Interim Report to ODPM Building Regulations Division under the Building Operational Performance Framework

IMPROVING THE FLOOD RESILIENCE OF BUILDINGS THROUGH IMPROVED MATERIALS, METHODS AND DETAILS

Report Number WP2c – Review of Existing Information and Experience (Final Report)

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June 2005

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Project Title:

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Reference Number: CI 71/8/5 (BD 2471)

Milestone number: WP2c

Report Number WP2c: Review of Existing Information and Experience (Final Report)

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The work reported herein was carried out under a Contract placed on the 18th July 2003 by the First Secretary of State. Any views expressed are not necessarily those of the First Secretary of State.

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TABLE OF CONTENTS

1. Executive Summary

This literature survey is an output from Work Package 2 of the research project “Improving the Flood Resilience of Buildings through Improved Materials, Methods and Details” (Ref CI 71/8/5 BD247), funded primarily by the Office of the Deputy Prime Minister (ODPM) and the Environment Agency (EA) and managed by CIRIA. It is a review of existing information and experience of the flood resilience and flood resistance of buildings. The review focuses on the interactions between building fabric and floods and includes:

- An overview of the interaction of buildings with flood water.
- A review of existing practice and guidance in the UK and overseas.
- An assessment of available data on the effect of flood water on building materials and structures.
- Recommendations for the test programme to be undertaken in the next phase of the project.

The difference between flood resistance and flood resilience can be defined as follows. Flood resistance is the ability of a building to resist the entry of flood water from the outside to the inside. In contrast, flood resilience can be defined as the ability of a building to resist exterior and interior damage as a result of flooding. It is apparent from the survey of design guidance that there is general agreement on the factors and techniques that need to be considered for flood resistant and flood resilient building design. However, much of the theory and reasoning supporting this advice is based on expert advice, assumptions and extrapolations. The advice is in the main derived from experience and a common sense approach; however, there is a general lack of scientific experimental data underpinning the recommendations. Much of the existing advice both from the UK and overseas contains similar information that has been repackaged and reissued several times.

It was found that there is little published scientific research into the performance of buildings and construction materials in floods, with only limited attempts to collect and analyse experiential data. Whilst it is acknowledged that there are several experts working in this field, generally their knowledge on flood damage and repair has not been systematically recorded.

The general consensus from the analysis of the literature and consultation with individuals is that the construction of flood resistant buildings with occupied ground floors and basements would be difficult to achieve in practice and dependent upon a very high level of construction quality. What little experimental work that has been done to assess flood resistance supports this view, highlighting the considerable structural and other difficulties in achieving a dry-flood proofed building.

Several other research projects that relate to effect of flooding on buildings and the urban environment have been identified. These include for example the EPSRC projects “Adapting Historic Buildings to Moisture Related Climate Change” and “Adaptation Strategies for Climate Change in the Urban Environment”, as well as the European funded project “Floodplain Land use Optimising Workable Sustainability”. It is suggested that the ODPM or Environment Agency (EA) assume a facilitation role to maximise cooperation between these projects, to enable information exchange and minimise unnecessary repetition.

The paucity of existing experimental data on the performance of building constructions subject to flooding indicates that the priority for the test programme should be to develop a series of baseline performance data on flood resilience for the most typical UK construction methods and materials. In addition to the generation of performance data, the output of such a programme would be to provide a set of analysis tools, methods and testing protocols, that could be adopted in the development and testing of other, novel forms of construction.

2. Introduction

This interim report is an output from Work Package 2 of the research project “Improving the Flood Resilience of Buildings through Improved Materials, Methods and Details” (Ref CI 71/8/5 BD247) and is a review of existing information and experience of the flood resilience of buildings. The aims of this Work Package are twofold:

- To determine the extent of the current knowledge on flood resistance and flood resilience of buildings and to collect
- To analyse the available information on the effect of flooding on common domestic and light commercial buildings and building materials, construction methods and details.

This information will be used to determine the scope of laboratory testing that will be conducted during Work Package 5 of the project. The focus of the project is on new buildings but the review also identifies work on flood repair and reinstatement of existing buildings. The review focuses on the interactions between building fabric and flood waters and does not address the wider issues of flood defences and flood management. The report covers the following areas:

- An overview of the interaction of buildings with flood water.
- A review of existing practice and guidance in the UK and overseas.
- An analysis of existing data on the effect of flood water on building materials and structures.
- Discussion of the data with conclusions and recommendations for the experimental programme.

3. Background

The recent occurrences of severe flooding in the UK, such as in Lewes in 2000, Boscastle in 2004 and in Carlisle in 2005, together with predictions of more frequent extreme flooding events from the Foresight Future Flooding Report (OST 2004), have served to highlight to the Government, financial institutions, insurers, building industry and the public of the need to improve the local flood protection of buildings in flood risk zones. This is driven by the requirement to protect the health and safety of individuals living and working in affected properties, as well as the need to reduce the rising economic cost of flooding.

Following the Better Building Summit in 2003, the report from the Sustainable Buildings Task Group (DTI 2004) recommended that, at the level of an individual building, the Building Regulations should require modern standards of flood resistance and resilience for all construction within areas of flood risk and also that insurance companies should require that repairs to previously flooded properties are made using flood resilient products and in a flood resilient manner. The report also recommended the establishment of a single national Code for Sustainable Buildings (CSB) (DTI 2004). A consultation exercise is now underway to determine the scope of the CSB. This includes discussions on how flood resilience measures might be considered as part of the Code

There is a general perception that flooding only causes damage to property. If this was the case then it would tend to put flood resilience outside the scope of the Building Regulations as it would be classed as a property protection measure. Indeed, this was the view taken by the 2004 review of Part C of the Building Regulations (ODPM 2004). However, flooding can inflict both physical and mental trauma on people. Studies of the health effects of recent floods in Bristol and Lewes have shown that there are clear links between flooding and ill health (Johnson M, 2005). The evidence from these studies enabled government law officers to confirm that flooding does fall within the scope of the Building Regulations, as the effects and consequences of flooding can have harmful effects on people's health (Johnson M, 2005). The negative health effects of flooding are mostly associated with an increased risk of common psychological and mental health problems and, to a lesser extent, an increased risk of the spread of communicable diseases (Hajat et al 2003).

In England and Wales, the new Sustainable and Secure Buildings Act (SSBA) (TSO 2004) has extended the scope of the Building Regulations to include a much broader range of works to existing buildings and consequently may allow flood resilience measures to be applied to existing buildings at flood risk. The ODPM is currently looking at the implications of the SSBA.

The Planning Policy Guidance Note PPG25 on Development and Flood Risk in England (DTLR 2001), SPP7 in Scotland (Scottish Executive 2004a) and TAN15 in Wales (Welsh Assembly Government 2004) all encourage development away from areas at risk of flooding. However, it is acknowledged that development will still take place in those areas already at risk of flooding or in areas that may become at risk as a result of climate change. Indeed, the Sustainable Communities Plan (ODPM 2003) outlines plans for new urban developments in the South East, some of which, including the proposed Thames Gateway, are in areas with significant flood risk. Recent reports by the Association of British Insurers (ABI

2004a, ABI 2005) point out that many of the areas in the Sustainable Communities Plan are situated either in the Thames estuary floodplain or a river flood plain or could otherwise be at risk of groundwater or sewer flooding due to the high proposed development densities. The ABI reports identify key considerations that it believes should be addressed if development is to take place in such areas.

PPG25, SPP7 and TAN15 require that new developments should be constructed appropriately so as to minimise the effect of flooding on occupants and users of buildings and that appropriate flood risk assessments should be carried out. Possible mitigation measures identified as part of the risk assessment might include improved flood defences. Other methods such as raising the ground floor levels of buildings above likely flood level might also be considered. However, in many cases where the risk is relatively low or the cost of improved flood defences too high, the most cost effective option for reducing the flood risk to an acceptable level may be to improve the flood resistance of buildings themselves by incorporating some form of flood protection at the level of the building, and by the use of flood resilient materials and improved building design. It should be emphasised that no solution is failsafe, and there will always remain an element of risk no matter which mitigation measures are adopted.

However, developers, building designers, the flood protection industry, regulators and other stakeholders in the management of flooding are concerned about the lack of detailed knowledge on the resistance to flooding of building materials, construction methods and details, and also the lack of guidance on the effective use of resilient and resistant building materials. There is an apparent lack of readily available field data or scientifically-based information on how flooded structures, components and materials behave. It is also believed that current guidance on improving the flood resistance of buildings has, in the main, been developed on the basis of expert opinion and extrapolation from known performance under non-flood conditions.

In July 2004 the Government launched the “Making Space for Water” consultation exercise to seek views on a broad range of flood and coastal erosion risk management issues to inform development of a new strategy (OST 2004). Responses on flood resilience and resistance from the Consultation encouraged the Government to:

a) Promote incorporation of appropriate flood resilience and resistance measures in new and existing buildings.

b) Incorporate flood resilience measures in the new Code for Sustainable Buildings.

c) Consider financial incentives to the adoption of flood resilience measures in existing properties.

d) Improve the quality of advice on flood resilience and resistance to property owners and to engage and train builders and surveyors to meet this objective.

The ODPM is currently consulting on a revised PPG25 that will provide clearer guidance on flood resilience (ODPM 2005).

4. Literature Review Methodology

The literature review methodology consisted of the following activities:

a) *Standard library search tools and methods at Leeds Metropolitan University and Leeds University libraries, including review of previous relevant Government and CIRIA reports.*

b) *Online searching using a range of online databases and search terms (see Appendix 1 for list of databases and terms).*

c) *Industry consultations and discussions with key individuals and organisations (see Appendix 2 for list of consultees). These responses are discussed in a separate section.*

5. The Action and Effects of Flooding on Buildings

5.1 *Source-Pathway-Receptor Model of Flooding*

A useful method of characterising flooding in the urban environment is the Source-Pathway-Receptor model as adopted in the Future Flooding Foresight report (DEFRA 2004). The main sources are identified as precipitation, snow accumulations, peak tides, waves and costal surges. Pathways include rivers, estuaries, coastlines, roads, cuttings, drainage systems and manmade infrastructure such as dams and reservoirs. Receptors include residential and commercial properties, infrastructure such as roads, railways and power plant, agricultural land, recreational facilities and natural habitat. DEFRA estimate that 1.6 million residential properties and 120,000 commercial and industrial properties are situated in river and coastal flood plains.

5.2 *Flood Actions*

Kelman (2002) and Kelman & Spence (2004) identify a range of potential effects that may be caused by the action of flood waters on dwellings. These are as follows:

a) *Hydrostatic Actions: These are the effects on a building of lateral and uplift pressure forces due to the hydrostatic pressure of surrounding flood water and saturated ground. The higher the flood depth then the higher the hydrostatic forces. The lateral forces on a wall will be concentrated at the bottom of the wall. Water will also be drawn into porous building materials due to capillary action.*

b) *Hydrodynamic Actions: The action of water flowing and moving around a building will give rise to hydrodynamic forces. As the water velocity and flood depth increases then these forces will also increase. The effects can be localised at specific building features such as corners. The hydrostatic pressure will vary according to the action of waves and fluctuations in flood height.*

c) *Erosion Actions: Erosion can be caused by water flowing around the building or by the actions of waves lapping at a building.*

d) *Buoyancy Actions: Buildings or components may exhibit buoyancy in flood water. For example, oil tanks, gas tanks and other elements that rely on self weight to ensure stability may be lifted and/or shifted with respect to their mountings.*

e) *Debris Actions: (actions from solids in the water): The action on the building of any debris contained in the flood water. This can be a static force such as in the case of a building up of silt or it could be a dynamic effect of an object being propelled against the building. There may also be enhanced erosion effects due to the abrasive properties of silt laden water.*

f) *Non-physical Actions: The building materials may be affected by the chemical composition of the water. For example, the water may be saline as in the case of estuary flooding or may contain contaminants such as sewerage or other chemicals that might be released as a result of failure of building components. There may be also biological actions such as mould growth resulting from the high humidity levels.*

g) *Direct Water Contact: Building materials may be affected by direct contact with the flood water. For example, they may swell, crack or even dissolve on exposure to water. These changes may be irreversible.*

Kelman and Spence also note that these various actions can interact with each other, and therefore combined effects may also be important. For example, uplift on a building due to the buoyancy effect will likely reduce the lateral hydrodynamic pressure required to move the building, and chemical interactions and water saturation of materials may reduce the pressure from physical actions such as erosion needed to further damage the materials. Kelman and Spence (2004) suggest that the most important effects in terms of flood damage are the lateral hydrostatic forces, lateral hydrodynamic forces and direct water contact.

The Federal Emergency Management Association in the United States (FEMA) identifies the rate of change in flood level (rise and fall) as an important factor (FEMA 1998). This is because when flood waters rise rapidly, water may not be able to flow into a house quickly enough for the level in the house to rise as rapidly as the level outside. Conversely, when floodwaters fall rapidly, water that has filled a house may not be able to flow out quickly enough, and the level inside will be higher than the level outside. In either case, the unequalised hydrostatic pressures can cause structural damage to walls and floors.

According to Proverbs and Soetanto (2004), the main characteristics of flooding that determine the degree of damage caused are the flood depth, flood duration and the level of contaminants in the flood water. As flood water depth increases or the flood duration increases, then the greater the potential damage to buildings. The DTLR interim guidance on preparing for floods (2002) states that flood depth is the most important factor for dwellings and identifies a range of issues related to flood depth as shown in Table 1.

Table 1 - Flood Damage for a Typical Residential Property (DTLR 2002)

Depth of Flood	Damage to Building	Damage to Services and Fittings	Damage to Personal Possessions
Below ground floor	Minimal damage to main building Water may enter basements, cellars and floor voids Possible erosion beneath foundations	Damage to electrical sockets and services in basements and cellars Carpets in basements and cellars may need replacement	Possessions and furniture in basements and cellars damaged
Up to half a metre above ground floor	Damage to internal finishes such as wall finishes and plaster linings Floors and walls becomes saturated and will require drying out Chipboard flooring likely to require replacement Damage to internal and external doors and skirting	Damage to downstairs electricity meter and consumer unit Damage to gas meters, low level boilers and telephone services Carpets and floor coverings may need replacement Chipboard kitchen units likely to need replacement White goods may need replacing	Damage to sofas, furniture and electrical goods Damage to small personal possessions Food in low cupboards may be contaminated
More than half a metre above ground floor	Increased damage to walls and possible structural damage	Damage to higher units, electrical services and appliances	Damage to possessions on higher shelves

The effect of contaminants in flood water on construction materials is little reported in the literature. An example of the kind of additional damage that contaminated flood water may cause is demonstrated by the anecdotal report of a flood in Germany (Pasche & Geisler 2005). They report an extreme flood event in Neustadt, where the flood depth reached 4 metres. As a result many heating oil tanks collapsed, releasing their contents into the water. The oil penetrated walls and floors, resulting in additional damage, even to normally resistant materials such as tile flooring. The consequence of this was that normally recoverable materials could not be cleaned or repaired and had to be replaced. The cost of repairing the oil damaged building was found to be three times that of building unaffected by oil.

5.3 *Potential Entry Paths for Flood Water into a Building*

No literature was found that identified the routes of flood water into buildings by experimental observation. According to the CIRIA report on flooding repair (CIRIA 2004a), the main entry points for flood water into a dwelling are likely to be as follows:

Through masonry and mortar joints where the natural permeability of both these materials, particularly the mortar, can be high, particularly if resistance is reduced by tip and tail application of mortar to perpends.

a) *Through the brickwork/blockwork.*

b) *Through cracks in external walls.*

c) *Through vents, airbricks and flaws in the wall construction.*

d) *Through or around windows and doors at vulnerable points such as gaps and cracks in the connection of the frames and walls.*

e) *Through door thresholds especially where these have been lowered to the ground to allow level access.*

f) *Through gaps around wall outlets and voids for services such as pipes for water and gas, ventilation for heating systems, cables for electricity and telephone lines.*

g) *Through party walls of terraced or semi-detached buildings in situations where the property next door is flooded.*

h) Through the damp proof course (DPC), where the lap between the wall damp proof course and floor membrane is inadequate. (This may also be the case if the two membranes have not been sealed or joined by a suitable sealant or adhesive.)

i) Through underground seepage which directly rises through floors and basements.

j) Through sanitary appliances (particularly WCs, baths and showers) caused by backflow from flooded drainage systems.

In addition to the flood entry routes identified in the CIRIA report (CIRIA 2004a), other potential paths for entry of water into a building might include:

a) Joints between building elements such as expansion joints between walls, at positions where different construction materials meet or between the floor slab and wall.

b) Through gaps in masonry, stonework and blockwork walls where mortar was omitted during the construction of the building, usually at perpends. Such gaps have been observed frequently by Leeds Metropolitan University on many dwellings during site assessments undertaken as part of research into airtightness and condensation risk (Johnston, Miles-Shenton & Bell 2004, Bell, Smith & Miles-Shenton 2005).

c) At the joints between windows and door and their frames where the seal is missing, not fully compressed or faulty. Indeed, as most doors open inwards, the lateral hydrostatic pressure of any flood water will tend to push the door away from the frame seal. This would suggest that in flood prone areas it would be prudent to install outward opening doors and windows[1]. This method might prevent the use of flood gates and flood boards. However, robust outward opening doors and windows with multipoint fasteners could be more effective at minimising flood ingress than standard inward opening doors fitted with flood protection products such as flood boards.

d) Narrow cracks and gaps can and do exist at the interface between brick, stone and block units and their bedding mortar (BIA 2004) due to the failure of the cement to masonry bond. This can be as a result of movement caused by thermal expansion/contraction, moisture movement or settlement. Water can move along these gaps more quickly than directly through either the mortar or masonry unit.

e) For suspended timber ground floor constructions where the water has already entered the wall cavity, then the water can enter at the interface between timber and mortar for built in joists or along the interface between timber and metal plate where a joist hanger is used. In addition water will be absorbed rapidly via the exposed end grain of a built-in timber joist.

There is little published data on flood entry paths in the literature. Some anecdotal data based on surveys of flood victims carried out by Wordsworth and Bithell (2004) suggest that, based on householder observations, water can enter properties via doors, low lying windows and through the walls. A survey of owners of recently flooded domestic properties (mostly masonry terraced properties) carried out by CIRIA (CIRIA 2002) indicated the following observed flood water ingress paths:

a) Water coming through openings (88% of respondents)

b) Water seeping through walls and floors (46% of respondents)

c) Water coming up through drains (37% of respondents)

Some of these potential flood water entry routes are shown in Figure 1 (CIRIA & Environment Agency 2003).

[1] Of course, it is recognised that such an approach could result in hydrostatic and hydrodynamic pressures that would have to be allowed for in structural design.

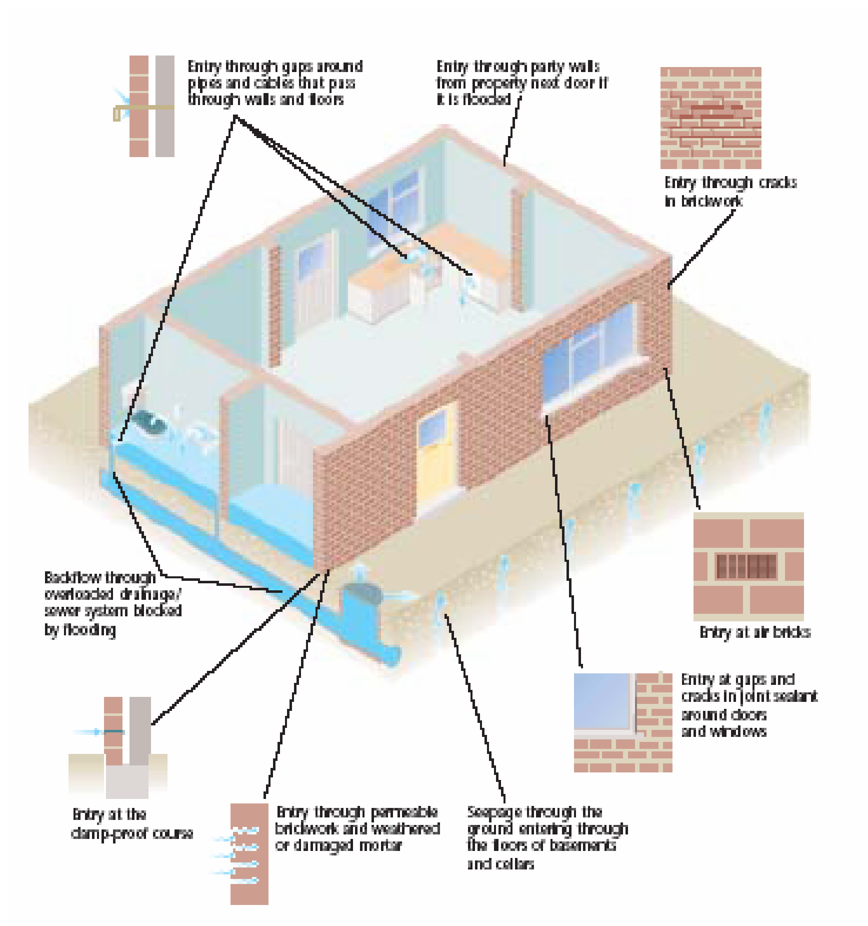

Figure 1 Potential Routes for Entry of Flood Water into a Dwelling (CIRIA 2003)

6. Review of Existing UK Guidance and Advice on Flood Protection of Buildings

This literature review found that the majority of existing UK guidance and advice on the flood protection of buildings is related either to the repair and reinstatement of buildings after a flood or to the installation of flood proofing measures on existing buildings. There is very little guidance on flood protection measures for new buildings.

Some attempts are being made to collate all the experiential information and guidance on the flood repair process. For example, the Flood Repairs Forum is developing a guide for the insurance industry which seeks to describe best practice for the investigation and repair of domestic properties, taking the whole process starting from the flood event all the way through to the owner returning to the property (Proverbs 2005)[2]. The document is still in an early draft form and, unfortunately, is not available for comment at this stage (May/June 2005).

Evidence from the UK floods of 2000 indicated that the emergency response was strongly dependent upon the use of sandbags as the main temporary flood defence measures and that public information on local protection and restoration could be improved (Bramley and Bowker 2002). Where buildings did have some form of additional local protection they noted a reduction in the cost of damage. They also identify three different types of local protection as follows:

- *Temporary and demountable barriers that prevent floodwater reaching the property.*

[2] The Flood Repairs Forum is a group comprising insurers, flood repair companies, expert investigators and loss adjusters.

- *Moveable barriers that seal potential routes into the building such as doors, windows, airbricks or skirts that prevent ingress directly through the fabric.*
- *Materials and techniques that minimise floodwater damage inside the property. This might include water resistant materials or the siting of fittings and living areas above flood level.*

The Building Research Establishment (BRE) have published a set of four repair guides (BRE 1997a, 1997b, 1997c, 1997d) which give some general advice on what actions to take following a flood. This advice is mainly concerned with procedures that will assist in the drying out of buildings and identifying those materials such as saturated insulation and chipboard that are likely to need replacement. An earlier BRE report (BRE 1991) also gives a range of advice to householders. Although the advice provides a reasonable review of the basic options, most of the recommendations are based on generalisations and are too generic to provide a detailed assessment of flood resistant design (Proverbs, Nicholas & Holt 2000).

The DTLR interim guidance document ”Preparing for Floods” (DTLR 2002) identifies some general principles of flood resistant design for new developments. These are as follows:

a) Ground floor levels should be raised above expected flood level.

b) Single storey buildings should be avoided.

c) Basements and cellars should be avoided.

d) For two storey dwellings consideration should be given to either using the ground floor for storage or garaging only.

e) Solid concrete floors are preferable to suspended floors as they provide a more effective seal against rising flood water.

f) Building fabric should be constructed of flood resilient materials.

The DTLR guidance document also gives some general advice on material selection. It suggests that water resistant paints or coatings be applied to the external face of walls to at least 500mm above the maximum level of flooding but that these coatings should also allow the wall to dry effectively after a flood. However, the guidance fails to mention the potential effect this treatment might have in terms of the need to ensure that the wall will have sufficient structural strength to resist lateral hydrostatic and hydrodynamic pressure due to deep water floods. The requirement for resistance to hydrostatic loads at high flood depths is mentioned in another section of the report relating to the use of flood barriers but not for waterproof coatings.

The guidance proposes that dense building materials are used for the wall construction in preference to lightweight materials, as these are more likely to resist water penetration. It is suggested in the report that gypsum plaster and plaster boards are not used on internal walls and instead recommends more resilient materials such as water-resistant render, lime-based plasters, ceramic tiles and hydraulic lime coatings. The guide emphasises the need to ensure that moisture is not trapped in the walls due to these low permeability coatings. The report indicates that there are no practical options for improving flood performance of timber framed buildings with plasterboard internal facing. In terms of insulation for solid walls it is suggested that materials are used that are rigid and-self draining and that insulation bonded directly to plasterboard be avoided. For cavity walls, the report recommends closed cell foam insulation over blown insulation or fibrous insulation.

The DTLR document contains several contradictions, although it is acknowledged that the report was based on best available advice at the time and was issued within a short timescale. Examples of these contradictions include the suggestion for the minimum height of waterproof coatings on walls mentioned above and the guidance relating to low permeability or waterproof coatings and the need to facilitate rapid drying. It is very hard to see how it is possible, in practice, to accommodate both properties. In a similar vein, one section includes the advice that solid concrete floors can be an effective seal against flood water but recommends in a different section that they should be designed with a gap around the edges to relieve hydrostatic pressures. There is no recognition in the guidance of these apparent contradictions, nor how they can be resolved. It is therefore recommended that the interim guidance be updated, to take account of these potential safety issues.

The Scottish Office flood design guidance report (Scottish Office 1996) is focussed on specific design issues and identifies the different issues that arise for the various construction types. The report highlights a range of general design considerations for a development site as follows:

a) Locate developments on high ground.

b) Raise ground where feasible.

c) Choose materials for substructure that are resistant to damage by freezing when wet.

d) Locate garage and utility areas on the ground floor of buildings.

e) Design buildings with two or more storeys.

Flood protection of buildings falls into three general strategies (Scottish Office 1996).

a) Raising the level of the ground floor above the potential flood level.

b) Keeping water out of the building. It is suggested by the Scottish Office that this is probably an unrealistic option due to the difficulty of achieving a completely watertight building in practice.

c) Accepting that water will enter a building and designing the building accordingly to allow easy drainage and quick drying. Construction materials can be chosen such that they are expected to suffer damage but are cheap and easy to replace or more robust materials can be selected with the assumption that they may suffer less damage but will take longer to dry out.

Specific guidance on important aspects for various different construction details is given in the Scottish Office document (1996) as shown in Table 2.

Table 2 - Scottish Office Flood Resilience Guidance

Construction Detail	Point to Consider
Ground Supported Floors	Damp proof membranes should be located as high as possible in the floor to reduce drying out times. Insulation materials should have low water absorption and be resistant to contaminants. Insulation laid directly under final floor finish may float. Service should not be located in the floor or if unavoidable should be in channels in the slab or screed.
Suspended Timber Floors	If the damp proof course is on top of the hardcore layer then this can be disrupted by flooding. Concrete sub floor layer should have a fall to allow easy cleaning and drying. Timber in floor elements and joists should be pressure treated. Joist hangers are preferred to built-in joists are less susceptible to distortion during wetting and drying. Insulation should be closed cell rigid foam or self draining. Reflective foils should be perforated. WBP plywood should be considered as a resilient flooring material. Access panels should be provided to allow easy cleaning under the floor.
Suspended Concrete Floors	A fall and drainage point should be provided to allow for draining of flood water. Hollow materials should have frequent drainage holes. Lightweight materials may take longer to dry than dense materials. Insulation laid directly under final floor finish may float.
Solid Masonry Walls	Can take a long time to dry out, with low density materials taking longer to dry than dense materials. Recommends using "F" rated bricks and >4 N/mm2 concrete blocks to minimise risk of frost damage. Insulation should be rigid board or self draining mineral wool batts. Insulation bonded to plasterboard should be avoided. External insulation may take some time to dry.
Cavity Masonry Walls	A wall with clear cavity will dry out quicker than solid wall but slower than filled cavity construction. Blown-in or loose cavity fill will be displaced and compressed following a flood. Partial fill will probably only marginally affect drying times compared to a clear cavity. Closed cell insulants will absorb minimal water but may restrict drying, whereas absorptive insulants may allow faster drying through vapour transfer. Weeps holes in the external leaf will allow easier water drainage and drying.

Framed Walls	Fixings should be corrosion resistant. Fibreboard sheathing may need to be replaced following wetting.[3]
Partitions	The plasterboard of stud partitions and panel partitions will likely need replacement following a flood. Partitions should be directly supported on concrete floor or on masonry under a suspended timber floor.

CIRIA have developed a range of online advice sheets (CIRIA 2003a, 2003b, 2003c, 2003d, 2003e, 2003f, 2003g, 2003h) based on the information in the CIRIA/Environment Agency booklet on the use of flood protection products in dwellings (CIRIA & Environment Agency (2003). This advice is based on existing literature and expert advice.

The new BRE suite of loss prevention standards for dwellings includes the LPS 2026 standard that covers flood resilience (BRE 2004). The standard defines qualitative performance requirements for different grades of flood resilience but does not give advice on how to achieve the required levels.

In order to conform to the LPS 2026 standard all buildings must have the following characteristics. Service outlets, cabling and conduits must be routed through the ceiling and upper walls, with no part below 1.2m from the floor. Only closed cell thermal and acoustic insulation may be used. All external doors must be of solid construction. The standard also defines three grades of flood resilience as follows:

- *Flood Proof - High level of performance that requires that only a small amount of water is permitted to enter the structure or living space of the building. There must be no material change or irreversible degradation in structural performance as a result of flooding. Floors, wall linings, insulation and other materials should be easily replaceable if damaged*
- *Flood Resilient - Medium level of performance that requires that modest amounts of water enter the property, that the water will drain effectively and rapidly and that the materials used in the construction are resistant to water damage, can be decontaminated and dry quickly. There must be no material change or irreversible degradation in materials used in wall and floor construction and wall linings, insulation and other materials shall be easily replaceable.*
- *Flood Repairable Lower level of performance that requires the water drains effectively from the structure, that there is no irreversible structural damage and that damaged materials can be replaced or repaired easily.*

Work carried out by the BRE on behalf of the ABI identified a range of measures that could be undertaken to improve the flood resilience of existing dwellings, either as part of repair following a flood or in anticipation of potential flooding (Broadbent 2004 & ABI 2003). The focus of this advice is to minimise potential future financial losses. The advice on repair and improvement methods given in this report is as follows:

a) *Genera*l

- Move services meters to at least one metre above floor level and place them in plastic housings.
- Move electrics to at least one metre above floor level with cables dropping from first floor level distribution down to power outlets at high level on the wall.
- Install one-way valves into drainage pipes. This prevents contaminated floodwater entering houses through pipes.
- Mount boilers onto the wall above the level that floodwater is likely to reach.
- Where the drive or garden slopes towards the dwelling then install drainage channels to intercept water flow.

b) *Floors*

- Replace sand–cement screeds on solid concrete floor slabs. Where screeds are damaged in floods, resistance to future damage may be improved by replacement with a denser proprietary concrete screed.

[3] This would be difficult to achieve if the sheathing is located on the inside of the cavity.

- Replace floor including joists with treated timber to make it water resistant/repellent. The timber is less likely to absorb water, enabling the floor to dry out more quickly and be more resistant to rot or distortion.
- Replace floor timber including joists with more robust timber/treated timber which is hardened. This timber is more resistant to becoming saturated with water, enabling it to dry out more quickly and be less likely to rot or distort.
- Replace timber wall plates and joists on sleeper walls with corrosion resistant steel alternatives. The steel joists are surmounted with treated timber boards.[4]
- Install a damp proof material around the ends of floor joists where built into walls, turning up the wall and with the timber on top. This will protect the joist ends from persistent dampness and consequent rot.[5]
- Replace oak floorboards with treated timber board. Oak boards are difficult to dry out and expensive to replace.
- Remove ash-bedding from underneath quarry tiles in Victorian houses. Ash-bedding retains moisture and impedes drying out.
- Replace chipboard flooring with treated timber floorboards. Chipboard has to be replaced if there is any chance of contamination. Other treated floorboards are more resilient to flood.[6]
- Raise floor levels above the most likely flood level. In general, this is only applicable when floodwaters do not rise much above the existing floor level and where the ceiling height of the property can accommodate it. Raising floors may require resetting doors and windows to higher cill levels and this will be an additional cost.
- Replace timber floor with solid concrete and provide tiled finish with falls to allow draining to sump and pump.

c) Walls

- Clear and repair air bricks/vents to suspended timber ground floors. This improves the under floor air flow and aids the drying out process making it less likely that building components will get damaged by long-term water logging. However, this may make water ingress easier.
- Install air bricks above the expected flood level and duct down to the floor void. Floodwater can travel easily through airbricks into buildings. Raising the vent above floodwater level may reduce the flow of water into a property, particularly to the sub-floor in the event of shallow flooding.
- Install a chemical DPC below joist level. This enables the structure below to be treated in a different way from that above. This helps to minimise the amount of dampness that gets above the DPC, potentially reducing the damage to the property and the amount of repair work that must be done above this level.
- Replace mineral insulation within internal partition walls with closed cell insulation[7]. Closed cell insulation is more likely to survive a flood without having to be replaced.
- Replace gypsum plaster with a more water resistant material, such as lime plaster or cement render on walls or silicon/mineral board in place of plasterboard. This reduces the extent to which floodwater will penetrate and significantly increases the probability that a wall will survive a flood without damage.
- Provide a dado rail at the dividing line between flood resistant treatment and normal construction as an indicator for future repair requirements.

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[4] Although the advice suggests using steel wall plates, this is an unusual technique for masonry dwellings for which components are unlikely to be readily available.

[5] Alternatively, steel joist hangers could be used instead of building the joists into the wall.

[6] Moisture resistant boards are now a requirement of the building regulations for rooms that may contain appliances that use water.

[7] However as this may have a detrimental effect on acoustic performance it may be necessary to design accordingly internal partitions with the required acoustic properties.

- Fix plasterboards horizontally on timber framed walls rather than vertically. In the case of a flood, this means less plasterboard will have to be replaced when repairing the walls.
- Coat exterior walls with a microporous spray coating every five years. This may be of some benefit in reducing floodwater ingress through the wall construction although it will not prevent penetration through cracks, joints and openings. It may make properties more difficult to dry out and may create durability failures in the existing materials.
- Re-point brickwork with a mix of 1:2:9 – cement/lime/sand mortar. Mortar tends not to be very flood-resistant and may disintegrate if immersed in floodwater. This could result in expensive repairs and potential structural damage to the property. The replacement mix would be significantly more likely to survive flood conditions without need for repair.
- Replace doors, windows, skirting boards, architraves, doorframes and window frames with fibreglass (GRP), plastic, uPVC or other similar water resistant alternatives. These do not absorb water or warp and so are more readily functional after a flood.
- Replace door hinges with rising butt hinges. These allow doors to be lifted off and placed in a dry place until the flood subsides.
- Fit kitchen units with extendable plastic or stainless steel feet or support on raised brick or stonework.

d) Interior

- Replace ovens with raised, built under type. These are more likely to be above the flood line but are lighter to move for deeper flood.
- Move kitchens to first floor rooms. Kitchen equipment can be difficult to remove in a flood and can be expensive to replace after one.
- Move washing machines to first floor rooms. Washing machines are heavy and impractical to move before a flood and are expensive to replace after one.
- Replace chipboard kitchen/bathroom units with plastic or similar units. Chipboard units generally have to be discarded after a flood, but plastic units may be disinfected and used again.
- Specify the least expensive kitchen possible and to expect to replace it after a flood.
- Replace baths having chipboard stiffening panels with cast iron or pressed steel models. Baths made from traditional materials are more resilient and are more likely to survive a flood.

The Scottish Planning Advice Note PAN 69 (Scottish Executive 2004b) notes that the use of water resistant materials and forms of construction can minimise flood damage. The document summarises the potential scale of damage for different materials (Table 3) and also highlights those materials that are either suitable or unsuitable for various building components (Table 4).

Table 3 - Summary of Potential Effects of Exposure to Flood Water (Scottish Executive 2004b)

Material	General Effects
Masonry, Concrete and Brick	In general masonry and concrete are unlikely to be severely damaged by contact with floodwater. In the case of coastal flooding, salt water may cause surface powdering and flaking of soft brickwork. Lightweight concrete may expand and contract depending on moisture content so wetting and drying may cause some cracking.
Timber	Timber swells and may distort on wetting. In timber framed buildings, swelling of immersed members could cause damage in other parts of the structure, e.g. through stresses on external cladding. Timbers that become wet and cannot dry may become at risk of decay in the long term.
Wall Finishes	Renderings containing cement are unlikely to suffer damage. Lime based plasters are preferable to gypsum which softens when wet. Similarly, following flooding, any plasterboard will probably be damaged beyond repair and require to be removed.
Metals	Metals are affected by the corrosive effects of sea water so resistant metals rather than mild steel should be used in coastal areas where flood risk is an issue.

Material	General Effects
Insulation	Close cell insulants will not absorb water but may restrict drying out of a cavity wall. Mineral fibre and other absorptive insulants will retain water and can lose their insulating properties or disintegrate over time.

Table 4 - Summary of Material Suitability for Building Components (Scottish Executive 2004b)

Component	Most suitable	Suitable	Unsuitable
Flooring	Concrete, pre-cast or in situ	Timber floor, fully sealed, use of marine plywood.	Untreated timber Chipboard
Floor Covering	Clay tiles Rubber sheet floors Vinyl sheet floors	Vinyl tiles Ceramic tiles	
External Walls - to max flood level	Engineering brick Reinforced concrete	Low water absorption brick	Large window openings
Doors	Solid panels with waterproof adhesives Aluminium, plastic or steel	Epoxy sealed doors	Hollow core plywood doors
Internal Partitions	Brick with waterproof mortar Lime based plasters	Common bricks	Chipboard Fibreboard panels Plasterboard Gypsum plaster
Insulation	Foam or closed cell types	Reflective insulation	Open cell fibres
Windows	Plastic, metal	Epoxy sealed timber with waterproof glues and steel or brass fittings.	Timber with PVA glues and mild steel fittings

Severn Trent Water utilise a predefined selection process called “Hydraulic Toolkit” when determining the most appropriate flood protection measure(s) to apply to properties affected by low depth sewer flooding (Burrup 2005). This selection process takes into consideration such factors as: how the water entered the property (overland or directly from sewer connection), whether the flood water entered curtilage through third party land, whether flooding was from below ground level, whether flood water entered property through air bricks? A range of protection measures are considered by the Toolkit. These include the following:

a) *Ground contouring.*

b) *Diversion of private drainage system.*

c) *Disconnection of sewer system in cellar or basement.*

d) *Installation of pumping unit in cellar or basement.*

e) *Installation of pre-packaged mini pumping.*

f) *Fill in hollow/suspended floors or cellars.*

g) *Protection of air bricks (periscopic vents or air brick covers).*

h) *Raise door thresholds.*

i) *Boundary treatments such as flood gates and flood walls.*

j) *Replacement of wooden doors with PVCu doors.*

k) *Installation of non-return valves in drainage system.*

l) Bolting down and sealing of inspection chamber covers.

m) Installation of stop logs (a type of sectionalised flood gate).

7. Approaches to and Examples of Flood Protection and Resilience of Buildings in other Countries

7.1 *United States*

The US Congress first established its National Flood Insurance Program (NFIP) in 1968 (Spence 2004). The NFIP is a federally backed scheme that makes flood insurance available in areas with known flood risk, as long as the communities have an approved floodplain management system and also adopt building regulations that comply with specified guidelines for flood resistance and resilience. The US Army Corp of Engineers (USACE) and the Federal Emergency Management Association (FEMA) publish a range of advice documents on flood resilience, many of which are incorporated into local building codes.

One of the most important NFIP requirements for buildings constructed in flood hazard areas is that they should be constructed using flood resistant materials. This requirement applies to both structural and non-structural materials. A flood resistant material is defined as a building material “capable of withstanding direct and prolonged contact with floodwaters without sustaining significant damage” (FEMA 1993). Prolonged contact is stated as a period of at least 72 hours. Significant damage is deemed to mean any damage that requires more than low cost cosmetic repair such as repainting. Building materials are categorised into five different classifications as shown in Table 5.

Table 5 - FEMA Flood Resistant Material Classification (FEMA 1993)

Classification	Class Description	NFIP Acceptability
5	Highly resistant to floodwater damage. Materials within this class are permitted for partially enclosed or outside uses with essentially unmitigated flood exposure.	Acceptable
4	Resistant to floodwater damage. Materials within this class may be exposed to and/or submerged in floodwaters in interior spaces and do not require special waterproofing protection.	Acceptable
3	Resistant to clean water damage. Materials within this class may be submerged in clean water during periods of intentional flooding.	Unacceptable
2	Not resistant to water damage. Materials within this class require essentially dry spaces that may be subject to water vapour and slight seepage.	Unacceptable
1	Not resistant to water damage. Materials within this class require conditions of dryness.	Unacceptable

The USACE have developed a set of recommended flood proofing regulations (USACE 1995) that can be incorporated into local building codes in the US. These include techniques for dry floodproofing that would not be allowable under the NFIP scheme.

The USACE has published case studies and examples of flood-proofed building in the USA (USACE 1984). The USACE report on general floodproofing techniques (USACE 1996) identifies three general approaches to floodproofing existing buildings as follows:

a) Raising or Moving a Structure - The structure is elevated such that lowest floor is above the expected level of floodwaters or alternatively relocated to an area of low flood risk

b) Constructing Barriers - Freestanding berms, levees or walls are constructed to a height above the expected flood level.

c) Wet Floodproofing - The structure is modified to allow water to enter a building and materials are used that are resistant to damaged by flood water.

The American Society of Civil Engineers (ASCE) has published a standard for Flood Resistant Design and Construction (ASCE 2000). This standard is mainly concerned with structural aspects of flood resistant/resilient design. Some of the pertinent information in the standard is as follows:

a) *New construction in a flood zone should be designed not only to resist flood damage but also not adversely affect any other properties.*

b) *Load bearing walls should be designed to take account of hydrostatic and hydrodynamic forces.*

c) *Where load bearing walls enclose an area that is below the expected flood depth and it has not been designed for wet floodproofing, then the wall must incorporate flood gates and valves that allow for automatic flow of flood water during a flood.*

d) *Dry floodproofing methods are generally not allowed in residential structures as they usually require some form of human intervention, good maintenance and sufficient flood warning for them to be fully effective.*

e) *Utilities and services should normally be located above the design flood elevation and sewer pipes fitted with anti backflow devices.*

The FEMA technical fact sheet on construction materials suitable for use in coastal buildings identifies a range of flood resistant materials as shown in Table 6 (FEMA 2005). Some specific examples of flood resistant materials are suggested such as pressure treated or naturally decay resistant timber (e.g. redwood, cedar, oak, cypress) and durable concrete mixes with a minimum 28 day cube strength of 5000psi (34 MPa) and water cement ratio not higher than 0.40.

Table 6 - Flood Resistant Materials for Coastal Construction (FEMA 2005)

Location	**Material**
Piles and Posts	Round, tapered wood piles preservative-treated for ground contact, at a minimum; square-section piles or wood posts preservative-treated for marine use
Piers	Reinforced concrete or concrete masonry units
Foundation Walls	Reinforced concrete or CMU, or wood that is preservative-treated for foundation or marine use
Beams	Solid sawn timbers and glue-laminated products, either naturally decay-resistant or preservative-treated for aboveground exposure; built-up members preservative-treated for ground contact
Decking	Preservative-treated or naturally decay-resistant wood, or composite wood members (e.g., manufactured of recycled sawdust and plastic)
Framing	Sawn wood or manufactured lumber (preservative-treated or naturally resistant to decay if in close proximity to the ground)
Exterior Sheathing	High-capacity shearwall sheathing rated “Exterior”
Sub-flooring	Plywood or oriented strand board (OSB) rated “Exposure 1,” or rated “Exterior” if left permanently exposed (e.g., exposed underside of elevated house on open foundation)
Siding	Vinyl or naturally decay-resistant wood
Flooring	Latex or bituminous cement formed-in-place, clay, concrete tile, pre-cast concrete, epoxy formed-in-place, mastic flooring, polyurethane formed-in-place, rubber sheets, rubber tiles with chemical-set adhesives, silicone floor formed-in-place, terrazzo, vinyl sheet-goods, vinyl tile with chemical-set adhesives, pressure-treated lumber or naturally decay-resistant lumber
Walls and Ceilings	Cement board, brick, metal, cast stone in waterproof mortar, slate, porcelain, glass, glass block, clay tile, concrete, CMU, pressure-treated wood, naturally decay-resistant wood, marine grade plywood or pressure-treated plywood
Doors	Hollow metal
Insulation	Foam or closed cell
Trim	Natural or artificial stone, steel, or rubber

A test protocol has been established by the National Evaluation Service to evaluate the effects of flood water on construction elements and structures (NES 2004). The procedure involves exposure of test specimens to simulated flood water by complete immersion for a period of 72 hours. This is followed by drying in laboratory conditions until the moisture content of the specimen returns to that prior to immersion. The maximum drying period is 28 days. The evaluation criteria for the specimens after the test are not clearly defined in the standard, but in general terms relate to strength, dimensional stability, cleanability and moisture content. Those materials that pass the test can be classified according to the FEMA classification as either Class 5 (Highly resistant to flood damage - suitable for external flood exposure) or Class 4 (Resistant to flood water damage - suitable for internal exposure).

The Louisiana State University information sheet on flood proofing existing dwellings gives some practical guidance on relatively inexpensive wet-flooding proofing measures (LSU 1999). A diagram showing some of the recommended techniques for walls and floors is shown in Figure 2. The main themes of the recommendations are as follows:

a) *Use flood resistant materials - Suggested materials include: clay tile, stone or brick with waterproof mortar; solid vinyl flooring with chemical-set adhesives; stained concrete; terrazzo; decay-resistant or pressure-treated woods; and rigid, closed-cell foam insulation.*

b) *Create flushable and drainable walls - Water should be allowed to drain freely from wall cavities. Suggested solutions are removable wallboards, baseboards and wainscoting.*

c) *Prevent wicking - Create horizontal gaps in materials such as plasterboard that can wick and fill with a suitable sealant.*

d) *Elevate Appliances and Utilities*

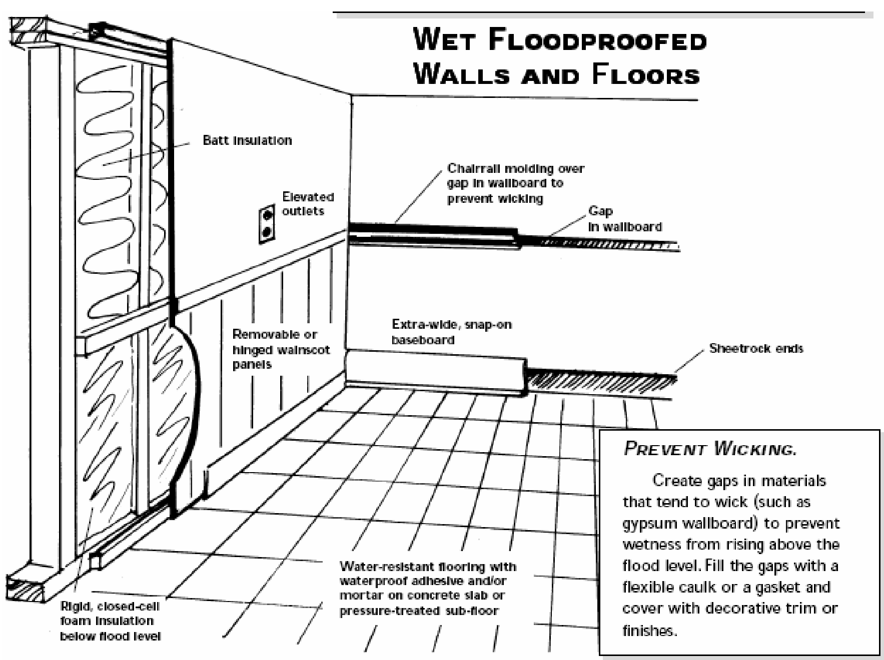

Figure 2 - Wet Flood-proofed Walls and Floors (LSU 1999)

FEMA have published a Homeowner's guide to Retrofitting (FEMA 1998) that describes 6 alternative strategies to protect an existing dwelling from flooding. These strategies are as follows:

a) *Elevation* - Elevating a house to prevent flood waters from reaching living areas by raising the lowest floor to or above the Flood Protection Elevation (FPE)[8]. This can be done by elevating the entire house, including the floor either on extended foundations, piers, piles or columns, or by leaving the house in its existing position and constructing a new, elevated floor within the house.

[8] The Flood Protection Elevation (FPE) is defined by FEMA at a position 1ft above the 100 year flood Base Flood Elevation (BFE).

For prefabricated timber framed houses, the construction is separated from its foundation, raised on hydraulic jacks, and held by temporary supports while a new or extended foundation is constructed below.

b) *Wet Floodproofing* - This is modifying the uninhabited parts of a house such as basement, garage and crawlspace so that floodwaters may enter but that minimal damage is caused either to materials or structurally.

c) *Relocation* - The house is physically lifted and moved to new location and new foundations in an area outside the flood risk zone. This is obviously much easier for timber framed dwellings common in the US than for UK masonry dwellings.

d) *Dry Floodproofing* - Making the building watertight below the expected flood level. Not recommended for flood depths over 3ft or for framed buildings due to potential problems with lateral hydrostatic forces and moisture durability issues.

e) *Levees and Floodwalls*

f) Demolition

Following severe flooding in the United States in 1993, the US Department of Energy commissioned research into appropriate retrofitted flood protection measures and resilient repairs that could be incorporated into flood damaged homes (Corbett & Everett 1995). One of the main recommendations from this study was that all plaster and plasterboard be removed and replaced as, even if plaster regains its strength it is a difficult material to decontaminate as it absorbs the contaminants very easily.

7.2 *Australia*

The planning approach in Australia varies from state to state (Blong 2004). In New South Wales, planning regulations do not allow the construction of residences with ground floor levels below the average 100 year recurrence interval flood. In contrast, in Queensland, the availability of flood maps is limited and local councils allow construction in areas with as low as a 10 or 20 year flood interval. Data from Thuringowa (Kelman & Pooley 2004) suggest that a minimum floor level approach is successful at reducing the extent of building flood damage.

The planning system in Alice Springs requires special planning approval for developments in the 1% and 2% (100 year and 50 year) flood zones (NTG 1999). Where house are built in the 1% flood zone, the minimum floor level of habitable rooms must be 300mm above the predicted level of a 1% flood. Development may be allowed at 300mm above the level of a 2% flood, if flood proofing control methods are incorporated into the building below this level. Flood proofing techniques are defined as either “complete floodproofing” whereby flood water is prevented from entering a property or “partial floodproofing” where the construction materials resist deterioration. Flood proof materials are apparently graded according to the following definitions but no details are given on which materials fit into which category:

a) Suitable - unaffected by submersion

b) Mildly Affected - some damage, but easily repairable

c) Significantly Affected - substantial damage, but still repairable

d) Severely Affected - requires replacement after submersion

Canterbury City Council in New South Wales defines flood resistant materials according to their suitability as shown in Appendix 5 (CCC 1999), and identifies the most suitable candidate materials as well as those that should be avoided if building in a flood risk area.

Blong (2004) concluded from his analysis of data relating to the proportion of damage for different building materials and elements for flooded buildings in Australia, that many building materials used in flood plains are inappropriate. Despite this evidence, there is no national building code to control building material selection for construction on floodplains.

The New South Wales Government has recently produced a comprehensive Floodplain Development Manual (New South Wales Government 2005). The floodproofing of buildings and the use of flood resistant materials are identified as possible property modification options that might be considered during the risk management process. However, it is made clear that floodproofing should be used in conjunction with other flood management measures. Floodproofing is defined in the manual as “the design and construction of buildings with appropriate water resistant materials such that flood damage to the building itself (structural damage) and possibly the contents is minimised should the building be inundated". However, the technical and practical advice given in the manual on how to actually design a floodproof house is limited in scope. There is general advice to move habitable areas to upper floors. It is also stated that buildings should be designed to withstand static and dynamic water loads, debris loads and buoyancy forces. Double brick wall construction is suggested as a flood resilient alternative to plasterboard and chipboard lined walls.

7.3 *France*

Following severe flooding in France in 1981, the French government set up a compensation scheme for natural disasters called Natural Catastrophe Insurance (Spence 2004). The scheme is funded by an additional levy on all insurance policies. Disaster mitigation is encouraged through new Risk Prevention Plans (Plan de Prévention des Risques - PPR) in areas considered at risk from specified hazards such as flooding. This allows insurance companies to refuse cover for buildings in high flood risk zones and to insist on preventative measures such as flood resilience in medium flood risk zones. Local planners will be legally barred from authorising any development in "red zones" on the new hazard zoning maps currently being drawn up by the French authorities (Crichton 2005). However, just as in the UK, there are no comprehensive guidelines on how to achieve flood resilience or flood resistance in buildings (Salagnac 2005). The hazard zoning maps are fixed by law, do not take account of local flood protection, and are subsequently difficult to change in the light of additional new information or local knowledge (Crichton 2004). There is a perceived lack of local participation in the creation of the maps (Crichton 2004).

Additionally in France, there is the Decennial Responsibility for all new buildings (Spence 2004). This means that all the parties involved in the construction process (developers, contractors, architects, surveyors, engineers, building control, planning authorities, manufacturers etc) all carry responsibility and are financially liable for 10 years (starting from the official hand over of the building) for the structural performance of the construction and any damage that might leave the building unsuited for use.

The Centre Scientifique et Technique du Bâtiment (CSTB) is currently researching the performance of adaptation measures that mitigate the vulnerability of buildings in flood zones with the aim of developing a tool to assess potential flood protection methods (Salagnac 2004). The CSTB has published a very basic guide on flood repair (CSTB 2002) which covers similar ground to UK guidance given in the BRE flood repair guides (BRE 1997a, 1997b, 1997c, 1997d).

7.4 *New Zealand*

The Building Research Association of New Zealand (BRANZ) has published a technical bulletin on measures to take when restoring a building after a flood (BRANZ 1993). The bulletin identifies some materials, such as plasterboard and particle board, that are most likely to require complete replacement following a flood, but does not contain any detailed advice on resilient repair methods.

7.5 *Germany*

Flooding in August 2002 in Central Europe from the river Elbe caused widespread damage and exposed the shortcomings of flood disaster management in Germany (DKKV 2004). Despite historical data of the potential scale of flooding along the Elbe, planning authorities allowed significant development and construction on the floodplain before 2002. Since 2002 a new Federal law has been drafted to integrate flood protection, flood-related construction and flood risk reduction in one law.

Some information on flood resistant construction has been published by the Federal Ministry of Transport, Building and Housing (BMVBW 2002). This identifies a range of building protection measures such as the use of anti-backflow valves, sealing of basements with bitumen, the use of impermeable concrete for walls and foundations, the installation of services at high level and the anchorage of oil/gas storage vessels. The report also gives a general list of the sensitivity of building materials to water as shown in Table 7.

Table 7 - Material Water Sensitivity (BMVBW 2002)

Material	Example	Water Sensitivity
Gypsum-based Materials	Plaster	-
	Plasterboard	-
	Plaster Render/Wall Plaster	-
Lime-based Materials	Mortar & Render	+
	Limestone	+
Cement-based Materials	Mortar & Render	+
	Concrete	+
	Concrete Blocks	+
	Concrete Floor	+
Fired-clay Materials	Brick	+
	Clinker Block	+
	Glazed Ceramic Tiles	+
	Unglazed Earthenware	O
Timber	Joists & Beams	- to +
	Floorboards & Planks	-
	Chipboard & Particleboard	-
	Cellulose insulation board	-
	Parquet flooring	-
Metals	Steel beams & joists	+
	Copper/Zinc sheet	+
Plastics	Various	- to +
Bitumen Materials	Gaskets	+
	Bitumen Paint	+

{"+" good suitability (no or limited water sensitivity), "O" moderate suitability (some water sensitivity)
"-" unsuitable (strong water sensitivity)}

The German Insurance Association (GDV) has divided Germany into three flood hazard zones using a new zoning system (Risk Management Solutions 2003).

Pasche and Geisler (2005) report some of the flood resistance techniques and strategies used in Germany. They indicate that most buildings in Germany are either of stone or concrete construction, and therefore the suggested flood resistance techniques are most appropriate for these two forms of construction. They suggest that a water resistant fabric for buildings is possible with the use of waterproof concrete for walls and floors.

The International Commission for the Protection of the Rhine (ICPR) has published a study that evaluates the potential reduction in damage that could be achieved by various floodproofing measures on buildings (ICPR 2002). However, the report does not go into any technical detail on any of the protection measures suggested, nor does it describe the data or methodological basis used for the estimates of damage reduction.

7.6 *Sweden*

In Sweden, the local authorities are responsible for both flood protection and planning, and open to legal action from property owners for the costs of damage caused by flooding. Swedish case law has ruled that the planning authorities are liable if it can be shown that buildings were constructed in an unsuitable location (Crichton 2005).

7.7 *Canada*

Following Hurricane Hazel in 1964, the Ontario planning authorities instituted a total ban on all construction within the 250 year return floodplain (Crichton 2005). New properties are only allowed on the edge of the zone if the ground floors are designed to be unoccupied. Any existing properties within the zone cannot be sold except to the town authorities, who purchase the buildings for demolition.

The Canadian Institute for Research in Construction (IRC) has published a general guide to flood proof construction (Williams 1978). This report identifies some of the factors that should be considered when building in a flood risk zone. These include:

a) *Consideration of the likely flood conditions such as height of maximum flood, velocity of water flow, duration/frequency of flood and other factors such as objects in the water.*

b) *Consideration of structural factors such as uplift and lateral forces caused by hydrostatic pressure of water on walls and floors can be important, especially for domestic properties.*

c) *Economic justification for any flood proofing measures should be undertaken using a cost-benefit analysis.*

The IRC report (Williams 1978) also identifies several basic flood proofing measures as follows:

a) *Building on Fill - The building is constructed on fill raised above the design flood level. This is the most widely used technique for flood proofing new dwellings in Canada.*

d) *Building on Piers, Columns, Piles or Bearing Walls - The building is elevated on a support system. The supports must be designed to resist damage from floating debris. This method has minimal effect on flood flows.*

e) *Making Lower Levels Watertight - The lower levels are sealed against water penetration by careful design of walls, drainage systems, floor slabs, doors and windows. Williams does not say how this method could be achieved in practice but does note that if this technique is used then the structure must be capable of withstanding the hydrostatic pressures.*

f) *Surrounding Buildings with Flood-Proof Walls or Berms - Williams identifies the disadvantages of this method as the potential for catastrophic failure and its impracticality in dense urban areas.*

g) *Wet Flood-Proofing - Flood damage is minimised by the use of water resistant materials. Again, Williams gives no more information on which materials would be suitable.*

h) *Flood Proof Services - The services of flood proofed buildings must also be resistant to flood damage. For example, sewer and water pipes should be fitted with anti-back flow valves and electrical and telephone systems should be located above the design flood level.*

i) *Flood Proof Basements - The advice for basements suggests two alternatives. Firstly, an un-drained system, designed to be watertight and strong enough to resist uplift and lateral forces. Secondly a drained system, with conventional walls and floors and a sump pump drainage system.*

7.8 *Netherlands*

Traditional construction methods in the Netherlands include flood resilient strategies to cope with the high risk of flooding. There are several examples of these traditional methods in the Zuider Zee museum in Holland (Crichton 2003b). These include tiled floors with a built in drain, solid floors with drainage holes and an underfloor drainage system, tiled internal walls and water proofed external walls above and below ground.

However, the current national approach to flood protection in the Netherlands has moved away from local protection of buildings and now appears to focus much more on significant investment in large scale flood defences (Kok et al 2002). Consequently, if flood defences did fail in the Netherlands then gross inundation would be the main problem.

8. Consultations with Key Organisations and Individuals

A range of individuals and organisations that we believed may have access to or knowledge of sources of unpublished information or data on flood resilience and flood resistance were contacted by telephone or email. In addition, a number of face-to-face interviews were held with specific individuals. Appendix 2 contains a list of the organisations contacted, the contact names and whether or not a response was received from them. It was agreed with the participants that, in order to allow them to be as open as possible, none of the comments they made as part of the consultation would be directly attributable to them or referenced.

It was evident from the response of the majority of the consultees, that it is generally acknowledged that there is a lack of scientific basis for much of the existing advice on flood repair, flood protection and flood resistance of buildings. It was also suspected that much potentially useful information is not recorded or readily accessible. For example, information on how different materials and constructions have performed in a flood may be recorded by flood repairers when they assess buildings for repair, but such data has not been analysed or published.

Many of the consultees felt that the concept of flood resilience was a valid and achievable objective but equally, that the idea of a totally flood resistant building was impractical and probably unachievable in reality.

It was believed that the approaches taken by different repair and damage management companies can differ to such an extent that, even where very similar properties on the same street have been affected by the same flood and the damage caused is of a similar nature, the time taken to dry and reinstate the buildings and the overall repair costs can vary considerably between buildings. Some of this difference is believed to be due to the response time of the clean up operation, some to the lack of clear guidance in areas such as drying and repair and some due to the different approaches to repair options taken by different insurers and loss adjusters.

Repair management companies have different approaches to flood damage reinstatement of buildings. Some take the view that the best approach is to replace as little as possible and to clean and repair wherever practical. Other companies may take a different approach and will replace and renew materials if this would mean the building is repaired more quickly or more cost effectively.

The current role of flood insurance is to reinstate the building to the same condition as it was before the flood. Any resilient improvement measures to a building would be viewed by the insurers as “betterment” and consequently would not be normally be considered by insurers as part of repair, even if resilience might reduce future flooding claims. Currently therefore the onus is on the building owner or householder to pay for and arrange for any resilient repairs. Although one can understand the position of the insurance industry with respect to betterment, this approach is likely to add to the insurance burden in the long term and seems to be at odds with ABI advice (ABI 2003) on repair and improvements for flood resilience.

There is an impression among some respondents that, due to the lack of guidance, some repair and flood protection companies are taking advantage of the situation by carrying out unnecessary or inappropriate works.

Discussions with the various parties indicate that a blame culture prevails within the flood repair industry. Organisations from different sectors of the flood repair process tend to suggest that the main causes of failings in the process are due to poor performance of other parts of the process. This indicates at some level a lack of cooperation between the various organisations. This may be due in part to commercial interests.

The discussions also suggest that there is a general lack of communication between all the interested parties in flood protection of buildings such as planners, building control officers, insurers, developers, government agencies and the water companies. The situation may be different in Scotland, where there are “Flood Appraisal Groups” (Crichton 2002).

There is anecdotal evidence that current techniques for resilient/resistant construction actually hinder the repair process. For example, there are reports that, after the recent floods in Carlisle, materials installed prior to the flood to impart resilience to walls have had to be removed by the repair companies in order to allow the building to dry effectively.

Several of the participants noted that the time elapsed from the end of the flood event to the commencement of drying out is critical to the success of the whole repair operation. Significant delays can cause additional damage to materials and potentially give rise to problems such as mould growth.

It is apparent from these discussions that there is a range of related research projects currently underway in the UK that include some aspect of the effect of flooding on buildings. It is also clear that there is little interaction or coordination between the projects. These projects include for example:

- *ASCCUE project - The EPSRC sponsored project "**A**daptation **S**trategies for **C**limate **C**hange in the **U**rban **E**nvironment" is being led by Manchester University (Manchester University 2005). The main aim is to develop an improved understanding of the consequences of climate change for urban areas and how they can be adapted to climate change. The building integrity work package of this project is investigating the direct effects of flooding and the indirect effects of water table variations on soil conditions. The study will translate these risks into estimates of the vulnerability of the building stock. The town of Lewes is being used as a case study.*
- *Adapting Historic Buildings to Moisture Related Climate Change - This is an EPSRC project consortium being led by UCL. One of the aims is to investigate the effect of flooding on old and historic buildings. The initial report of the first phase has been published (Pender & Cassar 2004). Further tasks will involve testing wall constructions and developing a model of the drying out process.*
- *FLOWS project - The "**F**loodplain **L**and use **O**ptimising **W**orkable **S**ustainability" project is a multinational project with participants from Germany, the Netherlands, Norway, Sweden and the United Kingdom (FLOWS 2005). It is funded by the European Regional Fund INTERREG North Sea programme. The FLOWS programme will look at the issues and deliver practical projects to identify how people need to adapt to live with water as a result of climate change. Work package 2 of the project involves several demonstration projects of retrofitted flood resilient buildings. The UK partners include Norfolk County Council, who are retrofitting a Housing Association property with resilience measures such as replacing skirting with UPVC equivalent and replacing plaster with water resistant equivalent, and Lincolnshire County Council who are establishing appropriate methods of resistance on a heritage building. HR Wallingford has maintained regular contact with the UK collaborators on this initiative.*
- *Flood Risk Management Research Consortium (FRMRC). This is a multi-funded initiative with a range of objectives. One of the key research areas is urban flood management although its scope is limited. Research into flood resistance and resilience is not one of the prime objectives of the consortium but frameworks for incorporation of techniques will be included as part of the overall objectives of flood risk reduction.*
- *There are other projects and networks relating to flooding in the urban environment that may be of broad relevance but are outside the scope of this literature survey. For example, there is the SUDSNET network of research groups in the field of sustainable urban drainage systems (SUDS).*

It was noted by some of the interviewees that many building owners, especially homeowners, do not want flood protection measures to be visible on the outside of their properties as this could potentially affect the value of the property.

Anecdotal evidence from householders who experience regular flooding indicates that, even when using well fitted secondary flood barriers such as flood gates, flood waters generally find their way through the fabric of the building. Often this can change from one flood to the next, with an apparently flood resistant dwelling with all its defences in place succumbing to flood waters when previously it had been dry. Indeed, householders who have experienced several floods will rarely rely on flood barriers alone, and tend to use them in conjunction with sump and pump systems to deal with any water that does get into the property.

The feeling of some participants was that lessons can be learned from traditional forms of construction, especially from old buildings situated in flood risk areas. This includes for example, the use of lime renders, lime mortars and tiled floors.

Several participants emphasised the potential health risks associated with flooded buildings, both to the owners and occupiers, and also to the repair industry professionals and contractors.

The main conclusions that can be derived from the comments of the consultees can be summarised as follows:

a) Flood resistant construction (i.e. that which is designed to prevent the entry of floodwater into a building) is thought to be unrealistic. Flood resilient construction (i.e. that which is designed to allow the controlled entry of floodwater into a building and enable the rapid draining, drying and decontamination of a building once the flood has passed) is thought to be potentially viable.

b) There has been little scientific research on the performance of buildings and construction materials in floods nor any significant attempts to collect and collate existing anecdotal and experiential data on the performance of buildings during floods. There has been research to analyse householder experience on the performance of buildings during floods, such as the survey of flood affected residents carried out by CIRIA (CIRIA 2002).

c) Historical methods of flood resilience such as the use of lime mortars and tiled flooring are thought to be effective but not well understood whereas some modern techniques such as waterproofing walls are thought to be detrimental to the drying process and long term durability of construction materials.

d) There is an apparent lack of coordination between the various interested parties in flood resilience and flood repair.

e) There is an opportunity for coordination of current research projects in the field.

9. Review of Scientifically Based Research on Flood Resistance and Resilience of Buildings

There is a limited amount of scientifically-based research on flood resilience of buildings and building materials in the literature.

Kelman and Spence (2003b) report their analysis of the calculated failure loads for a range of common building elements and components, and contrast these with the likely loads that may be imposed under different flood conditions. They identified the principal sources of flood induced loading on buildings as follows, noting that these functions could combine to give complex pressure patterns:

a) Pressure differential due to difference between internal and external water levels, where water infiltration rates are low.

b) Loads due to the velocity of floodwater. These can be uniform or variable.

c) Loads due to waves. These can impose temporary or oscillating pressures that start at around 40 kPa for a 0.5 m flood depth, and can go as high as 500 kPa for a 2.5m deep flood.

d) Impact loads from debris in the water. These will be short-lived and concentrated.

e) Sand and silt deposits may impose static loads as they pile up against external or internal walls.

Kelman and Spence (2003b) calculated the required failure loads due to hydrostatic pressure for a range of building elements. For example, the hydrostatic pressure needed for failure of 4mm thick glass double glazed units varied from 15 kPa for a 2 m high and 1 m wide unit to 184 kPa for a 0.25 m by 0.25 m unit. For typical UK masonry walls, they calculated that walls would begin to fail under combined hydrostatic and hydrodynamic loads of between 5 to 10 kPa at the base. A 10 kPa base pressure would equate to a 0.7 m flood at 3.5 m/s velocity. Even very strong masonry walls would fail at around 20 kPa. An example of the predicted failure curves for 2-storey brick/block walls due to hydrostatic forces is illustrated in Figure 3 (Kelman 2002).

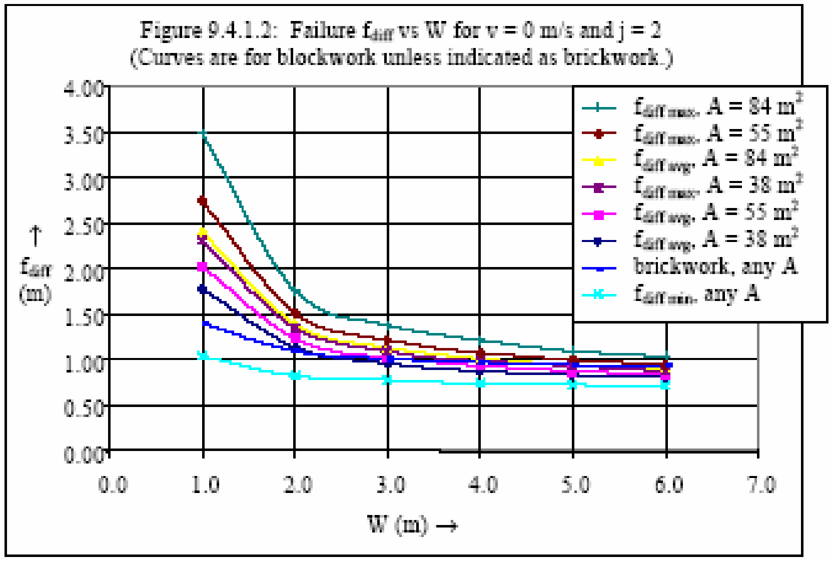

Figure 3 - Predicted Failure Curves for 2-storey Brick/Block Masonry Wall (Kelman 2002)

(F_{diff} = flood height difference outside to inside, W = wall width, A = floor area)

It is noted by Kelman and Spence (2003b), that the advice given by the DTLR (2002) on the flood resistance of solid floors is somewhat contradictory in that it recommends that solid concrete floors can be an effective seal against flood water seeping in from under the floor but which at the same time states that they should be designed with a gap around the edges to relieve hydrostatic pressures. A flow chart of potential failure mechanisms and likely degree of flood damage was developed as shown in Figure 4.

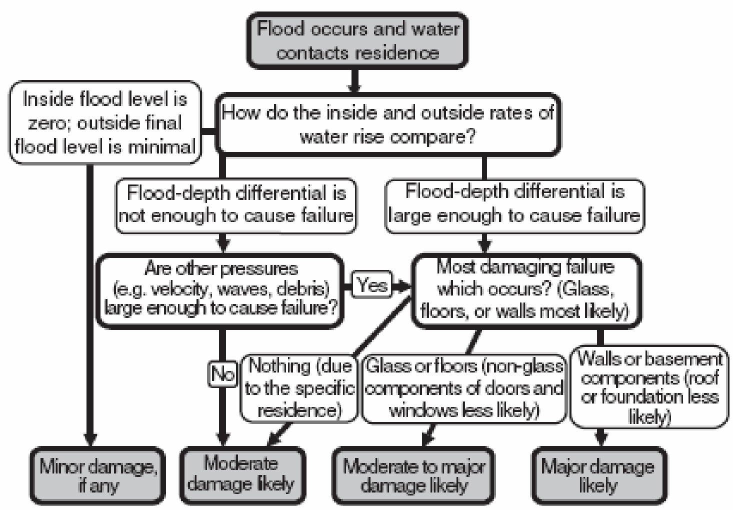

Figure 4 - Flood Failure Flow Chart (Kelman & Spence 2003b)

Oak Ridge National Laboratories (ORNL) and Tuskegee University in the United States have evaluated a range of building materials and construction systems by testing a series of small prototype structures under simulated flood conditions (ORNL 2005, Wendt & Aglan 2001). The test modules all had a footprint of 8ft x 8ft (2.4m x 2.4m), and were all variations of typical US timber frame constructions on either a concrete slab-on-grade floor or a raised floor. An example of one of the test modules is shown in Figure 5. One of the biggest advantages of this holistic test methodology is that it assesses the flood resilience of typical building element junctions as well as the resilience of the building elements and construction materials, and is most likely to represent the behaviour of a real building short of testing a full-size dwelling[9].

Figure 5 - Typical Module under Test from ORNL/Tuskegee Research Project (ORNL 2005)

The ORNL/Tuskegee test methodology was designed to test for physical resistance to the wetting, drying and cleaning processes associated with a flooding event and did not investigate any hydrostatic loading effects. The procedure they used for each test was as follows:

a) Test module erected in outdoor test basin.

b) Module flooded to a depth of 2ft (0.61m) above floor level (flood water pumped from nearby lake).

c) Flood waters left around the test building for 3 days.

d) After 3 days the flood waters were allowed to recede and the structures left unattended for a further 5 days. This time was designed to simulate the typical length of time it would take a homeowner to return to a dwelling after a flood.

e) The modules were then opened up to promote natural drying and they were cleaned and disinfected according to normal procedures.

f) The modules were then allowed to dry for a total of 28 days.

g) During the tests measurements were taken of relative humidity, temperature and moisture content of building materials. Local weather conditions were recorded on a weather station. The mechanical strength (e.g. flexural strength) of the building materials before and after the flood test was also measured. Protocols were also developed for visual observations.

Some of the findings of the ORNL/Tuskegee project were as follows:

a) North American dwellings are commonly faced with some form of lapped or butt-jointed siding. Of the types of siding investigated by the research team it was found that vinyl and fibre cement materials outperformed both painted plywood and hardwood siding.

b) The team found that both plywood sheathing and moisture-resistant gypsum sheathing both retained their integrity and strength but that, unlike the gypsum, the plywood sheathing had not dried to its pre-test condition.

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[9] Although such test cells are likely to provide a reasonable degree of correspondence between the laboratory and reality with respect to certain matters (for example water flow through junctions) they are, inevitably, limited. In particular, observed levels and durations of humidity within the cell and the impact on mould growth and drying characteristics need to take into account the context of the test cell itself when seeking to extrapolate to conditions in a real building.

c) The conclusion of the team on the performance of the timber frame was that, as long as the wall or floor materials allow the frame to dry then timber framing should be considered flood resilient. However, the data suggest that where a moisture retaining material such as fibreglass insulation is used in the external wall then this can extend the drying time for the timber such that it would become a durability issue.

d) Fibreglass batt insulation was found to wick and retain water, and contributed to high residual moisture levels and long drying times when it was used in wall or floor elements. In contrast, closed cell polyurethane insulation performed well, absorbing little moisture and surviving the flood test undamaged.

e) When used with fibreglass insulation, conventional gypsum plasterboard lost 50% of its flexural strength and had high moisture content at the end of the test, whereas a water-resistant fibre-reinforced grade of gypsum board was mostly unaffected. When plasterboard was used with a clear cavity it was found that it was possible to recover the material. Both types of board showed evidence of mould growth on exposed faces, which would be a concern. (see example in Figure 6)

Figure 6 - Interior Plasterboard Showing Surface Mould Growth after a Flood Test (ORNL 2005)

f) Carpets, vinyl and wood flooring all slowed the floor drying process, whereas ceramic and quarry tiles absorbed little water and did not significantly hinder the drying process. Timber sub flooring and framing retained high moisture levels when used with fibreglass insulation.

g) Attempts were made to dry-floodproof one of the modules. However, despite careful sealing and the use of door & window flood barriers, these attempts were unsuccessful at preventing the flood water from entering the test building. The research team concluded that measures to impart flood resistance to a building is extremely difficult to achieve and probably not practical for timber frame construction.

During the 1980's, the USACE conducted a series of tests on the structural resistance of brick facing walls and concrete block walls to hydrostatic loads (USACE 1988). A small range of wall configurations were tested. The results showed complete failure of the walls at flood depths of around 2ft (0.61m) for both brick and concrete block walls. Significant deflections of the walls began to occur at around 1ft to 1.5ft (0.3m to 0.45m). A test wall with simulated roof restraints withstood slightly higher loads. A picture of one of the test walls is shown in Figure 7.

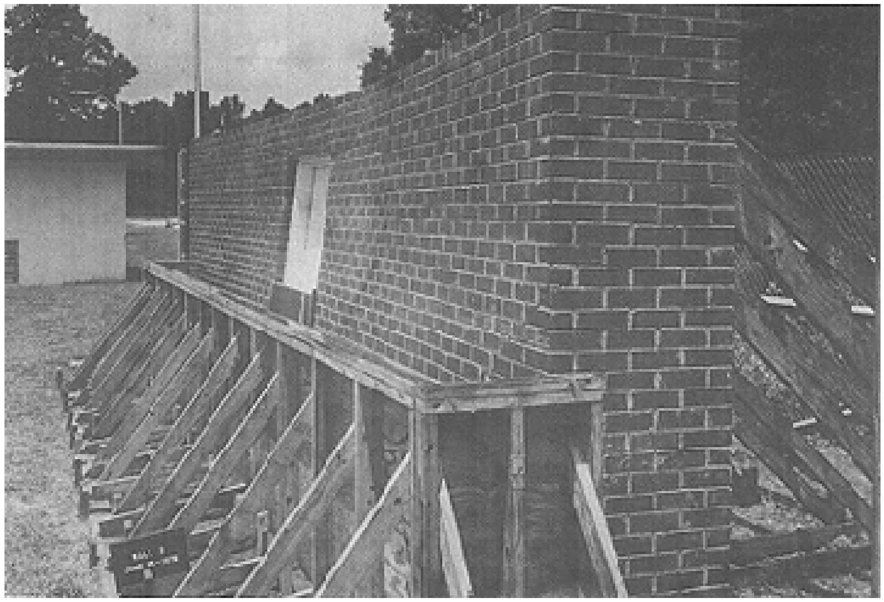

Figure 7 - Brick Wall Showing Failure after Hydrostatic Loading Test (USACE 1988)

The USACE also investigated potential wall sealing materials such as polymeric coatings and skirt systems and two full-scale test houses were also constructed and subjected to simulated flooding events. Some of the conclusions from this work were as follows:

a) Standard brick façade walls are generally not watertight when exposed to static flood loads.

b) Whist the test walls failed at flood water depths of around 2.4ft (0.73m), this improved to around 3ft (0.91m) for tests on full scale dwellings due to the additional strength provided by the composite action of the walls and roof. Wall failure is potentially very sudden and catastrophic.

c) The permeability of brick or block walls can be improved with some but not all of the most commonly available water resistant coatings. Clear silicone-based water repellent coatings on brick or block walls, were found to be ineffective at resisting even small hydrostatic loads. Acrylic polymer modified cement render coatings were found to be very effective at resisting water ingress, and durability studies indicate good long term durability. Asphaltic, epoxy and polyurethane coatings performed poorly.

d) External polymeric flood protection membranes were found to be difficult to make watertight effectively and consistently.

Proverbs and Soetanto (2004) report the development of a set of benchmark standards for the repair of flooded domestic properties in the UK. This work was based on the analysis of questionnaire surveys of chartered surveyors involved in the assessment of flood damaged properties. The respondents were asked to rate the performance of a range of flood repair strategies for various damage scenarios against a set of performance criteria (cost, quality, time, customer satisfaction, and overall performance). They found that the most commonly used strategies in practice were not necessarily the best performing strategy. Benchmark strategies for different materials and elements were developed taking into account all the performance criteria. Consequently, these benchmarks may not always reflect the best technical solutions. Some examples of these benchmark strategies for walls and floors are given in Table 8. It is apparent for some of the categories shown in this table that the benchmark repair may not necessarily reflect the flood resilience of the material. For example, in the case of both steel partition framing and internal lime render, the benchmark repair is for complete replacement, yet these two materials are identified in other sources as being water and flood resistant. Consequently, this data is probably of limited use in the selection of flood resilient materials or construction techniques for new buildings.

Table 8 - Example Benchmark Flood Repair Methods (Proverbs and Soetanto 2004)

Flood Damage Scenario	**Benchmark Repair Strategy**
Quarry Tile Floor - submerged by floodwater	Floor tiles cleaned in place
Solid Concrete Floor - submerged by floodwater	Floor is cleaned and allowed to dry
Suspended Timber & Chipboard Floor - submerged by floodwater	Replace chipboard and warped/rotten timber
External Wall - brick with cement mortar	Clean wall
External Wall - rendered finish	Clean render
Internal Wall - painted brick	Clean & repaint
Internal Wall - ceramic tiles	Replace tiles
Internal Wall - gypsum plaster finish	Replace all plaster
Internal Wall - cement/sand render with plaster skim	Clean plaster
Internal Wall - lime/hair plaster with lime putty finish	Replace all plaster
Internal Partition - metal framed with plasterboard	Replace metal components and plasterboard
Internal Partition - timber stud with plasterboard	Replace plasterboard

Woodward (2001) reports a test of a flood skirt protection system on a case study building. The test building was equipped with a proprietary skirt system and artificially flooded to a depth of 0.5m overnight. Checks for water penetration after the test showed no leakage into the building. No other measurements such as moisture contents or lateral movements were reported. A diagram showing a section though the flood skirt system is illustrated in Figure 8.

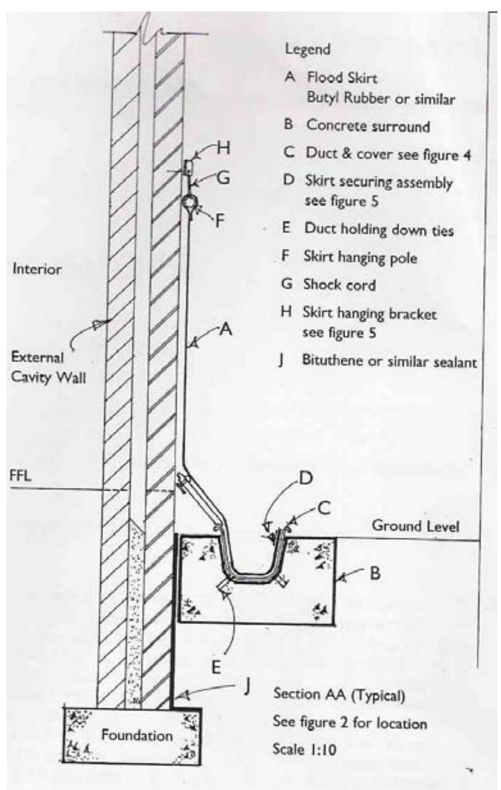

Figure 8 - Section through Floodskirt System (Woodward 2001)

10. Water & Flood Resistance Properties of Construction Materials

Latta (1962) identifies some of the main effects of water on building materials that have the potential to cause damage to the material or have detrimental effects on the durability of structures. These potentially destructive mechanisms include moisture expansion, corrosion, biological decay, blistering, efflorescence, chemical leaching and frost damage.

The majority of building materials such as wood, concrete, plaster, stone, brick and tile are porous in nature, with their structures comprising of networks of fine interconnected pores giving rise to large internal surface areas (Sereda & Feldman 1970). When dry, porous materials come into contact with water the initial wetting process is one of capillary action. Once the material is saturated then the process of water movement is controlled by permeability and hydraulic pressure differences.

Sereda and Feldman also suggest that it is a misconception that, where porous materials such as brick have been treated with hydrophobic additives such as silicone, this does not necessarily mean they will not allow the passage of water and may still become saturated. This is because water can be pushed into the material due to pressure differences and water vapour can diffuse and condense inside the material. The BDA (1989a) also argue that water repellent treatments should be used with caution on the outer leaf of masonry walls due to drying problems and thus there is a potential risk of frost damage and water penetration due to water saturated bricks.

10.1 *Fired Clay Brick*

Clay bricks are ceramic materials comprised mainly of silica and alumina combined with up to 25% of other components. The structure of the material consists of a relatively uniform ceramic matrix through which runs a network of voids, fissures and pores. The porosity can vary greatly between brick types, ranging from 1% to as high as 50%. It is the porous nature of brick which is the main driver for properties such as permeability and water absorption. The presence of these open pores in the ceramic allows moisture ingress to occur. Capillary action sucks water into the pore structure, with the degree of suction being related to the proportion of fine pores. Water is conducted by capillary action along the pore system into the interior of the brick. The rate of conduction is dependent upon the number of pores and their size. The greater the number of pores of finer size, the slower the rate of transfer. Conversely, the greater the number of pores of larger size the greater the rate of conduction. Additionally, moisture ingress will be assisted by the presence of any cracks within the material. Typical properties illustrating the variability in water absorption and suction rate for some different brick types are shown in Table 9 (Illston 1994).

Table 9 Properties of Clay Bricks (Illston 1994)

Brick Type	Compressive Strength (N/mm^2)	Water Absorption (weight %)	Water Porosity (volume %)	Suction Rate (Initial Rate of Absorption) ($kg/m^2/min$)
Handmade Facing	10-60	9-28	19-42	1.0-2.0
London Stock	5-20	22-37	36-50	-
Gault Wirecut	15-20	22-28	38-44	-
Keuper Marl Wirecut	30-45	12-21	24-37	1.0-2.0
Coal Measure Shale	35-100	1-16	2-30	-
Fletton	12-30	17-25	30-40	1.5-2.5
Perforated Wirecut	72.4	3.3	5.8	-
Solid Wirecut	109.9	4.2	10	0.28
Solid Wirecut	55.5	8.9	17.5	1.46
Solid Wirecut	21.3	21.2	35.2	1.87

Another characteristic of clay bricks that is important with respect to their interaction with water is the soluble salts left over from the firing process that are contained within the brick. These are usually sulphates of sodium, potassium, magnesium and calcium, the level of which can be as high as 5% by weight, but are typically around 0.1 to 1% (Jackson & Dihr 1996). These salts can leach out as moisture moves through the brick, giving rise to efflorescence. BS 3921 (BSI 1995) classifies the salt content of clay bricks as low (L) where the levels of soluble ions do not exceed the following limits:

- Magnesium 0.03%
- Potassium 0.03%
- Sodium 0.03%
- Sulphate 0.5%

Bricks classified as normal (N) according to BS 3921 have maximum limits for soluble ions as follows:

- Sum of sodium, potassium and magnesium 0.25%
- Sulphate 1.6%

In the UK, bricks are classified by BS3921 according to water absorption and compressive strength as shown in Table 10.

Table 10 - UK Brick Classifications

Brick Class	Compressive Strength (N/mm^2)	Water Absorption (weight %)
Engineering A	≥ 70	$\leq 4.5\%$
Engineering B	≥ 50	$\leq 7.0\%$
Damp Proof Course 1	≥ 5	$\leq 4.5\%$
Damp Proof Course 2	≥ 5	$\leq 7.0\%$
All Others	≥ 5	No limits

Another indicator of the water resistance of clay brick would be its frost resistance. Bricks are classified according to BS3921 in one of three categories as follows:

a) *Frost resistant (F). Bricks durable in all building situations including those where they are in a saturated condition and subjected to repeated freezing and thawing.*

b) *Moderately frost resistant (M). Bricks durable except when in a saturated condition and subjected to repeated freezing and thawing.*

c) *Not frost resistant (O). Bricks liable to be damaged by freezing and thawing if not protected as recommended in BS 5628-3 during construction and afterwards, e.g. by an impermeable cladding. Such units may be suitable for internal use.*

Garvin (2001) identifies some of the major durability risks associated with bricks exposed to floods. These include frost damage caused by freeze-thaw action when flooding occurs in winter, spalling caused by crypto-efflorescence and slow drying rates exacerbated by water repellent coatings. He also notes that bricks normally thought to be quite durable may become susceptible to damage as a result of flooding, indicating that existing brick classifications may not be a good guide for flood resistance. Crichton (2003b) also comments that masonry can take a long time to dry out and wet masonry is vulnerable to freeze-thaw damage.

An analysis of the literature concerning the drying of porous building materials by Proverbs el al (2000) indicates that there are two distinct phases of drying. The initial “constant rate drying period” can be influenced by environmental conditions such as temperature and humidity, whereas the second phase “falling rate drying period” is determined by other factors, suggesting that continued use of assisted drying after the initial period would not be productive. Proverbs et al (2000) also note that electronic moisture meters are thought to give a poor indication of true moisture levels due to the presence of salts. They also identify other work that shows, where two dissimilar materials are joined, the absorption rate of the composite material is driven by the material with the higher sorptivity.

10.2 *Concrete and Concrete Blocks*

The resistance of concrete to moisture ingress is related to its porosity and the degree of continuity between the pores (Illston 1994). Generally speaking, as porosity and the water/cement ratio increase, then water permeability increases. Low porosity also gives rise to high strength, so it is generally true that high strength concretes also have low water permeability. The permeability of any concrete will also be affected by the permeability of the aggregates used. Lightweight aggregates in particular can have relatively high permeabilities. In practice, concrete will have a permeability that is higher than that of either the aggregate or cement paste due to the presence of cracks and defects. These cracks and defects, when at the interface between the aggregate and cement paste, can be reduced by the use of cement replacement materials such as silica fume and with careful control of stresses due to drying and thermal shrinkage. A range of pore filling and hydrophobic waterproofing admixtures can also be added to the concrete mix.

A typical standard concrete with dry density of 2200 kg/m^3 has a porosity of 15%, saturation moisture content of 150 kg/m^3 and water absorption coefficient of 0.018 $kg/m^2s^{1/2}$ (Kumaran 1997).

A typical lightweight concrete with a dry density of 973 kg/m^3 has a saturation moisture content of 580 kg/m^3 and water absorption coefficient of 0.08 $kg/m^2s^{1/2}$ (Kumaran 1997).

Crichton (2003b) states that lightweight concrete blocks are susceptible to cracking after a flood due to expansion on wetting and drying shrinkage.

The drying times for various types of concrete block are shown in Figure 9. These data indicate that autoclaved aerated blocks dry more quickly from a saturated condition than other block types.

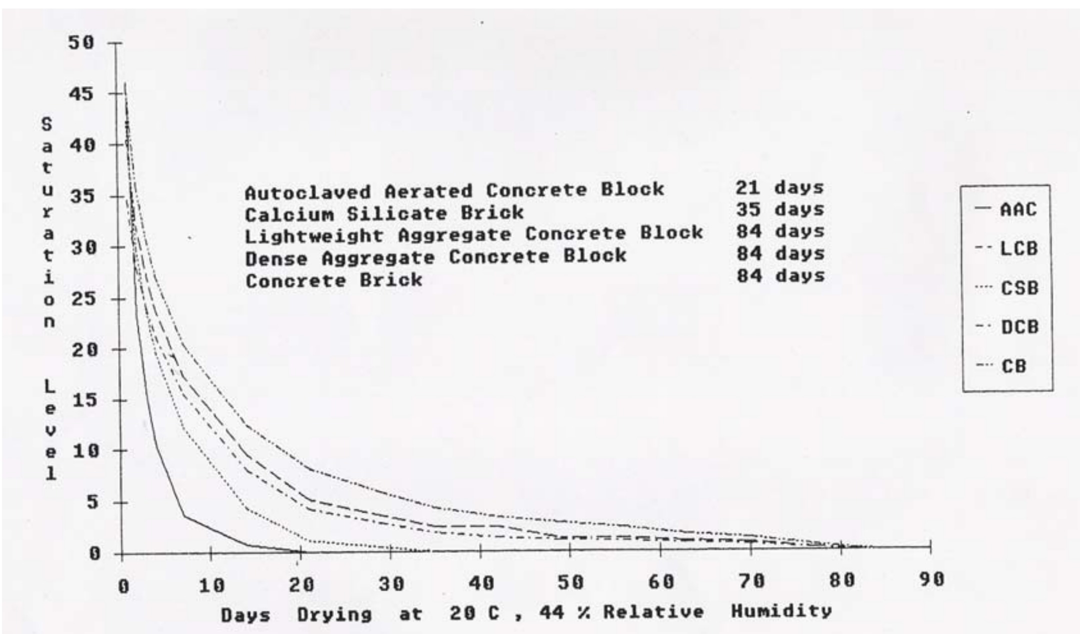

Figure 9 - Graph of Drying Times for Saturated Bricks & Blocks (H&H Celcon 2005)

10.3 *Timber and Timber Products*

Moisture in timber is present as free liquid in the cell cavities, as bound water within the cell walls and as water vapour. The flow of water through timber will only occur when the timber fibres are saturated (Illston 1994). The actual water absorption rate will vary according to the timber species. For example, the moisture absorption coefficients for pine, spruce and some typical timber products are shown in Table 11 (Kumaran 1997, Kumaran et al 2003).

Table 11 Timber Water Absorption Coefficients (Kumaran 1997, Kumaran et al 2003)

Timber Species	Transverse Water Absorption Coefficient kg.m^{-2}.s$^{-1/2}$	Longitudinal Water Absorption Coefficient kg.m^{-2}.s$^{-1/2}$
Pine	0.0040	0.0163
Spruce	-	0.0096
Plywood	0.0013 - 0.0039	-
Fibreboard	0.0021 - 0.0052	-
OSB	0.0011 - 0.0033	-

The indication from the timber frame industry is that the material used in the majority of new UK timber frame houses is European white wood. This has a relatively low moisture absorption rate and consequently should not cause any major problems with flood resilience as long as action to allow drying of the timber commences soon after the flood event (Newman 2005). This generally means removing the affected plasterboard, insulation and vapour control layer as soon as possible after the flood waters recede.

Reverse wall sheathing timber frame construction, where the structural OSB (oriented strand board) sheathing panel is positioned on the inside face of the timber frame panel, is not recommended for use in dwellings in flood risk zones as this makes it difficult to gain access to the cavity for drying purposes (Newman 2005).

It is suggested that moisture resistant grades of OSB and plywood flooring panels may be suitable as a flood resilient material, but this is dependent upon the drying process after a flood being carried out as quickly as possible to reduce any potential strength loss in the material (Newman 2005).

The drying out process is critical for timber. If too much heat is applied then this can give rise to cracking and distortion (Newman 2005).

A potential issue for treated timber immersed in water for long periods is the leaching out of the treatment chemicals into the flood water (Newman 2005). This could give rise to potential health risks from the contaminated water and would reduce the decay resistance of the timber. Effective timber treatments are a requirement for NHBC and Zurich guarantees.

Crichton (2003b) suggests that the distortion and swelling of wet timber can potentially cause damage to a building.

10.4 *Insulation*

Rigid closed cell foam insulation materials such as foamed glass, extruded polystyrene (XPS), polyurethane (PUR), polyisocyanurate (PIR) and phenolic foam have low water permeability and would be expected to be highly flood resilient. Rigid expanded polystyrene foam (EPS) differs slightly from these other rigid foams in that, due to the nature of its manufacture, it consists of fused expanded polystyrene beads, giving rise to some gaps between the beads. Generally speaking these rigid foam materials have relatively low water absorptions, typically less than 3% by volume as shown in Table 12 (Blaga 1974a & 1974b).

Table 12 - Water Absorption of Rigid Closed Cell Foam Insulation (Blaga 1974a & 1974b)

Rigid Foam Insulation Material	Typical Water Absorption (short term) % volume
Extruded Polystyrene (XPS)	<0.5 %
Expanded Polystyrene (EPS)	< 3.0 %
Polyurethane	<0.1 to 2.0 %

Crichton (2003b) notes that mineral wool and fibreglass quilt insulation below suspended floors tends to compact during a flood and it can be difficult to dry and recover. He suggests that it is possible to recover mineral wool, fibreglass and polystyrene panel insulation in cavity walls but that loose fill blown cavity wall insulation can be washed out, displaced and crushed.

10.5 *Gypsum Plaster and Gypsum Plasterboard*

Both gypsum plaster and the paper facing materials will soften when wet and regain their strength upon drying. However, repeated or prolonged exposure of gypsum to water will cause an irreversible reorientation of its crystalline structure and it will lose cohesion. Prolonged water exposure will also cause the paper to delaminate from the gypsum core of plasterboard. Water resistant grades of plasterboard are available that contain fibres and polymeric additives (USG 2005). These materials may be more flood tolerant than standard plasterboard.

10.6 *Lime Mortars & Renders*

Old and historic buildings were often built using lime mortars and renders. Lime has many advantages over Portland cement in terms of flood resilience. Lime plasters allow more water vapour transmission through the walls, which aids the drying process (Johnson 2004). Lime plaster can be used sacrificially in the repair process by acting like a poultice to draw out damaging salts from masonry, and can be replaced from time to time to maintain this process (Johnson 2004). Lime mortar will allow cyclical movement of a building without any major cracking (Scott 2005).

A potential concern relating to the use of lime mortars in conjunction with modern materials and processes is that there may be compatibility issues and possible long term durability problems.

10.7 *Test Methods*

The American National Evaluation Service test protocol as outlined in section 7.1 (NES 2004) is being developed to assess the flood resistance of building elements and materials to show compliance with the flood resistance requirements of the International Building Code (ICC 2000a). These codes are often incorporated into local building codes by local authorities in the United States to comply with the needs of NFIP (ICC 2000b).

A range of British and European standard test methods are available for the determination water absorption, water permeability and moisture resistance of the major categories of building materials. Relevant examples of these are listed in Appendix 3.

11. Water & Flood Resistance Properties of Construction Elements

The performance of assemblies of components, making up whole elements, is at least as important to the flood resilience of buildings as the performance of the materials that make up the components.

Black and Evans (1999) conducted a study of loss adjuster files of around 4000 claims records for major UK flood events from the 1990’s. Their statistical analysis of the data could find no significant difference in the distribution of flood losses between buildings constructed from different construction materials. The analysis showed that losses increased as flood depth increased and that further variation was likely due to factors such as duration of flood, velocity effects, contamination and the building construction materials. However, Black and Evans conclude that the historic claims records do not contain enough detail to make any conclusions on the difference in flood performance between different construction materials and construction types.

Traditional forms of construction of buildings near coasts and rivers that are exposed to some risk of flooding generally have evolved to have some degree of flood resilience. Wordsworth and Bithell (2004) note that many of these old buildings have floors made of stone slabs or concrete laid to falls to facilitate quick and easy drainage and cleaning. Walls are built in stone or well fired clay brick, with thin mortar joints to minimise damage and speed the drying out process. Furniture and floor coverings are designed to be easily removable. Materials such as particleboard that are readily damaged by water are avoided.

11.1 *Brick & Masonry Walls*

Relatively minor changes in construction methods of brick walls can have an impact on their performance in terms of permeability. For example, when using brick with frogs (indentation on one face of brick), then the brick can be laid with the frog either facing up or down. The general advice is to lay them “frog up” and to ensure that the frog is completely filled with mortar (BDA 1989b). If the bricks are laid “frog down” then this will make it more difficult to fill the frogs with mortar, and consequently would most likely make a wall constructed in this way more permeable than one constructed with the frogs facing up.

High quality workmanship in general and the complete filling of mortar beds is critical if brick masonry walls are to attain the maximum water resistance (BIA 2002, BIA 2004).

Kelman and Spence (2003a) have calculated that, for static flood water, the flood depth differential when many unreinforced masonry walls would suffer structural failure is of the order 1.0 to 1.5 metres. When the hydrodynamic forces of typical flood velocities are taken into account, this differential can be as low as 0.5m. They suggest that masonry walls should not be sealed above 0.9 to 1.0 metres.

Crichton (2003b) says that a clear cavity wall will dry faster than a solid wall. This would be due to the difference in thickness. A cavity wall with insulation takes the longest time to dry out. The insulation materials can also exhibit capillary action, and draw the flood water up into the cavity.

11.2 *Concrete Floors*

Crichton (2003b) notes that floating floors where a concrete screed is laid over polystyrene or polyurethane insulation can cause drying problems after a flood. The flood water can get trapped in the insulation layer and can only be removed by either removing the concrete layer or by using high pressure suction pumps in conjunction with injection of air under high pressure. It is also noted by Crichton that access may be required to gaps below solid floors so that contaminated silt and sewerage can be removed.

11.3 *Suspended Timber Floors*

It is suggested by Crichton (2003b) that suspended floors would be less vulnerable to shallow flooding due to the fact that suspended floor levels are generally around 200mm higher than solid floors. Crichton also suggests that joists built into walls are more vulnerable to flood damage that joist that are supported on metal joist hangers.

11.4 *Insulating Concrete Formwork (ICF)*

According to literature published by the ICFA (2003), buildings constructed using insulating concrete formwork (ICF) are more resistant to water ingress during a flood and suffer much less damage than other types of construction. There is no scientific data to support these claims although there are some US case-studies that suggest ICF homes are more resilient than framed houses (Sumrall 2002), although these studies are not described in any detail.

11.5 *Other Forms of Construction*

11.5.1 Modular Volumetric Buildings

There is no data in the literature on the flooding performance of volumetric modular construction. A case study identified during discussions with a major volumetric manufacturer in the UK indicates that such systems may exhibit some flood resilience (King 2005). In this example, a modular volumetric retail unit constructed from a light steel frame and structural insulated wall panels was flooded to a depth of 6 feet for three days. Although the flood water found its way into the building, the building was structurally sound and could have been fully reusable with cleaning and decontamination (with the exception of the MDF furniture which was irrecoverable). However, the main advantage of the modular system in this case was the fact that the retailer was able to have all the flooded modular units removed from the site soon after the flood waters had receded and replaced with identical new ones sourced from the modular manufacturer. This enabled the retailer to resume business one week after the flood. The flooded units could then have been refurbished off-site at the factory if deemed practical and cost-effective.

11.5.2 Floating Buildings

Several designs exist for floating flood resistant buildings. Project X Solutions in Australia (Project X Solutions 2005) have designed a floating flood resistant dwelling called the Ark House. In a flood situation, the house rises up on guides connected to supporting steel columns. Service connections such as power, water and sewerage are designed to accommodate this movement by either disconnecting or extending. Several US patents exist for other floating house designs such as that proposed by Carlinsky & Ackley (1996).

In the Netherlands, a housing scheme of several dozen floating houses is currently under development by Dura Vermeer (Deutsch 2004). These houses are of mostly timber construction with a hollow concrete base. There are no normal foundations, the building instead resting directly on the prepared ground and connected to 15 foot mooring posts with sliding rings and flexible service connections. In a flood, the dwellings will float. A picture of these dwellings being constructed is shown in Figure 10.

Figure 10 - Floating Homes Being Constructed in the Netherlands (Deutsch 2004)

A research team at Bristol University have designed a floating dwelling based on a column and ring support system (Han et al 2002). The design is for a 2-storey dwelling, with the lower third a reinforced waterproof concrete caisson they term a "casco". The upper part of the house is timber framed to reduce weight. Under normal conditions the house rests slightly below ground level in a foundation base consisting of a slab and lateral walls to which are connected the restraining columns. In flood conditions the house floats when the water level exceed 0.7 metres, and is connected to the columns by sliding rings. A schematic of the design is shown in Figure 10.

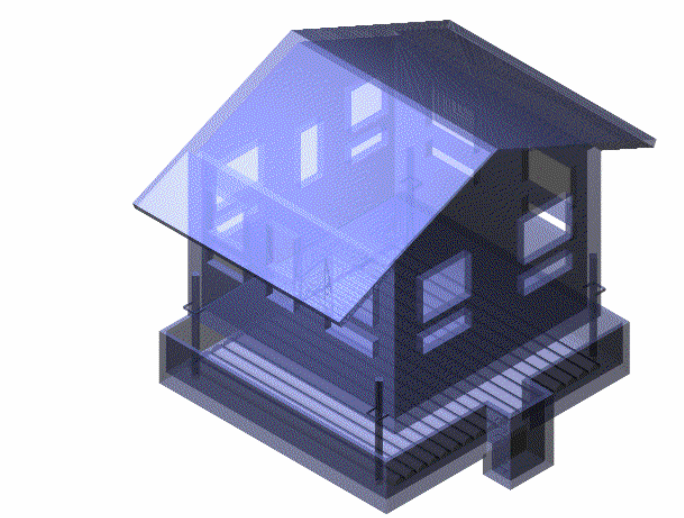

Figure 11 - Floating House Design (Han et al 2002)

Although there are several examples of 'floating houses' throughout the world, this is a novel concept in the UK.

11.5.3 Historic Buildings

The construction materials and methods used in old and historic buildings can vary enormously and can have significantly different behaviour to modern construction techniques. Some historic construction methods such as cob walls, clay lump walls and chalk blocks are very vulnerable to flood damage (Hutton & Marsh 2002).

11.5.4 Current Developments in Building Practice

There is some anecdotal evidence within the construction industry (Sovereign Homes 2005) of attempts to design buildings with raised ground floor threshold levels, with allowance in the foundations for flood conveyance beneath buildings.

11.6 *Commercial Flood Barriers*

A scheme for testing the performance of flood protection barrier products, such as door boards and air brick covers, has been developed by HR Wallingford in association with the Environment Agency and DTI. Suitable products that pass standard tests for performance criteria are awarded a BSI 'Kitemark' certification licence.

12. Discussion & Conclusions

It is apparent from the scope of the work identified in this literature survey that there is general agreement on the factors and techniques that need to be considered for flood resistant and flood resilient building design. However, as Proverbs et al (2000) point out, much of the theory and reasoning supporting this work is based on overgeneralisations, extrapolation of known behaviour and ad-hoc principles. The advice is in the main based on experience and a common sense approach, but there is a clear lack of scientific experimental data and analysis of case studies of flooded buildings underpinning the recommendations. Clearly, a more detailed assessment of how buildings interact with flood water is required, that takes into account all the variables of flooding for the wide range of construction methods and materials. The opportunity therefore exists to fill this gap in knowledge with a more rigorous and scientific study of flood resilience and flood resistance. The authorities in the United States have acknowledged the lack of data on flood resilience and have already begun research programmes to address the issues involved. The research that is being conducted on flood resilience is concentrating on the performance of domestic buildings.

The main purpose of the building regulations is to minimise any detrimental effects on the health and safety of individuals living, working in or around buildings. Development of regulations for flood resilience should therefore focus on those areas that are important for health and safety.

Whether a building is designed to be flood resistant or flood resilient, it will always requires some level of human intervention from the builder owner/occupant both before and after a flood event for the flood protection measures to be fully effective. It is partly for this reason, that flood regulations in other countries such as the US do not allow dry-floodproofing methods for new construction on a flood plain.

Human intervention may include the following activities:

- Before a Flood - For flood resistant construction it will be necessary to ensure that flood barriers, flood gates, vent covers, and protective membranes are in place. For flood resilient construction it may be necessary to open up flood drains and flood vents to allow water to enter and exit the property. Whether these measures can be implemented will depend upon the amount of flood warning given and indeed if the building owners are present at the time.
- During a flood - This may include for example manual operation of water pumps or deliberate flooding of lower levels.
- After a Flood - Immediate action after flood waters have receded might include removal of flood damaged materials, sacrificial materials and opening of windows to aid drying. It may be advantageous to do this before receiving advice from loss adjusters or damage repair consultants as the evidence from the literature suggests that time delays in this crucial period can have a significant influence on the success or otherwise of flood resilience strategies. A flood defence manual for every building in a flood risk zone that describes the actions that need to be taken in a flood situation would be useful. This could become an integral part of building regulations guidance similar to the Part L energy log book.
- Maintenance Issues - Flood protection systems will need to be maintained on a regular basis so that they will work as designed on the relatively rare occasions when needed. Householders and building owners can become complacent if unaffected by flooding for long periods of time and may neglect to carry out these vital maintenance tasks.

12.1 *Hierarchy of Flood Resilient/Resistant Design for Buildings*

Once the decision has been made that construction in a flood risk zone is unavoidable, then there are a range of design choices that are available that reduce the risk of flood damage. The degree of risk will vary for each alternative. Based on the technologies identified during this study, a hierarchy of flood resilient/resistant design could be developed that would highlight the design choices available as well as the relative risks associated with each option. A suggested form of such a hierarchy is given in Table 13 with some comments on the indicative, relative risks associated with each option taking into account the possible effects of climate change.

Table 13 - Hierarchy of Flood Resistant/Resilient Design

Design Option	Comment on Indicative Risk Factors
Elevation on piles, columns or piers	Columns/piers might be damaged by heavy objects in the water or be affected by erosion/scour in areas of rapid floodwater flow. The columns would also need to be strong enough to resist the potential drag of flows on the columns and the building they support. Occupants will require safe access routes in floods.
Building on natural high spots	Flood risk may increase in some areas due to climate change. This means that areas currently above predicted flood levels may become affected at some point in the future.
Elevation on man-made fill	The fill must be resistant to hydrostatic and dynamic forces. Flood risk may increase in some areas due to climate change. This means that artificial fill currently above predicted flood levels may become affected at some point in the future. The fill should also be resistant to heave and subsidence as a flood happens and subsides. May reduce the flood storage capacity of the built up area.
Occupied/living areas on 1st floor and above	If water is allowed into a garage on ground floor then any vehicles in the garage could float and cause structural damage. There will be a need to provide warnings and ensure exit routes to allow people to move vehicles away from the at risk area.
Floating buildings	Reliant on water proof base structure to float. This will also need to be strong enough to resist the potential drag of flows on the base and the building they support. Occupants will require safe access routes in floods. Flexible/detachable utility connections will be needed which will require regular maintenance checks.
Dry-floodproofing - lower levels occupied	Structural performance must be capable of withstanding expected hydrostatic and hydrodynamic forces. The flood resistance performance will be dependant upon human intervention to be fully effective.
Wet-floodproofing - lower levels occupied	The time elapsed from the end of the flood and commencement of drying operation is critical. Will require some sort of early warning system so that occupiers can evacuate the buildings.

12.2 *Comments on Flood Resistant Design*

The general consensus from analysis of the literature and consultations with individuals is that the construction of flood resistant buildings with occupied ground floors would be impractical, difficult to achieve in practice and dependent upon a very high level of construction quality. The experimental work conducted in the US on flood resistance highlights the difficulties in achieving a dry-flood proofed building.

One of the main theories supporting the concept of a flood resistant building is the assumption that the characteristics of water-retaining and water-resisting structures such as dams, water towers, basements and swimming pools might also be applicable to normal buildings in flood conditions. However, such water-retaining and water-resisting systems are designed to withstand static conditions. In contrast, flooding is a dynamic process involving both wetting and drying as well as periods of static and dynamic water pressure.

It is probable that a building of monolithic construction using a material such as cast in place reinforced waterproof concrete walls and floors may offer the best opportunities for a flood resistant design. Such a design would minimise potential leakage paths at element junctions and would have to be used in combination with high level outward opening windows and high level outward opening small sized glass-free doors, preferably all with marine standard watertight seals. Service entry points would also have to be at high level. Such as building would probably not be a nice place to live or work in or be acceptable aesthetically. The difficulties in achieving a fully flood resistant building are illustrated by the examples of failed buildings described by the USACE (USACE 1998). These examples include a building with a waterproof concrete wall and marine grade doors and seals where flood water was found to have entered the building through the wall when the external flood depth was only 1ft.

Another factor to consider in terms of flood resistant construction is that it is not always possible to control what happens to a building after construction. For example, owners and occupiers of building can make changes to the building fabric, such as drilling additional service penetrations through external walls and these are not always sealed effectively. This is commonly seen when buildings are tested for airtightness after owner occupation (Johnston, Wingfield, Miles-Shenton & Bell 2004). Cracks can form in walls and floors due to the expansion and contraction of building materials in response to thermal and moisture effects, and cracks can also be caused by ground movement. Such defects could render any water barrier less effective in many cases.

12.3 *Flood Resilient Construction - Material & Design Considerations*

Single storey dwellings and basements in flood risk areas are inherently vulnerable to flood damage and also present a high risk of serious injury or loss of life in extreme floods. It is recommended that such designs be discouraged in flood risk areas. However, any restrictions on the construction of single storey dwellings could limit the availability of suitable accommodation for people with reduced mobility. Basements are considered such a risk in the United States that, where existing buildings in designated flood risk areas are being improved, then it is generally a requirement of the building regulations that these be eliminated by filling in (FEMA 1998).

Walls with cavities (either normal cavity wall construction or solid wall construction where the core is filled with loose materials) generally take longer to dry out than other forms of construction.

Some relatively simple design measures are identified in the literature as important for flood resilient construction. These could be readily incorporated into regulation subject to consultation without the need for extensive testing. Such measures could include:

a) Raising door thresholds, although any design would have to allow for disabled access to comply with Part M of the regulations.

b) Service entry points and meters (e.g. gas, electricity, water and telephone) should be located above predicted flood levels.

c) Internal service wall locations should be located above predicted flood levels, taking into account the requirements of Part M and Part P of the building regulations.

d) Windows should be located above predicted flood levels.

e) Solid external doors with no glass.

f) Glass patio doors, large windows and conservatories with large areas of glass are susceptible to damage due to hydrostatic and hydrodynamic forces and their use should be avoided in flood risk zones.

g) Anti-backflow valves for sewer and drain pipes should be fitted as standard in areas of flood risk.

h) The use of plasterboard and gypsum based materials should be avoided.

Flood protection measures such as removable flood barriers and covers that involve human intervention should be avoided for new construction.

The thickness of any external wall will have an impact on its flood resilience. Generally speaking, as the thickness of a masonry wall increases then its resistance to flood water penetration will increase due to the increased permeability path through the wall.

Consideration should be given to design features that enhance or speed up the drying process. This might include for example additional weep holes at the bottom of cavity walls to allow water to drain out. There may also be devices that could be incorporated into a design to facilitate drying.

For example, a prototype ceramic anti-damp nozzle is currently under development by a Scottish SME that could be incorporated into walls (IRC Scotland 2004).

The design for surface water drainage in the immediate vicinity of a building should be considered in conjunction with the flood resilience of the building itself. This requires a more holistic approach to the drainage design of whole developments as recommended in PPG25, TAN15 and SPP7.

12.4 *Desirable Properties of Flood Resilient and Resistant Materials*

Taking into consideration all the information gathered in this literature survey it is possible to identify some key characteristics that would contribute to the flood resistance or flood resilience of construction materials and the various different construction methods. These characteristics are listed in Tables 14 and 15. It is suggested that these properties could be ranked in order of importance and then used to help define performance criteria for the test programme. It is unlikely that one material or construction method will be able to fulfil the requirements of all the criteria.

Table 14 - Desirable Characteristics of Flood Resistant/Resilient Materials

Desirable Material Property or Characteristic	Comment
Easy to clean	
No chemical reaction with water	
Quick drying	How fast is quick?
Tolerant of accelerated drying processes	Take advice from BDMA on techniques.
Low level of water absorption	
Low rate of water absorption	This would be related to the expected flood duration and material thickness.
Minimal or no expansion when wet	
Minimal or no distortion when wet	
Resistance to cracking during drying process	
Minimal change in mechanical properties when wet	
No physical deterioration during prolonged exposure to water	
Tolerant to the action of common cleaning chemicals and disinfecting agents	
Minimal or no leaching of salts or other constituents or chemical components	This is a potential health and safety issue or could affect the durability of components. There may be an issue of leaching of timber preservatives.
If bonded to other materials, adhesion is retained when wet and after drying	
Flood resistant/resilient materials should have similar or superior long-term durability performance to standard building materials	For example, moisture resistant coatings should not result in inferior freeze-thaw properties.
Flood resistant/resilient characteristics of the building durable for the life of building	If not durable for life of the building then there must be some form of maintenance regime.
Resistant to the growth of moulds	

Table 15 - Desirable Characteristics of Flood Resistant/Resilient Construction Techniques

Desirable Property or Characteristic	Comment
Allows controlled flow of water into a building and unimpeded flow out of the building	A requirement for resilient construction.
Water flowing in is filtered to remove contaminants	
Minimal gaps and cavities in the construction where water can penetrate and collect	

Desirable Property or Characteristic	Comment
Minimal number of junctions between elements and building components	
Minimal requirement for human intervention or action before a flood	Measures such as flood barriers normally require flood warning and manual installation for them to be effective
Minimal requirement for human intervention or action during a flood	For example manual operation of pumps/vents or internal deliberate flooding with clean water.
Minimal requirement for human intervention or action after a flood	For example removal of panels or valves for drying.
Capable of withstanding hydrostatic pressures from high flood levels	Specifically a requirement for flood resistance - applies to walls, floors, windows and doors.
Flood resistant/resilient characteristics tolerant of typical construction defects	
Flood resistant/resilient characteristics tolerant of building movement due to thermal & moisture effects	
Compatible with other parts of the building regulations	Any special details must no impact negatively on other aspects of building performance such as energy efficiency, acoustics, fire performance etc.

12.5 *Building Regulations for Flood Resilience and Flood Resistance*

The main role of the building regulations in terms of flooding should be to minimise the risk to health and safety. However, the level of performance of buildings subject to flooding that gives an acceptable degree of health and safety has not yet been defined. For example, the priority may be to allow buildings to dry out more quickly and reduce repair times thus reducing the risk to the health and safety of occupants. Health and safety aspects are being addressed in Task 3 of the project.

It is important that any recommendations for flood resilience in the building regulations do not negatively impact on other aspects of the regulations such as fire performance, thermal performance and disabled access.

12.6 *Coordination with Other Flooding Projects*

Several ongoing research projects that relate to effect of flooding on buildings and the urban environment have been identified (see section 8). These projects include for example the Flows project and the ASCCUE project. It is essential to maximise collaboration between these projects where appropriate, to enable information exchange and synergy with the recommendations in the *Making Space for Water* report, and to minimise unnecessary repetition, that one organisation takes a coordination role. It is suggested that there is considerable scope for Environment Agency and/or the ODPM to assume such a role.

13. Recommendations

13.1 *Experimental Programme*

13.1.1 Test Methodology

The scarcity of existing experimental data on the flood resilience and resistance of construction materials and techniques indicates that the priority of this projects test programme should be to develop a series of baseline performance data for the most typical construction methods and materials. However, the varied nature of modern construction materials and methods means that it would be impossible to test every single form, material and combination. It is recommended that the test programme should therefore include, as a minimum, the following standard construction techniques in their most common form.

a) Brick-block cavity masonry wall with cavity insulation

b) Insulated timber frame wall

c) Insulated steel frame wall

d) Concrete wall

e) Steel frame with insulated steel cladding (mainly industrial and commercial shed style buildings).

Advice can be sought from the House Builders Federation (HBF), Construction Products Association (CPA), NHBC or some of the larger housing developers on the most typical materials and details for each method. Advice should be sought from the Metal Cladding and Roofing Manufacturers Association (MCRMA), SCI (Steel Construction Institute) and Engineered Panels in Construction (EPIC) on the most appropriate forms of steel frame construction.

The test programme should also aim to cover some of the construction variables and typical material types for each of the construction forms. Potential variables include the following:

a) The effect of different brick types and properties should be investigated, as a minimum, for brick masonry wall tests. This should include bricks with a range of water absorptions. It is suggested that these cover the water absorption ranges <5%, 10%-15% and >20%. A comparison of typical examples of engineering brick, common brick and soft hand-made brick may also be useful (advice should be sought from the Brick Development Association (BDA) on the most appropriate materials).

b) The effect of mortar thickness and mortar formulation for masonry and block walls.

c) The effect of cavity depth and size/number of wall ties.

d) The effect of brick or block shape could also be investigated. For example, walls constructed with frogged bricks, perforated bricks, cellular/multi-cellular blocks or hollow blocks may display different characteristics to solid bricks or blocks due to the potentially shorter water paths.

e) The effect of different concrete blocks for cavity masonry walls should include AAC (Aerated Autoclaved Concrete), lightweight blocks, medium density blocks and dense blocks. Thin jointed AAC construction should also be considered.

f) The effect of different insulation types - especially for brick-block and framed construction methods.

The properties and performance of hydraulic lime mortars and renders as a flood resilient material should be specifically included in the programme as they have been identified as potentially useful flood resilient materials. Advice should be sought from a hydraulic lime manufacturer as to which grades to select for test and the most appropriate application methods.

The literature survey has identified several potentially flood resilient external and internal facing materials such as waterproof cement renders and hydraulic lime mortars. Advice should be taken from manufacturers on potential candidate materials and systems that could be tested.

An important factor identified in the literature for flood resistance is how well junctions between elements perform. The test programme should therefore aim to investigate the performance of junctions.

Due to the extensive range of options and permutations, it is suggested that consideration should be given to statistically designed experiments (DOE) for suitable parts of the experimental programme. This would enable several factors to be tested at the same time and would potentially reduce the overall number of tests required. It should also be possible to develop a matrix of test options. For example, a matrix of some of the factors for brick construction that might be considered is shown in Table 16.

Table 16 - Example Test Matrix

	Brick Water Absorption		
	<5%	10%-15%	>20%
Solid Brick			
Frogged Brick			
Perforated Brick			
Thick Mortar Layer			
Thin Mortar Layer			

13.1.2 Test Parameters

The test parameters should include assessment of the effect of a range of flooding variables. These should include the following:

a) Flood depth - a range of flood depths should be considered, up to a safe maximum hydraulic loading. This might include for example the typical height of a wall up to window sill level (around 900mm). It may also be beneficial to conduct some of the tests to destruction. The ORNL tests used a standard flood depth of 2ft so it may be useful to include this flood level for direct comparison.

b) Flood duration. (The ORNL tests used a 3 day duration.)

c) Drying time. (The ORNL tests used a 28 day drying time)

d) Hydrodynamic forces have been identified in the literature as an important factor that affects flood resistance, and that has not been studied experimentally in any detail.

e) Contaminants such as oil, sewerage, silt and the effect of salt water will affect construction material performance during flooding. However, the scope of this project is limited initially to the effects of freshwater and silt laden water.

13.1.3 Measurement Parameters

Measurement parameters should include the following:

a) Overall leakage volume and rate.

b) Moisture content of materials before, during and after the test. It should be noted that surface moisture probes are unlikely to give a realistic measure of true moisture levels. Advice on moisture measurement methods should be sought from UCL who are currently developing new methods to dynamically monitor moisture levels in construction materials (Davies 2005).

c) Porosity of materials.

d) Water permeability.

e) Any movement of components or construction elements during the test.

f) Measurement of overall water content of construction components. A novel approach might be to install load cells underneath the components during the tests.

g) Visual assessment of the materials and components before and after the tests. A protocol should be developed to ensure repeatability and would need to detect any visible structural deterioration of the material or component, any colour changes and the appearance of any mould or efflorescence salts or bulk changes due to saturation.

h) Detection of chemical leachates. It is recommended that the test water used for the flooding tests be analysed for the presence of any chemical extracted from the test materials. For example, timber preservation chemicals may be leached from timber components.

13.2 *Flood Resilience Research Network*

It is recommended that some form of research network be established to coordinate and prioritise the activities of the various research groups currently working on the flood resilience of buildings. This network could be similar to the existing SUDSNET network for sustainable urban drainage systems or Floodrepair.net, with the coordination role being undertaken by the EA, ODPM or CIRIA.

13.3 *Human Dimension*

The priority of regulations for the flood resilience of buildings must remain the health and safety of individuals living and working in and around buildings. The extent of the knowledge of the effect of flooded buildings on human health is limited and needs to be further explored. More information is needed on mould growth in the high humidity conditions of flooded buildings and on the potential health effects of chemicals such as wood preservatives that may be leached from building into flood waters.

It is also apparent that the success of flood resilient or flood resistant building design will rely on some level of human intervention during any flooding event.

13.4 *Holistic Approach to Flood Defence*

It is recommended that any approach to implement regulations for the flood resilience of buildings must be considered in the context of a holistic approach that considers the inter-relationship between all aspects of flood risk management in the urban environment. Such an approach must consider the whole development rather than the level of the building, and would include such issues as the effectiveness of existing flood defences and site drainage systems, the influence of building location, orientation and density, as well as the flood resilience of the buildings themselves. Flood resilience measures on their own should not be used to permit development in areas that would otherwise be unacceptable.

13.5 *Source-Pathway-Receptor Model at Building Level*

It is suggested that a useful method of presenting the results of the experimental programme would be to develop a source-pathway-receptor model at the level of the building. A similar approach has been adopted by the EA for flood risk management.

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15. Acknowledgements

The authors wish to thank all those individuals and organizations who contributed to this report.

Appendix 1 - Databases and Search Terms

Databases

Compendex

British Standards Online

Construction Information Service

Environment Online

Metadex

ANTE

Ceramic Abstracts

Corrosion Abstracts

Engineering Materials Abstracts

Materials Business File

Mechanical Engineering Abstracts

Academic Search Elite

Architectural Publications Index

Barbour Index

Search Terms

“flooding”

“flood”

“flood resistance/flood resistant”

“flood resilience/flood resilient”

“flood protection”

“flood proof”

“flood repair”

“flood damage”

“flood design”

“water resistance/water resistant”

“water permeability”

“water absorption”

“moisture resistance”

“water uptake”

“building material durability”

“construction material durability”

Internet Based Search Engines

www.google.co.uk

www.azom.com

Appendix 2 - List of Organisations and Individuals Contacted

Organisation	Contact Name	Responded
Severn Trent Water	Margaret Burrup	Yes *
Wolverhampton University - Flood Research Group	David Proverbs	Yes *
Cambridge University – CURBE	Ilan Kelman	Yes
Building Research Establishment (BRE)	Chris Broadbent	Yes
National Flood Forum	Gill Holland	Yes
British Damage Management Association	Mike Waterfield	Yes
Oak Ridge National Laboratories (US)	Robert Wendt	Yes
Norwich Union	John Wickham	Yes
CSTB (France)	Jean-Luc Salagnac	Yes
NHBC	Neil Smith	Yes
Brick Development Association	Ali Aresteh	Yes
TRADA	Paul Newman	Yes
UK Timer Frame Association	Bryan Woodley	No
Construction Products Association	John Tebbit	Yes
Association of British Insurers (ABI)	Sebastian Catovsky	Yes
Benfield Hazard Research Centre	David Crichton	Yes
National Flood School	Chris Netherton	Yes
Flood Protection Association	Ron Whitehead	Yes
Cambridgeshire County Council	Helen Elliott	Yes
BIFM	Valerie Everitt	Yes
HBF	Ian Hornby	Yes
Kings Arms Public House, York	Mike Hartley	Yes
Bradford University	John Blanksby	Yes
Flood Hazard Research Centre	Prof Edmund Penning-Rowsell	No
Dundee University	Andrew Black	Yes
UCL	Nigel Blades/May Cassar	Yes
Floodskirt Ltd/ Woodward Associates	Glyn Woodward	Yes
H+H Celcon Ltd	Peter Hazael	Yes
Concrete Centre	-	No
Insulated Concrete Formwork Association	-	Yes
CERAM	Prof Geoff Edgell	No
Telling Lime Products Ltd	Tony Barker	Yes
Disaster Advice Ltd	Jeff Charlton	Yes
University of Manchester	Darryn McEvoy	Yes
Palmer Partnership	Geoff Pitts	Yes
Chartered Institute of Loss Adjusters	Julie Parker	Yes

* Face-to-face interviews were conducted with these individuals

Appendix 3 - Testing Standards for Water Absorption, Permeability, Flood Resistance and Moisture Resistance

BS 1881-122:1983 Testing concrete. Method for determination of water absorption

BS EN ISO 15148:2002 Hygrothermal performance of building materials and products. Determination of water absorption coefficient by partial immersion

BS EN ISO 12570:2000 Hygrothermal performance of building materials and products. Determination of moisture content by drying at elevated temperature

BS EN ISO 12572:2001 Hygrothermal performance of building materials and products. Determination of water vapour transmission properties

BS EN ISO 10545-3:1997 Ceramic tiles. Determination of water absorption, apparent porosity, apparent relative density and bulk density

BS EN 772-11:2000 Methods of test for masonry units. Determination of water absorption of aggregate concrete, manufactured stone and natural stone masonry units due to capillary action and the initial rate of water absorption of clay masonry units

BS EN 1015-18:2002 Methods of test for mortar for masonry. Determination of water absorption coefficient due to capillary action of hardened mortar

BS EN 1609:1997 Thermal insulating products for building applications. Determination of short term water absorption by partial immersion

BS EN 1925:1999 Natural stone test methods. Determination of water absorption coefficient by capillarity

BS EN 12087:1997 Thermal insulating products for building applications. Determination of long term water absorption by immersion

BS EN 12088:1997 Thermal insulating products for building applications. Determination of long term water absorption by diffusion

BS EN 13755:2002 Natural stone. Test methods. Determination of water absorption at atmospheric pressure

BS EN 1062-3:1999 Paints and varnishes. Coating materials and coating systems for exterior masonry and concrete. Determination and classification of liquid-water transmission rate (permeability)

PAS 1188-1:2003 Flood protection products. Specification. Building apertures

PAS 1188-2:2003 Flood protection products. Specification. Temporary and demountable products

PAS 1188-3:2003 Flood protection products. Specification. Building skirt systems

BS EN 13564-1:2002 Anti-flooding devices for buildings. Requirements

BS EN 13564-2:2002 Anti-flooding devices for buildings. Test methods

BS EN 13564-3:2003 Anti-flooding devices for buildings. Quality assurance

BS 7543:2003 Guide to durability of buildings and building elements, products and components

BS EN 321:2002 Wood-based panels. Determination of moisture resistance under cyclic test conditions

Appendix 4 - NFIP Flood Resistant Material Classifications

(FEMA 1993)

Material	Classification				
	Acceptable		Unacceptable		
	5	4	3	2	1
Flooring Materials					
Asphalt Tile					•
With asphaltic adhesives			•		
Carpeting (glued down type)					•
Cement/bituminous, formed-in-place		•			
Cement/latex, formed-in-place		•			
Ceramic tile					•
With acid-and alkali-resistant grout			•		
Chipboard					•
Clay tile	•				
Concrete, precast or in-situ	•				
Concrete tile	•				
Cork					•
Enamel felt-base floor coverings					•
Epoxy, formed-in-place	•				
Linoleum					•
Magnesite (magnesium oxychloride)					•
Mastic felt-base floor covering					•
Mastic flooring, formed-in-place	•				
Polyurethane, formed-in-place	•				
PVA emulsion cement					•
Rubber sheets					•
With chemical-set adhesives	•				
Rubber tile					•
With chemical-set adhesives		•			
Silicone floor, formed-in-place	•				
Terrazo		•			
Vinyl sheets (homogeneous)					•
With chemical-set adhesives	•				
Vinyl tile (homogeneous)					•
With chemical-set adhesives		•			
Vinyl tile or sheets (coated on cork or wood product backings)					•
Vinyl-asbestos tile (semi-flexible vinyl)					•
With asphaltic adhesives		•			
Wood flooring or underlay merits					•

Material	Classification				
	Acceptable		Unacceptable		
	5	4	3	2	1
Wood composition blocks, laid in cement mortar				●	
Wood composition blocks, dipped and laid in hot pitch or bitumen				●	
Pressure-treated lumber	●				
Naturally decay-resistant lumber	●				
Wall and Ceiling Materials					
Asbestos cement board and cement board	●				
Brick, face or glazed	●				
Common				●	
Built in cabinets - wood				●	
Built in cabinets - metal	●				
Cast stone (in waterproof mortar)	●				
Chipboard					●
Exterior sheathing grade				●	
Clay tile - structural glazed	●				
Clay tile - ceramic veneer wall tile (mortar set)		●			
Clay tile - ceramic veneer (organic adhesive)				●	
Concrete	●				
Concrete block	●				
Corkboard				●	
Door - hollow wood				●	
Door - lightweight panel construction				●	
Door - solid wood				●	
Door - metal hollow	●				
Door - melamine				●	
Fibreboard panel					●
Fibreboard panel asphalt coated				●	
Gypsum plasterboard				●	
Plaster				●	
Exterior plaster sheathing panel				●	
Glass sheets, tiles, panels		●			
Glass blocks	●				
Hardboard - all types				●	
Insulation - closed cell		●			
Insulation - batts, blankets					●
Metals, non ferrous (aluminium, copper, zinc)			●		
Metals, ferrous	●				
Mineral fibreboard					●
Plastic wall tile set in waterproof adhesive & grout			●		

Material	Classification				
	Acceptable		Unacceptable		
	5	4	3	2	1
Plastic wall tile set in water soluble adhesive				•	
Paint, polyester-epoxy and waterproof		•			
Paint, other types					•
Paperboard					•
Partitions, pressure treated wood	•				
Partitions, metal		•			
Partitions, fabric covered					•
Partitions, unreinforced glass		•			
Partitions, reinforced glass		•			
Partitions, gypsum block					•
Rubber mouldings and trim		•			
Steel panels with waterproof adhesive	•				
Steel panels with non-waterproof adhesive				•	
Stone, solid, artificial or panel with waterproof grout	•				
Strawboard				•	
Wood, solid standard				•	
Wood, naturally decay resistant	•				
Wood, pressure treated	•				
Plywood, marine grade or pressure treated	•				
Plywood, exterior grade				•	
Plywood, standard grade					•

Appendix 5 - Australian Classification of Flood Resistance of Construction Materials

(CCC 1999)

Component	Most Suitable	Second Preference	Third Preference	To be Avoided
Flooring and sub-floor structure.	Concrete slab-on-ground Monolithic construction. Note: Clay filling is not permitted beneath slab-on-ground construction, which could be inundated. Suspension reinforced concrete slab.	Timber floor (T&G boarding, marine plywood) full epoxy sealed, on joints.	Timber floor (T&G boarding, marine plywood with ends only epoxy sealed on joints and provision of side clearance for board swelling.	Timber floor close to ground with surrounding base. Timber flooring with ceilings or soffit linings. Timber flooring with seal on top only.
Floor covering.	Clay tile. Concrete, precast or in situ. Concrete tiles. Epoxy, formed-in-place. Mastic flooring formed-in-place. Rubber sheets with chemical-set adhesives. Silicone floors formed-in-place. Vinyl sheets with chemical- set adhesive.	Cement/bituminous formed-in-place. Cement/latex formed-in place. Rubber tiles, with chemical-set adhesive. Terrazzo. Vinyl tile with chemical-set adhesive. Vinyl-asbestos tiles asphaltic adhesives. Loose rugs. Ceramic tiles with acid and alkali-resistant grout.	Asphalt tiles with asphaltic adhesive. Loose fit nylon or acrylic carpet with closed cell rubber underlay.	Asphalt tiles (A). Carpeting, glue-down type or fixed with smooth-edge or jute felts. Ceramic tiles (A). Chipboard (particle board). Cork. Linoleum. PVA emulsion cement. Rubber sheets or tiles (A). Vinyl sheets or tiles (A). Vinyl sheets or tiles coated on cork or wood backings fibre matting (sea-grass matting).
Wall Structure (Up to the DFL.).	Solid brickwork, blockwork, reinforced, concrete or mass concrete.	Two skins of brickwork or blockwork with inspection openings.	Brick or blockwork veneer construction with inspection openings.	Inaccessible cavities. Large window openings.
Roofing structure (For situations where DFL. is above the ceiling).	Reinforced concrete construction. Galvanised metal construction.	Timber trusses with galvanised fittings.	Traditional timber roof construction.	Inaccessible flat roof construction. Ungalvanised steelwork eg. lintels, arch bay tie rods, beams etc. Unsecured roof tiles.
Doors.	Solid panel with water proof adhesives. Flush door with marine ply filled with closed cell	Flush panel or single panel with marine ply wood and water proof adhesive. T&G lined door, framed	Fly-wire doors. Standard timber frame.	Hollow core ply with PVA adhesive and honeycomb paper core.

Component	Most Suitable	Second Preference	Third Preference	To be Avoided
	foam. Painted metal construction. Aluminium or galvanised steel frame.	ledged and braced. Painted steel. Timber frame fully epoxy sealed before assembly.		
Wall and ceiling linings.	Asbestos-cement board. Brick, face or glazed in waterproof mortar. Concrete. Concrete block. Steel with waterproof applications. Stone, natural solid or veneer, waterproof grout. Glass blocks. Glass. Plastic sheeting or wall with waterproof adhesive.	Brick, common. Plastic wall tiles. Metals, non ferrous. Rubber mouldings & trim. Wood, solid or exterior grade plywood fully sealed.	Chipboard exterior grade. Hardboard exterior grade. Wood, solid (boards or trim) with allowance for swelling. Wood, plywood exterior grade. Fibrous plaster board.	Chipboard. Fibreboard panels. Mineral fibreboard. Paperboard. Plaster-board, gypsum plaster. Wall coverings (paper, burlap cloth types). Wood, standard plywood strawboard.
Insulation.	Foam or closed cell types.	Reflective insulation.	Bat or blanket types.	Open cell fibre types.
Windows.	Aluminium frame with stainless steel or brass rollers.	Epoxy sealed timber waterproof glues with stainless steel or brass fittings. Galvanised or painted steel.		Timber with PVA glues mild steel fittings.
Nails, bolts, hinges and fittings.	Brass, nylon or stainless steel. Removable pin hinges.		Mild steel.	