded storey of a low, average and high quality house (up to 3 m) is assumed to be 30 days, 45 days and 75 days, respectively. For the flat buildings only the content items inside the flat resident apartment are considered ,because there are no content elements in the commonly shared areas such as lobby.

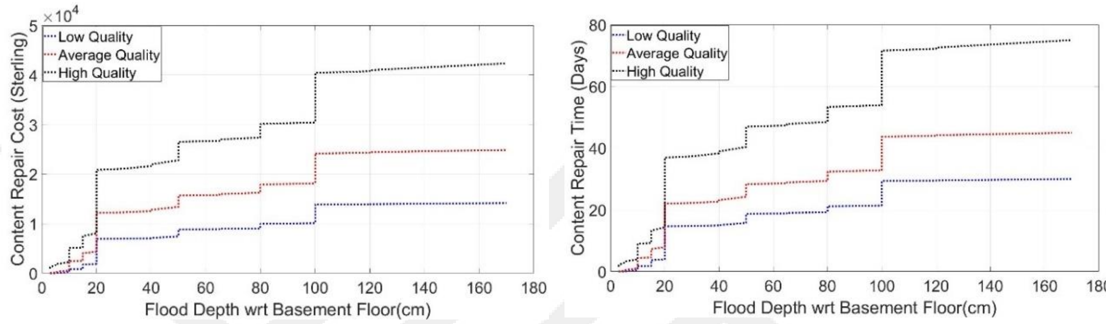

Figure 3-15 Content flood repair cost and time models for the finished basement of one or two storey single family house with a floor area of 100 m^2

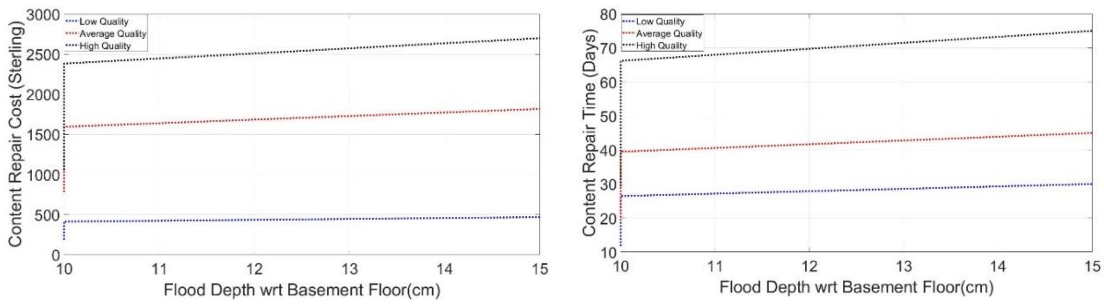

Figure 3-16 Content flood repair cost and time models for the unfinished basement of one or two storey single family house with a floor area of 100 m^2

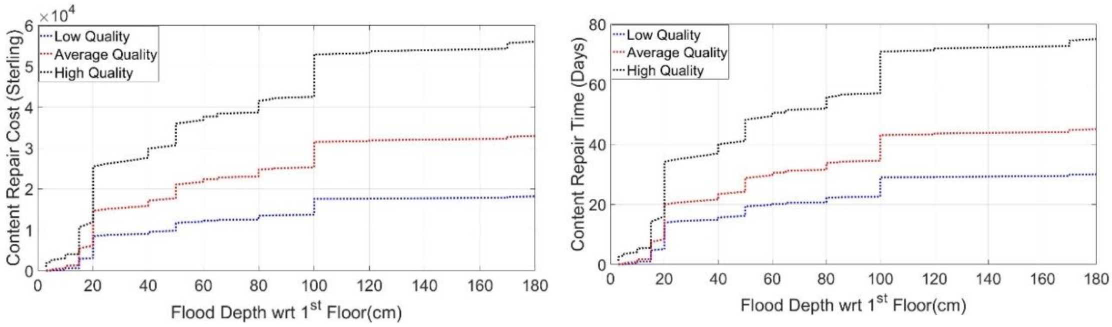

Figure 3-17 Content flood repair cost and time models for the 1st storey of one storey single family house with a floor area of 100 m^2

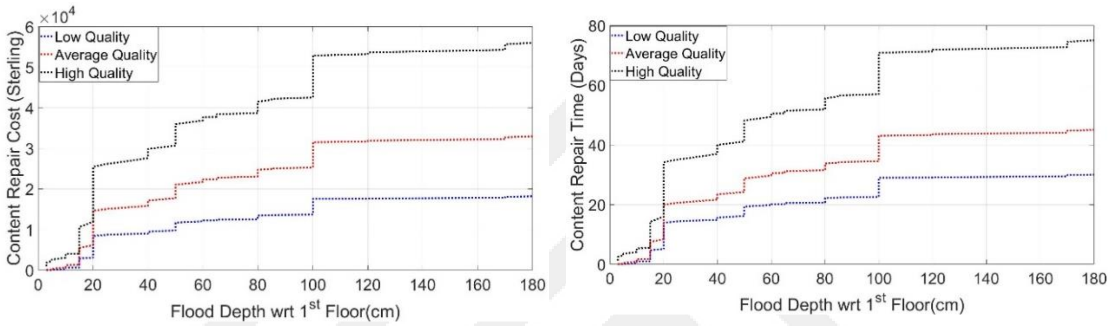

Figure 3-18 Content flood repair cost and time models for 1st storey of two storey single family house, with a floor area of 100 m^2

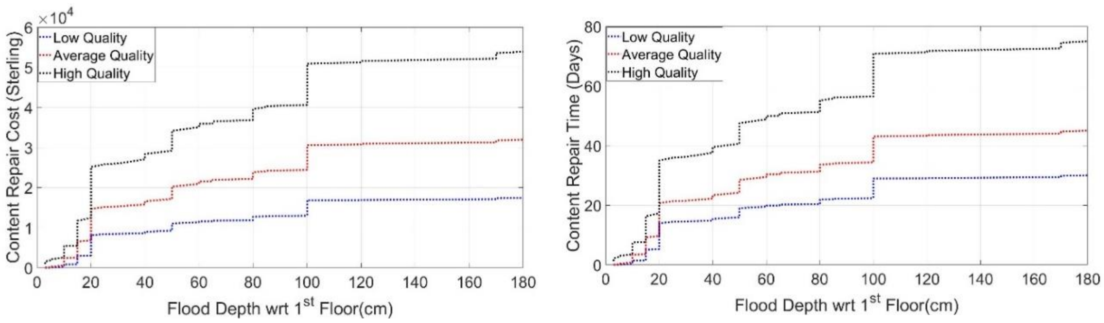

Figure 3-19 Content flood repair cost and time models for 1st storey of one storey single family slab-on grade house, with a floor area of 100 m^2

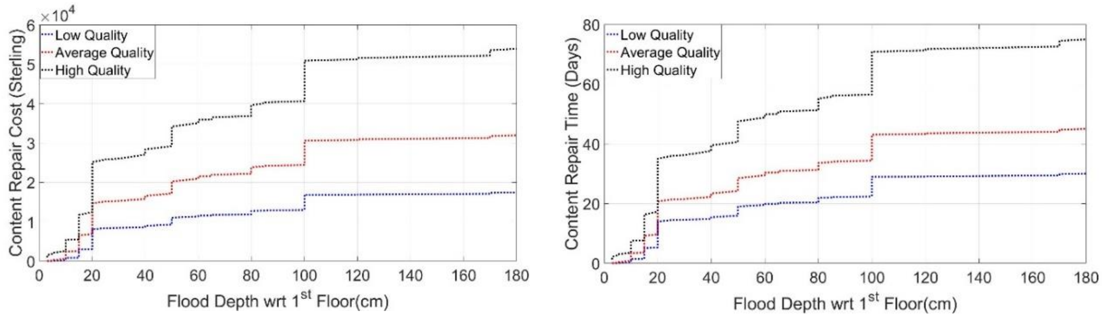

Figure 3-20 Content flood repair cost and time models for 1st storey of two storey single family slab-on grade house, with a floor area of 100 m^2

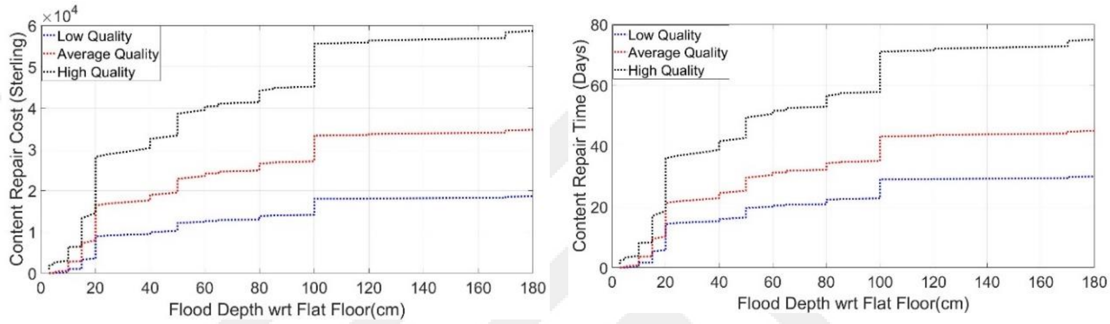

Figure 3-21 Content flood repair cost and time models for the apartment resident of low-rise or mid-high rise flat building with a floor area of 60 m^2

Maximum content repair time and repair cost values for each building typology are shown in the Table 3-10. The results in the Figures 3-15 to Figure 3-21 and also Table 3-10 show that loss values on content values in the unfinished basements for single family houses are too little compared to others, because these basements are unoccupied and there are content items only related to storage room. Also, the results show that first storey of single family houses with basement and flat resident have the highest content repair time and repair cost because of having two bedrooms for the considered storey. Moreover, all the models generally reach to maximum values around 1.5 m with respect to floor level. As expected, the models show that content repair cost and time values increase as home quality increases.

Table 3-10 Maximum (up to 3 m) content loss and time values for every building typology (note: all floor areas for single family houses and flat apartments are assumed to be 100 m^2 for comparison)

Building Typologies	Fully Flooded Floor (up to 3 m)	Max. Value for Content Loss			Max. Value for Content Time		
		Low	Ave	High	Low	Ave	High
Single family detached house	Finished basement storey	14162	24889	42350	30	45	75
Single family detached house	Unfinished basement storey	467	1817	2700	30	45	75
One storey single family detached house with basement	1^{st} storey	18169	32946	55987	30	45	75
Two storey single family detached house	1^{st} storey	18169	32946	55987	30	45	75
One storey single family slab-on grade house	1^{st} storey	17440	31960	53908	30	45	75
Two storey single family slab-on grade house	1^{st} storey	17440	31960	53908	30	45	75
Low or med/high rise flat buildings	Flat resident	18636	34764	58686	30	45	75

3.5 Content Relative Flood Analyses

As in Chapter 3.3, relative flood analyses are made for content elements in this chapter. The same building replacement values mentioned in Chapter 3.3 are used for relative content flood analysis. The ratio of content elements to building replacement value varies between 10% and 35% for all building typologies (see Figure 3-22). In addition, the ratio of content values to building replacement values for different house qualities for a building typology is shown (see Figure 3-23). Three different building replacement values are used for different house qualities (see Table 3-4). Figure 3-23 highlights the importance of construction quality, although different house qualities have different building replacement values.

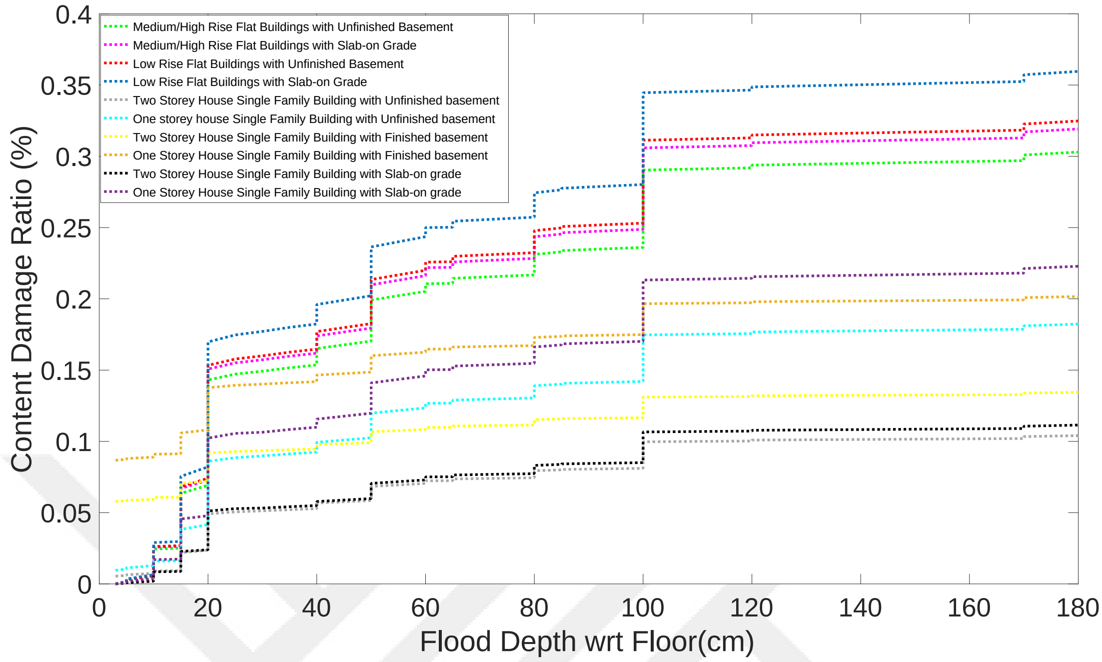

Figure 3-22 Content damage ratio for all building typologies with average quality

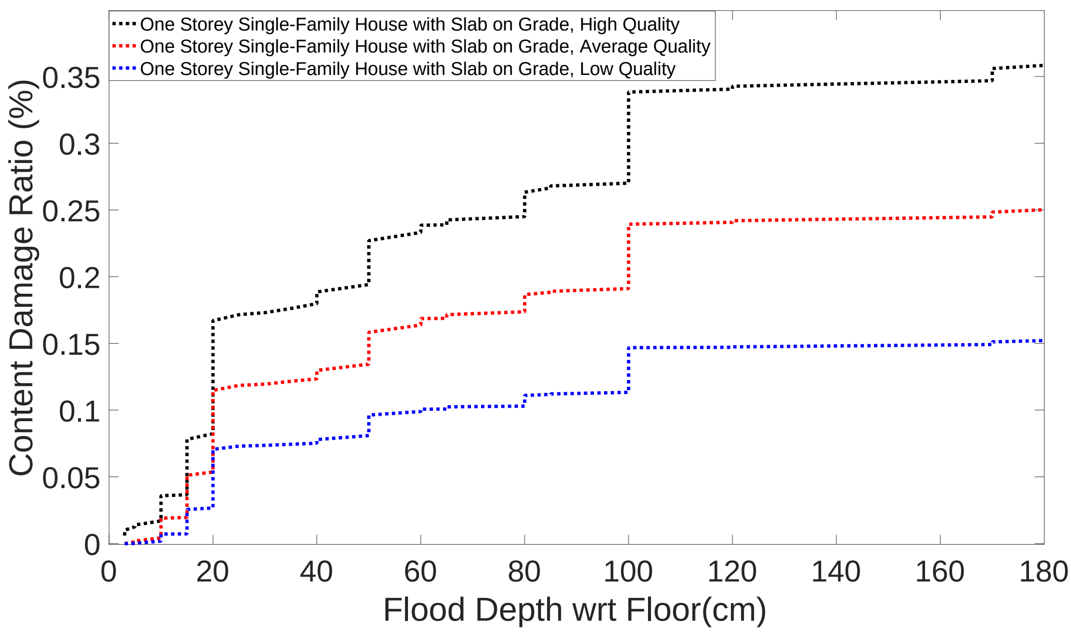

Figure 3-23 Content damage ratio for slab-on grade 1 storey house

3.6 Comparison with Existing Models

3.6.1 Comparison of Non-structural Flood Loss Models

There are many flood loss models in the literature for different regions. Following the study by Jongman et al. [56], the most common flood models are summarized shown in Table 3-11. All the flood loss models use the flood depth to assess losses. Some models use empirical relations based collected flood data, and some flood models use synthetic relations. Multi-coloured manual (MCM) [19] and Huzinga et al. [20] present loss models for UK. MCM has created flood loss models for various building typologies and home qualities. Also, MCM models only examined damage assessment on aggregated buildings [19]. Similarly, Huizinga et al. present a relative flood loss model for UK residential buildings in their study. However, in these studies, there is no information about the flood repair time. In this section, MCM models are preferred to compare with our own models in absolute values.

The post-1985 detached house in the Multi-coloured Manual (MCM) is compared with the detached one storey slab-on grade house in our model to understand the capability of our model. In these comparisons, losses on non-structural and content elements are compared together as total repair cost. MCM expresses property quality based on resident's social grade. Social grade DE is assumed to denote the lowest quality, while social grade AB is assumed to denote the highest quality in our models (see Figure 3-24). There are some differences between our models and the MCM models. The MCM flood loss models start at -30 cm, but the depth in our models start directly at the first-floor elevation in building typologies without basements. Since the detached house in the MCM model is 60 m^2, this comparison is made for the same area of 60 m^2 for our detached one storey slab-on grade house. In overall, our models show comparable results comparing to MCM curves.

Table 3-11 Different flood loss models [56]

Flood Damage Model	Scale	Location	Characteristics	Approach	Cost base	Damage Metric
FLEMO	Local Regional National	Germany	Depth Contamination	Empirical	Replacement values	Relative
Damage Scanner (DS)	Regional National	Netherlands	Depth	Synthetic	Replacement values	Relative
Flemish Model	Regional National	Belgium	Depth	Synthetic	Replacement values	Relative
Hazus-MH	Local Regional	USA	Depth Duration Velocity Debris Rate of rise Timing	Empirical-synthetic	Replacement values Depreciated values	Relative
Multi-coloured Manual (MCM)	Local Regional	UK	Depth	Synthetic	Depreciated values	Absolute
Rhine Atlas	Local Regional	Switzerland, Germany, France, Netherlands	Depth	Empirical-synthetic	Depreciated values	Relative
JRC Model	Regional National European		Depth	Empirical Synthetic (Statistical)	Depreciated values (averaged)	Relative

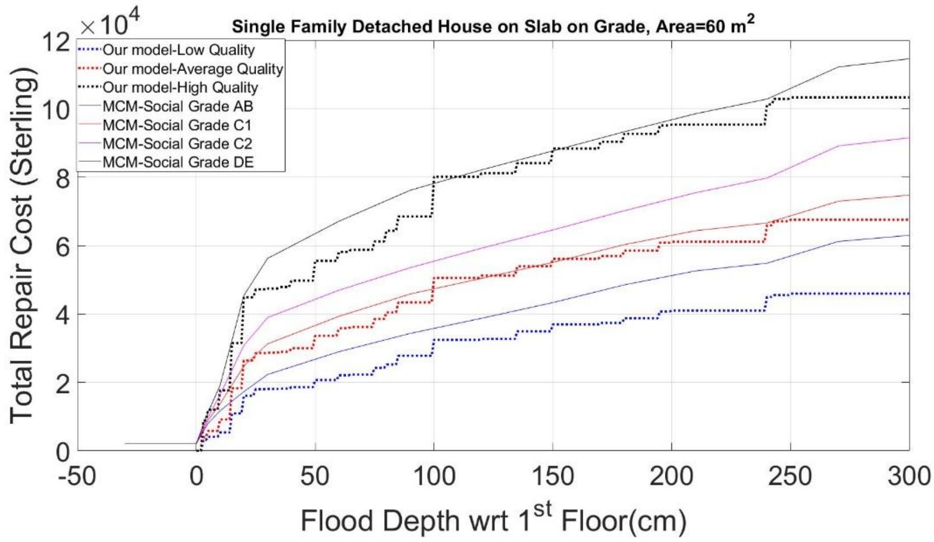

Figure 3-24 Comparison of our flood loss models and MCM flood loss models for slab-on grade house with an area of 60 m^2

Similarly, comparisons between the MCM models and our models are illustrated for the flat apartment in Figure 3-25. The 36 m^2 post-1985 flat house in MCM is compared with the 36 m^2 flat house in our model. Even though this area is found to be small but it is still used in the comparisons, since MCM study states using same area. In these comparisons, losses on non-structural and content elements are compared together as total repair cost. As a result of the comparison, the total flood loss cost gives very similar results to the MCM's repair cost. This shows that the assumptions in our model are logical, based on the considered area.

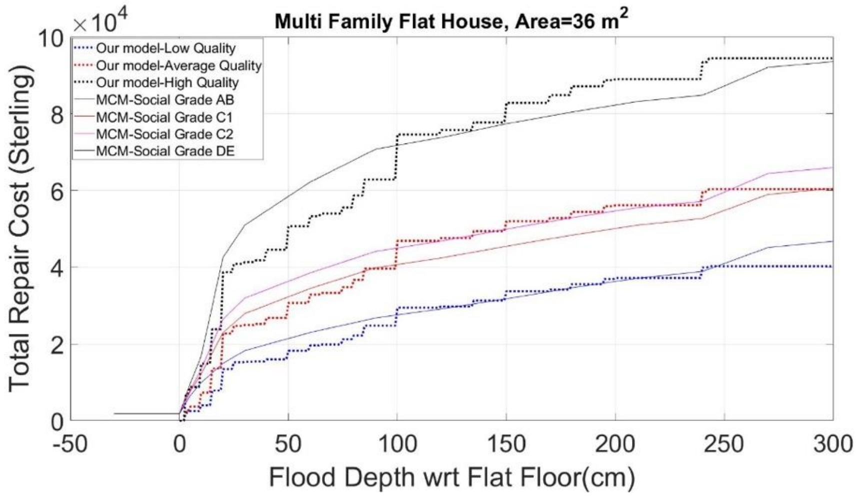

Figure 3-25 Comparison of our flood loss models and MCM flood loss models for flat resident with an area of 36 m^2

3.6.2 Comparison of Flood Repair Times

There is very limited information in the literature on this subject. The only detailed study is given by HAZUS [15]. In this section, our repair times are compared with the flood times mentioned in the HAZUS. The sum of the flood physical restoration times and clean-up times in HAZUS are considered, as shown in Table 3-12. In order to compare our flood time values with the values of HAZUS, a month is assumed to be 20 working days and our flood time values are divided by 20 working days. In general, it is seen that our times are comparable to the times by HAZUS, but they give larger values for multi family houses. It should be noted that our time models consider cascading repair work and tend to give upper limit values for times. More future improvements should be done on repair calculations considering the dependency between repair work items.

Table 3-12 Comparison of flood repair times at the flood depth of 3m

Building Typologies	Our Model (Months)			HAZUS (Months)
	Low	Ave	High	
SF, One Storey with Finished Basement	12	12.7	14.5	9-12
SF, Two Storey with Finished Basement	12	12.8	14.6	9-12
SF, One Storey with Slab on Grade	6.6	7	7.9	6-9
SF, Two Storey with Slab on Grade	6.7	7	7.9	6-9
MF, Low rise Flat with Slab on Grade	13.2	14	15.9	6-9
MF, Low rise Flat with Basement	18.3	19.2	21.3	-
MF, Medium/High Rise Flat with Slab on Grade	13.4	14.3	16.2	8-12
MF, Medium/High Rise Flat with Basement	18.6	19.5	21.6	-

3.7 Sensitivity Analyses

Different floor areas (64, 100, and 135 m^2) are considered to see the sensitivity of flood loss estimates to a change in these variables.

As the floor area increases, the total repair cost increases as expected. More floor area means more amount of items used in the house, so more repair cost values are seen in Figure 3-26. However, it should be noted that the increase in the cost is not directly proportional to increase in the area, since some items, such as equipment, may not be affected by increase in floor area.

Similarly, repair time models at each flood depth are also obtained in Figure 3-27. Again, different areas are considered to assess the repair time estimates. Also, as expected again, increase in the floor area leads to a larger repair time (Figure 3-27).

Flood loss and time models are also found to be highly sensitive to a change in other parameters such as story height, unit prices and individual damage-depths of the components.

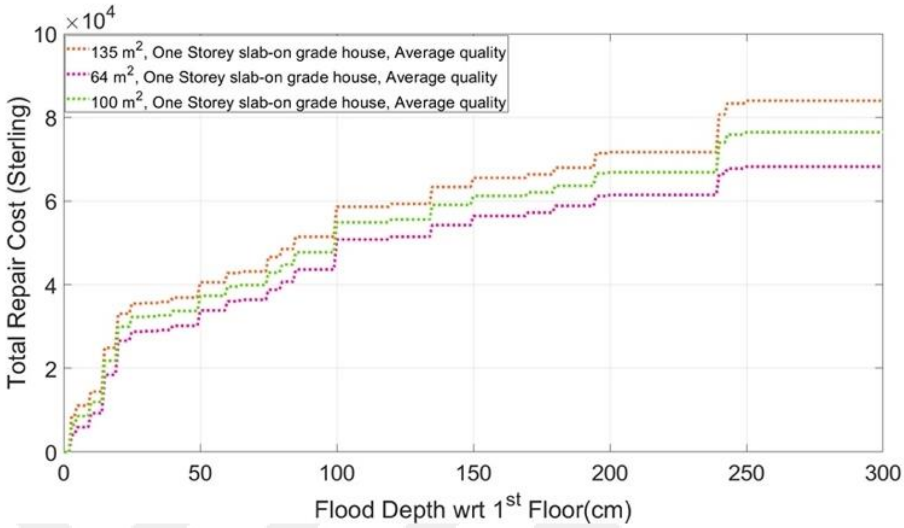

Figure 3-26 Total flood repair cost models based on different floor areas

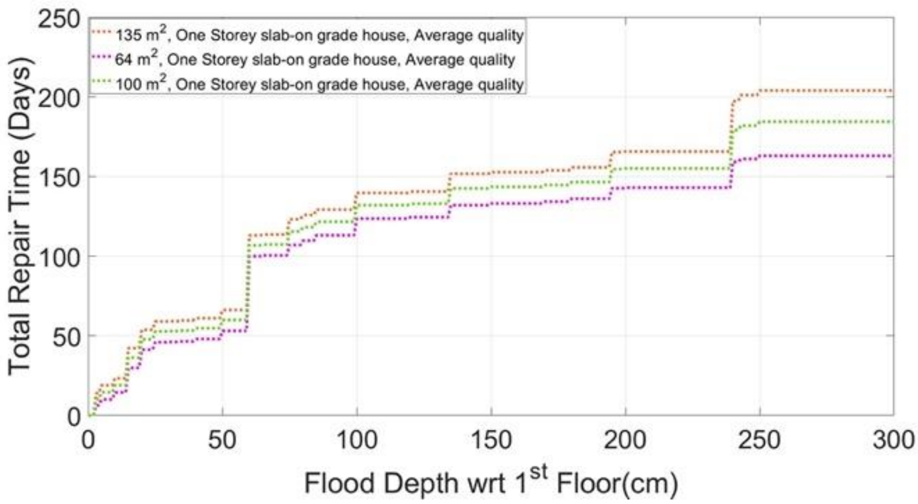

Figure 3-27 Total flood repair time models based on different floor areas

CHAPTER 4

BENEFIT ANALYSES ON FLOOD RETROFIT ACTIONS

This chapter discusses retrofitting processes that can be applied to residential houses to make them more resistant and resilient to flooding. Through cost-benefit analyses, existing retrofit options are investigated for residential houses to understand their efficiency in mitigation against flooding. Retrofit actions are analyzed only for single-family houses in this section but the same methodology followed in retrofit analyses here can be also applied to other case studies.

Retrofitting techniques are divided into mainly three groups: elevating the home, dry floodproofing and wet floodproofing techniques [57]. Elevating the home is very expensive and not practical, therefore it is not considered in this study. The floodproofing techniques are selected for their applicability on the basis of an individual building. Before explaining the flood proofing retrofitting methods, it is necessary to clarify where water can enter the house so that flood proofing retrofitting techniques can be applied appropriately based on entry way of water.

4.1 Entry Ways of Flood Water into Buildings

Figure 4-1 shows which ways water can enter a building. Flood water can penetrate the building's exterior walls or party walls, leaking through damaged mortars and hairline cracking in the brickwork. The amount of leakage varies according to the type of brick material, the condition of the wall, and the source and characteristics of the flood. The most common way for flood water to enter a house is through doors and windows. Voids can be found in the frames of doors and windows, and floodwater can seep into the house. If hydrostatic and hydrodynamic flooding forces applied on these doors and windows become significant, flooding may even cause them to totally collapse and may allow all flood water inside [58]. In addition, the service entrance points, and vents of the buildings are other ways, where floodwater can leak in from outside the house. Another entry point of floodwater is through the basement slab which is vulnerable to groundwater flooding. Since the basement slab is exposed to buoyancy forces, cracks and structural failure may occur on the slab which can cause leakage of water inside. Another point is that excessive sewage water due to flooding in the sewer system can back up and come inside the house from toilets and washing machines.

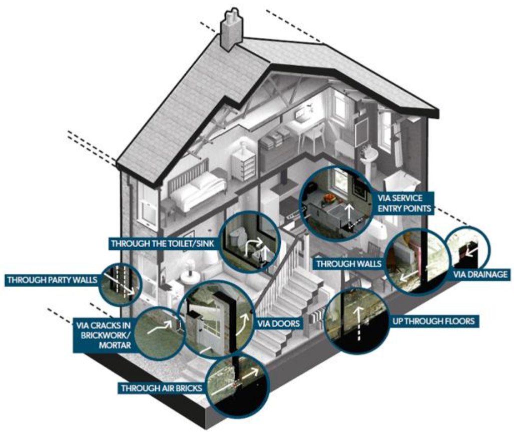

Figure 4-1 Points of water entry [58].

4.2 Retrofitting Measures

Flooding mostly causes significant damage to non-structural elements and contents, more often comparing to damage on structural elements. Therefore, this section focuses on reductions in non-structural and content damage and the related retrofit measures.

Retrofitting measures are divided into dry floodproofing and wet floodproofing. The following sections describe common retrofit actions taken for each measure type.

4.2.1 Dry Floodproofing Measures

Dry floodproofing strictly does not allow water to pass through the structure. This method aims to keep floodwater outside the structure. However, keeping the water out may cause some problems. As the water level increases outside the structure, the hydrostatic forces, buoyancy forces, and forces of saturated soil can damage the external walls and basement slabs [59]. With the rise of floodwaters, structural cracks may occur on the house's exterior walls and basement slab due to the flood forces. Even the exterior walls may collapse, and basement slab may result in expansions due to wetness and wide cracks can form in the concrete. Therefore, dry floodproofing techniques are allowed to be applied up to usually 600 mm high with respect to floor level to avoid any structural damage to the structure [59].

Tanking to external or internal walls is one of the important techniques for dry floodproofing actions. Tanking can be done on the interior or external walls of the building and ensures that the walls are resistant to flood waters [60]. The important parts of the tanking application are the use of damp-proof membrane and water repellent [59]. Using these materials makes the water permeability of the tanked wall low, so it becomes more resistant to flood water. This application is limited up to 600 mm height because of damage that may occur on the walls due to hydrostatic forces. An example of the tanking application can be seen in Figure 4-2.

Figure 4-2 Basement tanking [60].

Before the tanking is applied on the outer walls, it may be considered to apply repointing on the mortars at first. Repointing application can be used if there are any cracks on the mortars, especially on the obsolete or damaged ones, between masonry bricks. This application further reduces the water permeability of the mortar. The repointing process can be also considered as a maintenance process; the old or damaged mortar is raked off and replaced with a new one [58].

After any repointing is done on the mortars, the wall is covered with a damp-proof membrane, then cement-lime-based plaster is applied and water repellent cement is added to this plaster, thereby reducing more the water permeability of the plaster and increasing water resistance [61]. Finally, oil-based painting is applied. All these processes define the retrofit action of the tanking on the inner or outer face of exterior wall. There is a difference between tanking to the inner face and outer face. This difference is that tanking slurry is used when applying the tanking retrofit action on the outer face, and a damp proof membrane is used when tanking for the inner face. Another difference is that the inner insulation material is replaced when tanking is applied to the inner face. Mineral-based insulation is usually used in walls and slabs, and this insulation material is very sensitive to water. As a part of inner face retrofit action, closed-cell insulation material, which is more resistant to water, can be used instead of mineral-based insulation material [62].

The tanking application can also be applied to slabs. Slabs are subjected to buoyancy forces due to rising ground water level and therefore cracks may occur on them. As a result, water may leak into the house. Tanking on the slab is carried out as follows: floor finishes in all rooms are first removed and liquid tank is then applied on the floor to reduce water permeability [60]. The removed floor finishes are then put back in place and used again. Figure 4-3 shows an example of tanking retrofit action applied to the slab.

Figure 4-3 Application of tanking retrofit action to the slab [63].

Any water entry into the house can be thrown out with the help of an external drainage system and a sump pump. A 25 cm deep pit is first dug along the around of the house and a membrane is laid inside this pit, because moisture and water that may come from the soil are not desired. Then a porous pipe is laid along the pit and connected to a sump pump. The pit is then filled with gravel and leveled. The way how this system works can be described as follows: The water coming into the house is first filtered through the gravels and enters the porous pipe, then the water is sent to the sump pump through the pipes, and the pump sends the water away from the house [63]. With external drainage systems, it is aimed to remove the floodwater from the house without damaging the content of the house and also without damaging the structural and non-structural elements of the house. An example of the external drainage system can be seen in Figure 4-4.

Figure 4-4 External drainage system [63]

As an alternative to the tanking retrofit action, rendering can be applied to inner and outer face of exterior walls. Rendering can be used for bricks, concrete, or over insulation. The rendering process acts as an important barrier, not allowing any water to pass through the outer wall. Although the renders are not resistant to flood water with the same extent as in tanking, they act as a temporary barrier by blocking the water for a while [59]. The rendering process closes the gaps or cracks in the masonry wall, preventing floodwater from passing through these permeable points. In addition, the retrofit process of rendering prevents the direct contact of the masonry wall with the flood water and delays the water absorption of the wall for a while. Before applying rendering to the exterior wall, mortars are improved by repointing, as in the tanking retrofit application. Then the rendering is applied to outer walls. Lastly, cement lime-based plaster and oil painting are applied to the exterior walls. When rendering is applied on the inner face of external walls, the gypsum plasterboards are removed, and rendering is applied to the inner face of masonry walls. In addition, insulation is replaced with closed-cell insulation for the inner application. Then cement lime-based plaster, which is more resistant to water is used, and finally, oil-based painting is applied on the top of the rendering applied to the inner faces [58] and [61]. In Figure 4-5 shows how the rendering process is applied to walls.

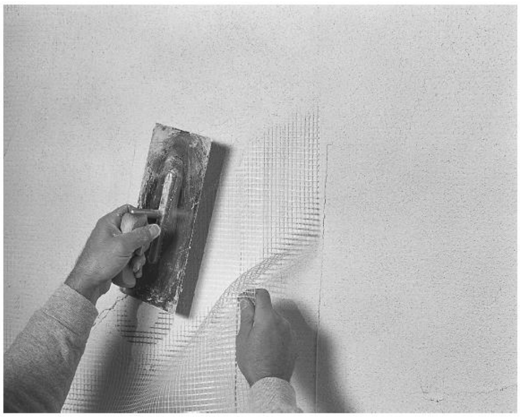

Figure 4-5 Application of rendering [60].

As another retrofit action, a 600 mm high extra wall can be built around the exterior wall [62]. This extra wall is usually built with class A engineering bricks. Because class A engineering bricks are stronger than standard bricks, they can show a more resistant performance against the hydrostatic forces that occur with the rise of water. Therefore, the extra wall can reduce the formation of cracks in the exterior masonry wall of the house up to 600 mm high and prevents floodwater from leaking into the house [62]. In addition, an insulation material that is more resistant to water and rendering process are applied to this wall. Thus, the water permeability and vulnerability of the wall are further reduced. An example application is shown in Figure 4-6.

Figure 4-6 Adding an extra layer wall around the house's external wall [62]

Another dry floodproofing retrofit action has the same purpose as the previous retrofit action. This retrofit process aims to strengthen the external masonry walls of the house against hydrostatic forces by placing grouting inside the walls. With this process, it is desired to reduce the cracks and increase the water impermeability of the wall. In this way, water leakage from the wall into the house is reduced. Holes are made at a few points of the exterior wall, and grouting is put into the masonry wall through these holes. With grouting, the masonry wall has a more durable structure than the standard wall [62]. An example of this retrofit action can be seen in Figure 4-7.

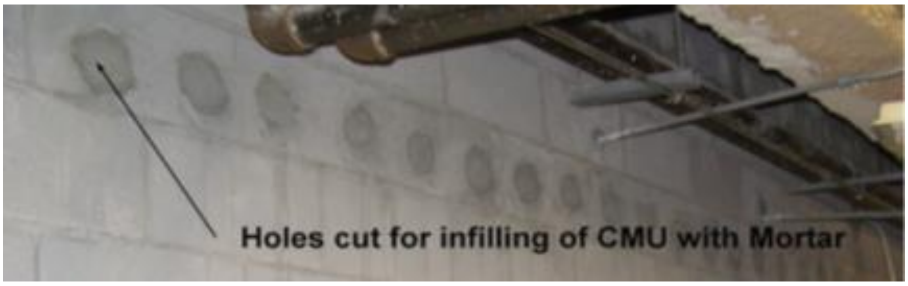

Figure 4-7 An example of a grouted masonry wall [62].

Windows can be entry points for water, as described in Section 4.1. Especially the windows in the basement floor can become one of the critical water entry points with the rise of the water. As the water rises, the hydrostatic forces applied on the windows increase. With the increase of the force, the window glass may break, or the water may enter the house through the gaps in the window frame. In order to prevent this problem, the windows in the basement floor can be removed and a wall can be built instead (see Figure 4-8) [62]. However, the building code does not allow this retrofit action because the code requires a window to be provided in the basement as an escape point in case of fire. Even the window is above the ground level, it might be better to still keep it open due to decoration or architectural reasons. This retrofit action is therefore excluded in the retrofit action set considered in this study.

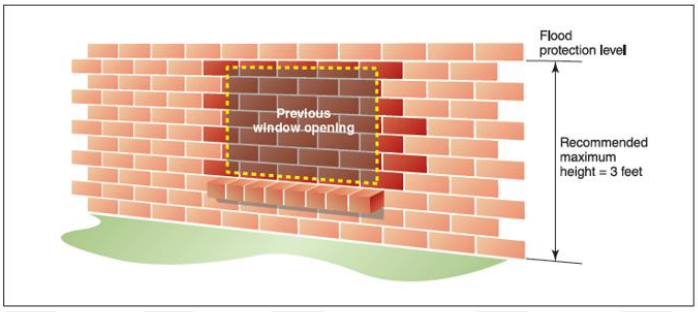

Figure 4-8 Retrofit actions of closing window openings [62].

When a flood occurs, the sewage can enter the house from the toilet or washing machine. To solve this problem, a non-return valve is usually installed on the pipes at the points where dirty water can enter the house (see Figure 4-9). These valves can be installed on the pipes inside the house or on the main pipe outside the house [57].

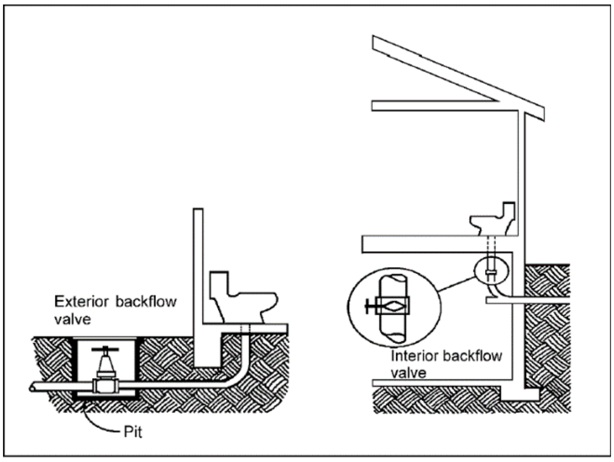

Figure 4-9 An example of non-return (or backflow) valve [57].

All of the retrofit actions mentioned so far are permanent retrofit actions. As a temporary measure, a temporary barrier (see Figure 4-10) can be placed at the front of the door of the house just before the flooding. However, the flooding may occur without warning or the residents (especially elders) may not have enough time or ability to place the barrier themselves just before the flooding. Therefore, temporary measures may not yield effective results compared to permanent measures [63]. However, this retrofit action is still considered in this study to examine its efficiency on loss reductions.

Figure 4-10 Using a temporary door protection barrier [60].

4.2.2 Wet Floodproofing Measures

In wet floodproofing, unlike dry floodproofing, it is desired that the flood water enters the house after a specific height (usually 600 mm), because the floodwaters can cause structural damage to the house. For this purpose, air bricks are usually placed on the house's exterior walls at a height of 600 mm from the ground to allow water entry after the floodwater exceeds 600 mm [60]. To ensure this, the air bricks are placed at the four sides of the house (see Figure 4-11).

Figure 4-11 An example of air brick [60]

In wet floodproofing, the materials inside the house are replaced with materials that are more resistant to water and have low water absorption. For example, one of the items in houses that can get damaged when in contact with water is floor finishes. Floor finishes are divided into three different construction quality classes in our model: low quality, average quality, and high quality. In the low-quality home, linoleum sheet is usually used in the bathroom, and carpet is used in the other rooms. Linoleum sheets and carpets are very unstable materials against water. The water absorption of the carpet is exceptionally high. When linoleum sheets and carpets contact water, their adhesives may be damaged and dislodged, or both materials may swell. Therefore, these two materials can be replaced with more water-resistant materials such as floor tile material [61]. Floor tile can withstand water longer than commonly used materials. Even the skirtings can be also replaced with the skirtings of the floor tile.

In the average quality house model, vinyl sheet is used as the floor finish in the bathroom and carpet in the other rooms. Vinyl sheets and linoleum sheets are very similar to each other. Just like when a linoleum sheet comes into contact with water, a vinyl sheet can get also damaged and deteriorate when it comes into contact with water. Therefore, these materials can be replaced with floor tiles.

Vinyl sheet is used as the floor finish in the bathroom of a high-quality house case study, and wood blocks are used in the other rooms. As it is known, wood is a susceptible material against water and can be damaged quickly similar to the cases above, and the floor of a high-quality house can be replaced with a floor tile. However, the floor tiles used in these three quality-home models are different from each other and are separated according to their quality. For example, slip-resistant mosaic floor tile type is used as a floor covering in the bathroom of a high-quality house, but riven Chinese slate floor tile is used in the low-quality one. So floor coverings vary according to the quality of the house.

The gypsum plasterboard, which is used as a wall finish on the interior wall of the house, is also very sensitive to water. Instead of using gypsum plasterboard on the walls, water resistant cement lime-based plaster and water repellent cement are used as a wet floodproofing retrofit action on the walls [61].

Another non-structural element that can be damaged by water is painting. More water-resistant paint, oil paint, can be also used as one of the retrofitting alternatives [61].

Wet floodproofing for ceiling non-structural items are similar to the retrofit actions applied to the wall finishes. Again, using water-resistant materials can increase the water resistance of non-structural elements. For example, plasterboard and insulation materials used on the ceiling can be removed and cement lime-based plaster and insulation, which are more resistant to water, can be used.

The interior doors (inside the house) are usually made of softwood material. Softwood doors are not resistant to water; when they come into contact with water, the door and door frames can become dislodged, swollen, and damaged. Therefore, hardwood moisture-resistant MDF doors, which can withstand water longer, can be preferred. Similarly, wood-framed windows can be also replaced with PVC-framed windows. PVC framed windows do not get easily damaged by water, only cleaning the frames after the flood may be sufficient [61]. In summary, as it is described in detail above, floor finishes, doors, and windows can be replaced with water-resilient materials to reduce the flood losses.

In addition, since electrical items (e.g., outlets and electrical cables) and mechanical items (e.g., electrical heaters and domestic water boilers) are susceptible to water and can deteriorate easily when they come into contact with water [63]. So, they should be totally replaced once they get water damage. However, some of these items are difficult to replace. For example, the electrical cables are behind the wall plasterboard. If the electrical cables get damaged, in order to replace them, the plasterboard should be removed, and the wires should be renewed, and the plasterboard should be placed again, then painting is usually done. Making these processes takes high cost and long labor time, so the workload and workmanship can be increased when we consider a whole house. Like cables, outlets can be also affected by water quickly. So one main retrofit action for electrical items is to simply raise them to a specific height to reduce the flood damage at least in shallow flooding.

Since mechanical items are expensive, two different wet floodproofing retrofit actions can be considered for them. Firstly, the mechanical items can be also raised on the same floor, to a place higher than half the floor height [57]. Second, these items can be moved to the upper floor. This latter option can be better especially in a scenario, where the entire lower storey is flooded. An example of this retrofit action can be seen in Figure 4-12.

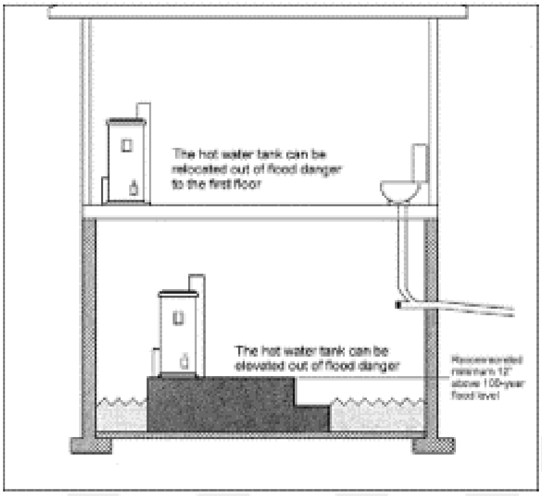

Figure 4-12 Raising of mechanical items [57].

4.3 Retrofit Cost Analyses and Comparison with Existing Studies

In this section, our retrofit action prices and the retrofit action prices found in the literature are compared. Some of these comparisons are in terms of individual retrofit actions and some in retrofit packages (more than one action). Here, retrofit action prices are compared for a typical house with a floor area of 50 m^2. Since, some of the existing retrofit prices in the literature are generally calculated based on a 50 m^2 house.

As it can be seen from Table 4-1, Table 4-2 and Table 4-3, the prices of our retrofit action or packages are generally comparable to the examples found in the studies by Defra [64], Bowker et al. [65], and Aertz et al. [66], respectively. However, in the retrofit action comparisons specified in Table 4-1 to Table 4-3, there are some price differences in some retrofit actions. This is because, the quality of the materials, the material properties and the application size (e.g., the retrofit area or the retrofit length) of the retrofit actions reported in the literature are not clearly stated.

As a result of these comparisons, it has been understood that our retrofit actions are in general based on a logical basis.

Table 4-1 Comparison of costs of retrofit actions with Defra [64]

Retrofit Actions	**Our Retrofit Cost (£)**	**Defra's (Medium) Cost (£)**
Two demountable door guards and two airbrick covers	650	1960
Two flood-proof doors, two airbrick covers and external wall render/bricks (20 m)	2272 (without flood-proof door)	3320
Resilient plaster, removable doors, internal wall rendering, resilient kitchen, raised electrics and appliances for 50 m^2 house	7025	7830
Concrete/sealed floors, resilient plaster, removable doors, internal wall rendering, resilient kitchen, raised electrics and appliances for 50 m^2 house	11325 (clay floor quarries)	11870
Move service meters	1200	1500
Move electrics	1346	700-1100
Install one-way valves	520	1500
Replace floor with treated timber	4308 (clay floor quarries)	3200-5100
Install airbricks above flood level	455 (24 each)	300-400
Replace mineral insulation within internal partition walls	778	600-900

Table 4-2 Comparison of costs of retrofit actions with Bowker [65]

Retrofit Actions	**Our Retrofit Action Costs (£)**	**Bowker's Cost (£)**
External rendering (20 m)	1622	1000-2000
Airbrick (24 each)	455	2500-3000
Backflow valve	520	50-500
Sumb pump	470	50-2500
Internal doors	1076	400 upwards
Internal tanking	Approximately 1406, assumed to be up to 0.6 m height	6000-10000
Flooring	8390 for average quality house	5500-6500

Table 4-3 Comparison of costs of retrofit actions with Aertz [66]

Retrofit Actions	**Our Retrofit Action Costs (£)**	**Aertz's Cost (Dolars)**
Waterproof membrane	13.33 per m^2	18.7 per m
Drainage line around perimeter of the house	56 per m	39.4 per m

4.4 Benefit-Cost Calculations

In this section, it is aimed to calculate the benefit-cost ratios of the above-mentioned retrofit actions. Flood retrofit actions can reduce possible flood losses, but their benefit-cost ratios should be first calculated regarding whether the cost of these retrofit actions is effective or not.

In this study, it is focused more on retrofit packages (more than one retrofit action) instead of individual retrofit actions, since the retrofit packages are more effective and practical in loss reductions when these selected individual actions are applied together. Totally 9 different retrofit packages are created by combining different retrofit actions described above for benefit-cost analyses, divided in two main groups: packages that include only dry-flood proofing actions (RP1-6; see Table 4-4); and packages that include only wet-flood proofing packages (RP 7-9; see Table 4-5).

Table 4-4 Only dry-floodproofing retrofit packages (RP 1-6)

All RP include:	Tanking to slab, external drainage system, backflow valve, temporary barrier
Additionally:	
RP 1	Tanking to outer leaf of external wall up to 0.6m
RP 2	Tanking to inner leaf of external wall up to 0.6m
RP 3	Rendering to outer leaf of external wall up to 0.6m
RP 4	Rendering to inner leaf of external wall up to 0.6m
RP 5	Partially grouting external walls up to 0.6m
RP 6	Adding 0.6m high-external wall

Table 4-5 Only wet-floodproofing retrofit packages (RP 7-9)

RP 7	Airbrick, improving internal items, raising electrical items and elevating mechanical items above mid-storey height.
RP 8	Airbrick, improving internal items, raising electrical items above mid-storey height, relocating mechanical items to upper storey
RP9	Airbrick, relocating mechanical items to upper storey

The ‘benefit-cost ratio (B/C)’ is the benefit gained after the retrofit package is applied to house divided by the cost of the retrofit package, as described in Equation 4-1.

The benefit gained from the loss can also be called 'avoided loss (AL)'. This ratio B/C shows whether the cost of these retrofit packages is effective or not. If the B/C is greater than one, it means that the retrofit package is cost-effective.

$$B/C = \frac{Benefits\ (Avoided\ Loss\ )}{Retrofit\ Cost} \tag{4-1}$$

Analytical approaches, as described in Chapter 3, are applied on three different construction quality (low, average, high) 100 m^2-houses with slab-on grade foundations to get the flood repair cost and time models with or without the nine retrofit packages. The results of benefit analyses are reported at the flood depths of 0.5 m, 1.5m and 2.5m-depth in the Table 4-6, Table 4-7, and Table 4-8 respectively. The results include the ratios of benefit to retrofit cost B/C as well as percentages of reductions in repair cost RC% and repair time RT% for each retrofit package considered in the study. Again, if the B/C for a retrofit package in Table 4-6 to Table 4-8 is greater than one, it means that the implementation of that retrofit package benefits the homeowner.

Results show that all dry floodproofing retrofit packages (RP 1-6) are very effective at a flood depth of 0.5m (see Table 4-6), as expected. These RPs provide more than 90% reductions in losses and repair times, and the remaining losses are only due to outside cleaning costs associated with exterior walls and site vegetation.

Table 4-6 also shows the sensitivity of the results with respect to construction quality. Retrofitted high-quality homes have a higher B/C (between 2.19 and 3.02) comparing to low quality ones (between 1.26 and 1.94) for dry-floodproofing retrofit packages.

Table 4-6 Benefit-cost ratio (B/C), loss reduction (LR), and time reduction (TR) ratios for a 100 m^2 single family slab-on grade house at 0.5 m flood depth

	Low Quality			Average Quality			High Quality		
	B/C	LR %	TR%	B/C	LR%	TR%	B/C	LR%	TR%
RP 1	1.59	96	92	2.09	95	92	2.62	97	93
RP 2	1.74	96	92	2.28	95	92	2.80	97	93
RP 3	1.45	96	92	1.91	95	92	2.44	97	93
RP 4	1.58	96	92	2.08	95	92	2.61	97	93
RP 5	1.94	96	92	2.53	95	92	3.02	97	93
RP 6	1.26	96	92	1.67	95	92	2.19	97	93
RP 7	0.28	72	72	0.41	77	74	0.65	86	80
RP 8	0.29	72	72	0.41	77	74	0.66	86	80
RP 9	3.22	13	8	4.85	18	9	7.79	24	9

Table 4-7 Benefit-cost ratio (B/C), loss reduction (LR), and time reduction (TR) ratios for a 100 m^2 single family slab-on grade house at 1.5 m flood depth

	Low Quality			Average Quality			High Quality		
	B/C	LR%	TR%	B/C	LR%	TR%	B/C	LR%	TR%
RP 1-6	0.00	0	0	0.00	0	0.00	0.00	0	0
RP 7	0.42	55	30	0.56	60	0.33	0.86	70	40
RP 8	0.43	55	30	0.57	60	0.33	0.96	70	40
RP 9	3.22	7	2	4.85	10	0.03	7.79	15	3

Table 4-8 Benefit-cost ratio (B/C), loss reduction (LR), and time reduction (TR) ratios for a 100 m^2 single family slab-on grade house at 3 m flood depth

	Low Quality			Average Quality			High Quality		
	B/C	LR%	TR%	B/C	LR%	TR%	B/C	LR%	TR%
RP 1-6	0.00	0	0	0.00	0	0	0.00	0	0
RP 7	0.44	40	33	0.57	42	35	0.83	49	41
RP 8	0.50	44	34	0.68	49	37	1.01	59	43
RP 9	3.22	5	2	4.85	7	2	7.79	11	2

Among these first six RPs (dry-floodproofing packages) in Table 4-6, RP5 seems having the highest B/C ratios for all quality homes (between 1.94 and 3.02). The retrofit action of grouting used in this package is cheaper compared to other retrofit processes, therefore giving the best option to make the exterior wall waterproof up to 0.6 m.

Table 4-6 also shows that it is not cost-effective to apply wet floodproofing retrofit packages RP 7 and RP 8 for 0.5m-flood depth with B/C ratios giving less than 1.0. Even RP 7 and RP 8 reduce losses more than 70%, they are highly costly for a flooding scenario case up to 0.5m. However, the retrofit action of relocating mechanical items to upper storey (RP 9) reduces losses between 13% (low quality) and 24% (high quality) and repair times around 9%, when applied alone. While this RP seems the most optimal wet floodproofing option for a 0.5 m-flood depth, giving the largest B/C ratios from 3.22 (low quality) to 7.79 (high quality), it is not effective in reductions as other RPs.

Similarly, the benefit analyses are performed on all RPs at other flood depths of 1.5m and 2.5m in Table 4-7 and Table 4-8 respectively. As expected, dry flood proofing options (RPs 1-6) do not provide any benefit once flood depth exceeds 0.6m (i.e., the application height for dry floodproofing). As the quality of the house increases from low to high level, the B/C ratios also increase for all retrofit packages but most of them are less than 1.0. Based on comparisons on B/C ratios in Table 4-7 and Table 4-8, while RP 9 obviously seems to be the best retrofit action for all quality homes, the next best alternative seems to be RP8. However, loss and time reductions in RP9 (between 2% and 15%) are not effective as much as in the RP 8 (between 30% and 70%).

To better see effects of RP8 on loss and time reductions at all flood depths in comparison to effects of dry-flood proofing actions, Figures 4-13 and 4-14 show the repair cost and time models of an average quality 100 m^2-house without any retrofit and with flood retrofit packages RP8 and RP1-6 (dry flood-proofing packages). The areas under the models can be assessed to better compare efficiency of the packages, and RP8 obviously proposes the best reductions, more than half of original losses and repair times comparing to reductions by RP1-6.

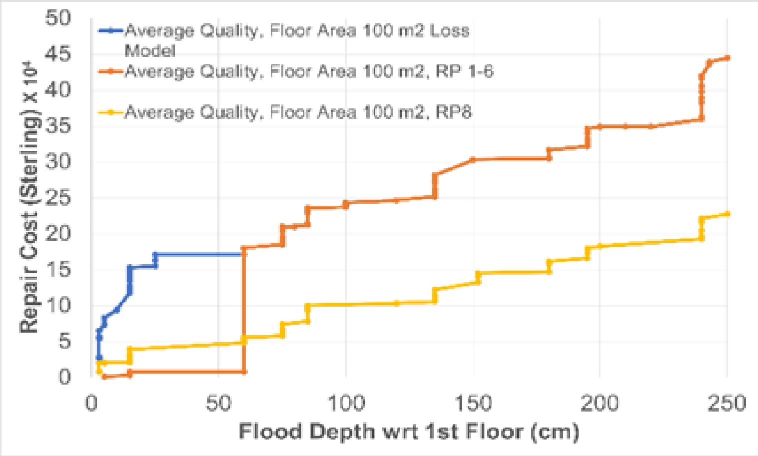

Figure 4-13 Repair cost-damage curves without retrofit, and with retrofit packages RP 1-6 and RP 8

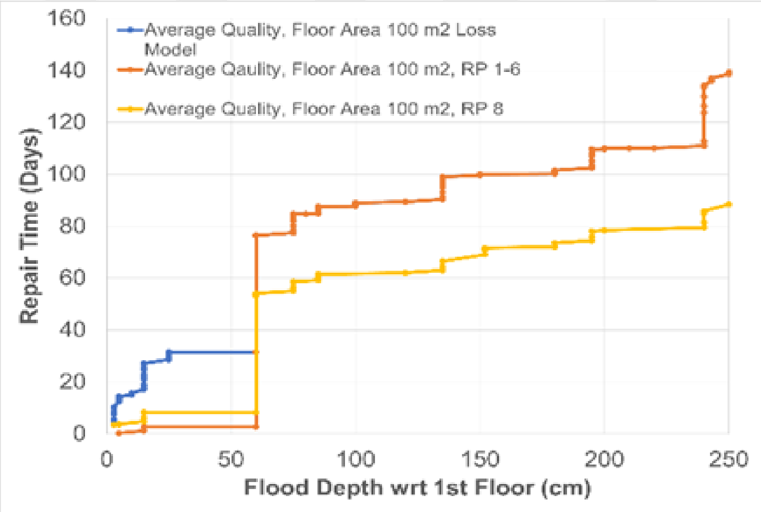

Figure 4-14 Repair time-damage curves without retrofit, and with retrofit packages RP 1-6 and RP 8

In summary, results show that RP8 generally gives lower B/C ratios (below one) for 'one' flooding scenario, but it seems to be the most beneficial retrofit package if 'overall' reductions in costs and times are considered for several potential flooding scenarios with depths up to 2.5m. In this package, especially relocating the mechanical items and raising the electrical items are observed to be the most contributing ones to the reductions in losses and times.

4.4.1 Sensitivity Studies on Benefit-Cost Analyses

Cost-benefit analyses together with uncertainty quantification are required to make reliable decision-making in taking appropriate flood retrofit actions. Sensitivity studies are thus performed to evaluate effects of some key factors and their uncertainties on flood loss and time estimates. For example, Table 4-9 shows the results of sensitivity studies on B/C ratios for a single family slab-on-grade house retrofitted with RP1. It shows sensitivity results for different floor areas and different construction qualities. As the area increases, while the B/C ratios decrease for a high-quality house, they don't show much sensitivity to a change in the area for a low-quality house. In addition to floor area and construction quality, the effects of uncertainties in location and unit price of building items and foundation type have been found significant for the retrofit models.

Table 4-9 Cost-benefit ratio (B/C), loss reduction (LR) and time reduction (TR) ratios for RP1 considering single family slab-on grade houses with different floor areas at 0.5 m-flood depth

	Low Quality			Average Quality			High Quality		
	B/C	LR%	TR%	B/C	LR%	TR%	B/C	LR%	TR%
65 m^2	1.59	96	90	2.12	95	0.90	2.77	97	92
100 m^2	1.59	96	92	2.09	95	0.92	2.62	97	93
135 m2	1.61	96	93	2.08	95	0.92	2.54	97	94

CHAPTER 5

CONCLUSIONS

5.1 Summary

This study considers direct damage on several single-family and multi-family residential buildings with or without basements at the individual building level (i.e., at micro-scale). Moreover, this study considers direct flood repair cost (i.e., flood loss) and repair time assessments for typical UK residential buildings. Residential practices in EU countries and UK have been considered to create typical case studies of residential buildings. Since water-entry damage to interior of buildings is the most common damage type observed in previous flood events, this study focuses on flood losses of only non-structural building items (i.e., fixed items in the building) and content items (sofa, tv, personal accessories etc.) using analytical (i.e., synthetic) approaches.

First, a typical single-family residential building and a multi-family residential building in UK are disassembled into components. With a focus on non-structural flood losses and content flood losses, flood damage potential of each non-structural component is considered for various flood depths. Relative losses associated with flood-repair costs and times for each damaged component are obtained considering the individual damage-depths of the component. Second, all components and their associated variabilities are assembled to estimate the total non-structural losses and repair times on buildings. Finally, several retrofit actions (i.e, dry or wet floodproofing) are explored to understand their effects on flood damage for residential buildings. By performing benefit analyses on both repair cost and time, the “optimum retrofit strategies” are investigated.

5.2 *Overall Results and Conclusions*

Considering several UK single-family and multi-family residential building case studies with or without basement and with different construction qualities, flood repair cost and time models have been developed using ABV (i.e., Assembly-based Vulnerability) method. Results show that water-contact can give severe damage on interior non-structural building items and content items, leading to significant flood loss and repair time values especially for a fully-flooded story. All loss models increase as the water height increases as expected, regardless of household material quality. Building items such as flooring and equipment are found to be very vulnerable to even shallow flooding (small water depths). Electrical items such as water heater and furnace, usually located directly on the floor, are highly valuable and thus more sensitive to water comparing to other interior items. Also, sensitivity analyses on the flood loss models show that the models are highly sensitive to a change in construction quality and area, and other parameters such as story height, unit prices, unit time and locations of items. This fact indicates that integration of uncertainties into the loss models is required for reliable estimates.

Efficiency of dry floodproofing and wet floodproofing retrofit actions have been also investigated in this study. Retrofit actions are found not to perform adequately on their own, but if grouped together as a package, they may be more effective and useful mitigation solutions to the homeowners. Retrofit packages that include grouting the external walls, relocating the mechanical items and raising the electrical items are found to be the most effective actions contributing to reductions in losses and times.

Moreover, shallow flood-depth events (<0.6m) are more likely to occur, thus B/C ratios at these depths may be more important. In addition, parametric studies show that uncertainties affect the benefit results significantly. Therefore, more effective retrofit packages should be thoroughly investigated considering these prescribed issues to perform probabilistic studies on cost-benefit analyses.

Lastly, the flood repair cost and time models and retrofit options developed in this study can be used as predictive and mitigation tools by a wide range of constituencies seeking to assess and reduce future flood impacts on homes, to improve public policy, insurance portfolio risk, and to arrange disaster response and management plans. Considering the decision approach for the retrofit packages mentioned in this study, homeowners can decide which retrofit package to use to reduce flood damage. In addition, insurance companies can advise their customers in this regard. As the use of retrofit actions in residential buildings increases, the flood damage to residential buildings will decrease and thus insurance companies will cover less damage and homeowners will pay less insurance premium rates. Authorized units in countries can improve building policies especially for the buildings in the flood-prone areas.

5.3 Limitations and Future Work

The list below shows the limitations of the study and give ideas on potential future research that can be done on the same topic:

- While the results reported in this study are based on 'direct' repair costs and times, more comprehensive studies should be performed considering 'indirect' losses, for example, rental costs due to unoccupancy of the houses.
- This study assumes cascading repair work items to calculate the repair time for flood damage on houses. More realistic repair time schedules are needed to develop flood time models.
- Hybrid flood loss models (synthetic and empirical) can be created by updating

the developed synthetic flood loss models in this study with empirical data.

- Moreover, shallow flood-depth events (<0.6m) are more likely to occur, thus benefit-to-cost ratios at these depths may be more important. Further studies should be done on cost-benefit analyses to understand effects of retrofit actions at shallow depths.
- Sensitivity studies show that uncertainties affect the flood loss and retrofit analysis results significantly. Therefore, probabilistic loss models and retrofit analyses are needed considering these uncertainties.

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