DESIGNING FOR DURABLE WOOD CONSTRUCTION: THE 4 DS
Designing for durable wood construction

D.G. HAZLEDEN
President, HouseWorks Building Science Inc., Vancouver, BC, Canada
P.I.MORRIS
Wood Preservation Scientist, Composites and Treated Wood Products,
Forintek Canada Corp., Vancouver, BC, Canada

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Abstract

While there are examples of ancient wood buildings which have stood the test of time, there are also examples of new buildings which have suffered deterioration problems within a few years of construction. Changes in materials, design and construction methods have been suggested as the culprits and there has been a tendency to look for a magic bullet to solve the problem. Recent work shows that a number of factors have combined to cause these problems. The solution has to be equally multifaceted. Although wood is a very versatile building material, designers need to bear in mind its biological origin when using it in construction. Moisture management is the key and, in the temperate rainforest climate of coastal British Columbia, controlling rain penetration is critical. Such control requires defense in depth which can be summarised as 4 Ds: Deflection, Drainage, Drying and Durable materials. In combination, these may provide sufficient capacity to balance the rainfall load. However, it is necessary to provide over-capacity to allow for imperfect design and construction and for aging. Durable wood construction therefore requires 4D thinking in the sense of four-dimensions: three-dimensional detailing, and the effect of time, the fourth dimension, on long-term performance.

Keywords: Durable, wood, construction, deflection, drainage, drying, durability.

1 Introduction

This paper describes an approach to defense in depth against rain penetration, particularly for multi-occupancy residential wood-frame buildings in a temperate cool wet climate. In Vancouver, there are many examples of wood frame buildings which are 60 to 80 years old with no signs of moisture problems. Europe and Japan have examples centuries old. Recently, a rash of problems with water leaks in multi-occupancy buildings in Southwestern British Columbia has raised awareness within the construction industry of the need to improve the entire process of design, construction and building operation

In 1995, Canada Mortgage and Housing Corporation (CMHC) set up the Building Envelope Research Consortium (BERC) to research technical solutions to the problem. A field survey (Morrison Hershfield 1996) confirmed that the major problem was rain penetration, rather than construction moisture, or air leakage leading to condensation. It highlighted a combination of poor, or absent, design details and poor construction practice, not poor quality materials or lack of maintenance, as the major areas of concern. Rain entered at penetrations, not through the face of the cladding. Problems occurred on buildings with vinyl and wood siding as well as stucco-clad walls, but stucco was the dominant cladding type used during this period. Stucco-clad walls did have more extensive symptoms suggesting that stucco may have impeded drying of these walls. The survey pointed to window-surrounds, saddle flashings, balconies and walkway membranes as key areas where rain was penetrating the envelope. Buildings with simpler designs performed better. They had fewer water-trapping features and fewer penetrations where errors in design and/or construction could lead to water ingress. East- and South-Facing walls had more problems than North- or West-facing walls, probably because wind-blown rain normally comes from the East and South-East in the Vancouver area. The presence and width of overhangs was correlated with fewer problems. In general, these conclusions, based on data, supported those based on observation and experience. They formed the basis for commencing the localized Best Practice Guide (BPG).

The BPG was funded by CMHC and published in basic form in the fall of 1998. It contains specific information for wood frame apartment design and construction in the coastal climate area of BC. The document is over 200 pages, contains 29 detail drawings and 6 animated computer files showing sequential application of components (Morrison Hershfield and RDH Building Engineering Ltd. 1998).

During the discussions of the BPG steering committee it became obvious that while the complex nature of the problem required a complex set of solutions, a simple set of basic principles could get the core message across to the construction industry. It was found that the basic principles for management of rain penetration could be described in terms of four words beginning with the letter D.

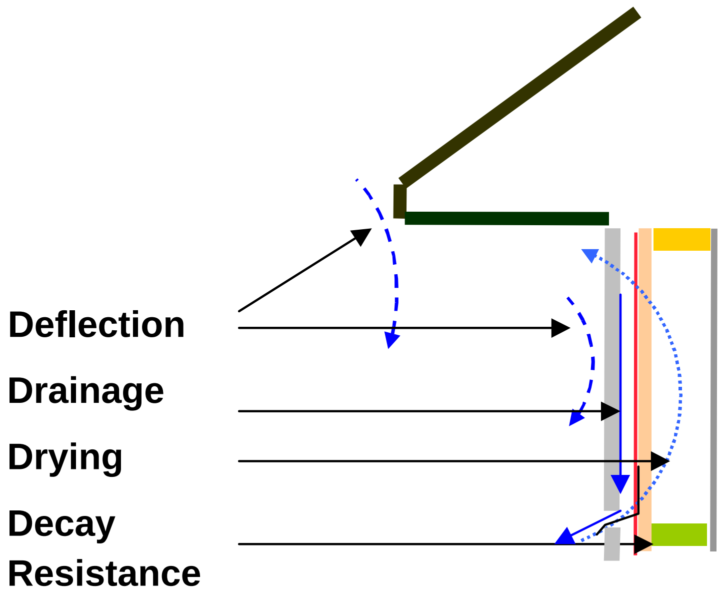

Fig. 1: The four D's of wall design

2 The Four Ds

Deflection: Wherever possible rain should be deflected so that it fails to hit the wall. Wind-blown rain that does impact the wall, should be deflected to drip away from it. Roof overhangs are the primary rain deflectors. Siding profiles and flashing are two design elements which can promote deflection at the wall surface. Pressure-equalized cavities can also be considered as deflection mechanisms since they eliminate some of the forces which can promote ingress of water through the cladding (Morrison Hershfield 1994). Deflection is the first line of defense for the wall system and this is estimated to be capable of dealing with perhaps >90% of rain incident on a building in the Vancouver area, given a properly designed deflection system. The rainfall load on the walls is then reduced to <10%. Sufficient is known about this phenomenon to design buildings to provide deflection.

Drainage: If water penetrates the cladding it should be drained out as quickly as possible. Research over the years has shown that face-sealed walls will only work in very special circumstances and therefore the majority of buildings should use a concealed barrier or drained cavity system (Morrison Hershfield 1992, 1994). Vinyl siding and wood siding over battens can provide this drainage path. There is considerable discussion as to whether drainage is possible between stucco and the building paper, using one or two layers of paper. Due to doubts as to the effectiveness of this system, the City of Vancouver has mandated a 19mm cavity using battens behind stucco. Recently, outside the City of Vancouver some construction has incorporated stucco systems using 4-8mm geomats (drainage matting) intended to provide enhanced drainage capacity. Most of the detailing which was recommended based on the Atlantic moisture studies (Canada Mortgage and Housing Corporation 1994) was of the drained-cavity type, however, all of this work was on wood or vinyl siding, rather than stucco. Nevertheless, there is a reasonable knowledge base on drainage.

A properly detailed drainage system can theoretically deal with the remaining 10% of water which might pass the outer cladding barrier. Theoretically this reduces the load to < 1% which is a reasonable target. It is highly likely that no wall construction is perfect. Liquid moisture will find a way into the wall and vapor pressure reversals will occur driving moisture into the wall, therefore a third line of defense is required.

Drying: In the event that moisture penetrates or circumvents the cladding and the moisture barrier (and to deal with initial construction moisture) walls should be designed to dry to the outside. Research by Forintek shows that the Vancouver coastal climate will allow protected and ventilated lumber to reach an equilibrium moisture content of <19% (Forintek unpublished data). Thus, wood frame drying to the exterior may be possible in this climate. However, systems of wall construction used in recent years may not provide adequate drying rates in this climate, even if the ingress of water can be minimized by proper detailing. Previous research provides analysis tools which predict that vapour migration is insufficient in itself to dry bulk moisture from walls in short periods in Vancouver (National Research Council, unpublished data). Once a piece of wood is infected with the spores of decay fungi, decay advances at a rate dependent on the temperature and moisture levels in the wood. Since temperatures in coastal BC do not fall low enough over the winter to retard fungal growth until moisture levels decline below the problem level in summer, moisture levels must be reduced relatively quickly. How quickly is a matter of some debate, but it is generally thought that if the moisture level stays in the +30% range, decay fungi may become established in as little as 3 months. A project designed to more accurately define the threshold time at a range of moisture contents and temperatures which will lead to mould and decay is underway.

Decay Resistance: This could also be termed moisture tolerance or safe storage of water. In its natural state wood has a built-in moisture tolerance. The perishable sapwood of softwoods has the ability to tolerate moisture contents up to 20% on a continuous basis without suffering biodegradation. Higher moisture contents can also be tolerated for shorter time periods (Viitanen 1997a, 1997b). The heartwood of moderately durable species, such as Douglas fir, may be able to tolerate moisture contents up to 23%. Durable wood species, such as western red cedar may be able to tolerate moisture contents up to 35%. As a result, wood systems have a higher capability than steel systems to safely store small amounts of water. A 1.2m x 4.9m (4ft x 8ft) section of wood frame wall can tolerate around 5kg water (increasing from

12 to 20% mc) without suffering from decay or mould growth. In a steel frame wall, 5kg water could be trapped as liquid in the track leading to corrosion. Where the first three Ds can not reliably maintain wood components continuously below 20% moisture content (or higher for a only few days at a time) the decay resistance of the wood must be enhanced. This is typically done via pressure preservative treatment. The type and level of treatment required will depend primarily on the severity of the moisture hazard and the types of wood-destroying organisms in the local area.

Employing these four Ds, could help those involved in design and construction to ensure the durability of wood buildings.

3 Load/capacity balance throughout the building life cycle

The development of a Best Practice for Wall Design by the BERC necessitated the consideration of the evolution of the wall from the initiation of the project by the developer through to the end of the mortgage period and eventually the end of the useful life of the building. The life of the building can be considered to comprise seven stages:

1 Initial concept and preliminary design response to market.
2 Design Development.
3 Construction Documents
4 Construction
5 Initial occupation to five years.
6 Five years to mortgage period of 25-years
7 Twenty-five years to life expectancy of 80 years.

Stages 5, 6 and 7 were separated to accommodate the different effects of aging over the short and long term. Planning for success in the functioning of the building envelope has to consider the activities impacting on the envelope at each stage in the building's life. As with structural performance, there are loads which will come into play at each stage, all working to cause the structure to fail. In the case of structural design, these are gravity loads, occupancy loads, wind loads, seismic loads, and thermal loads. All have to be accounted for and additional levels of capacity built into the design of the structure to deal with events based on their likelihood of occurrence. In the case of the building envelope design for durability in a rainforest climate, rainfall could be considered as a load impacting on moisture management performance. Additional loads include construction moisture, plumbing leaks, soil moisture, and humidity resulting from occupant activity, but these are not the subject of this paper. For the purpose of rain penetration control, the load can be considered as the total amount of water falling on a point in space annually. In the case of **Deflection**, capacity is the degree to which that rain is prevented from falling onto the wall or water on the wall is encouraged to drip away from the wall. In the case of **Drainage** and **Drying** capacity it is moisture removal in liquid and vapour form, and in the case of **Decay resistance**, it is safe storage capacity without component failure.

Each decision in the design and each trade involved in construction affects the load on, or the capacity of, the system. The load must be accommodated in the design of the envelope with sufficient capacity to prevent failure.

4 The Acknowledgement of imperfection in the design, construction and operation of walls

Failure of the building envelope can be defined as “failure to prevent build-up and retention of moisture greater than the safe storage capacity of the wall system”, or “failure to prevent ingress of water into the building interior sufficient to cause substantial damage to fixtures and fittings”.

The causes of failure are as numerous as the architectural details and the number of parties involved in the design and construction of the building exterior. It becomes a complicated task to trace all the factors. The underlying problem is easier to identify. The concept, design, construction, and operation stages of wood frame envelopes is based an assumed degree of perfection which is impossible to achieve. The reality is that all these stages of the life of the building have a probability of perfection less than 1.0 potentially contributing to failure unless this imperfection is compensated for in the original design.

The total capacity at each point is the sum of the capacities for deflection, drainage, drying and durability (Figure 2). The height of the left-hand side of the column for each stage in the life cycle represents the intended capacity as a percentage of the load. The height of the right hand side of the column at each stage indicates the effective capacity (Figure 2).

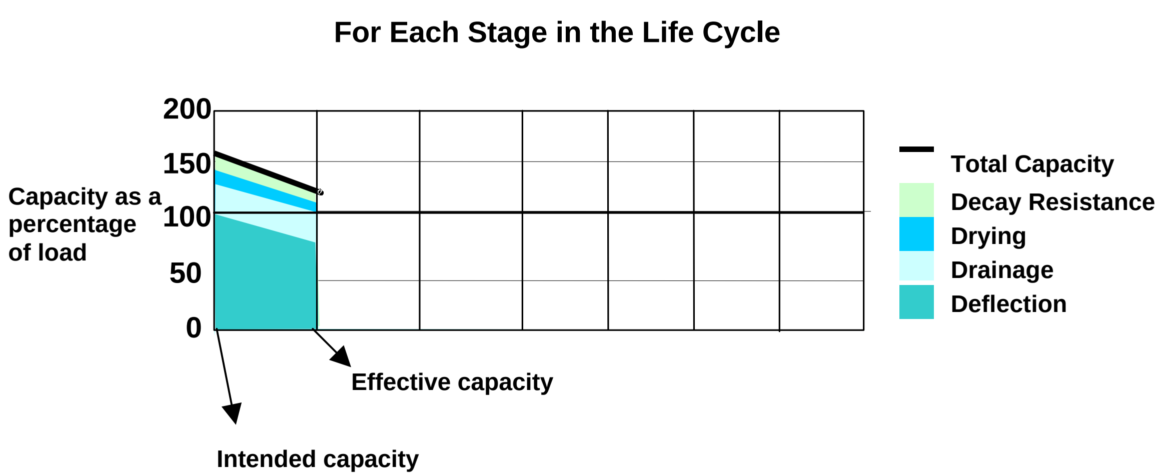

Fig. 2: Intended capacity vs effective capacity

In the case of stages 1 to 4, this takes into account the probability of perfection and the impact of less than perfect design or construction in reducing capacity. In the case of stages 3 to 7, this takes into account aging and weathering effects in reducing the capacity of moisture management systems.

5 Using load/capacity balance and probability of perfection to assist decision making throughout the life of the building

In Figures 3 to 6, the block of shading should be thought of as a series of histogram columns, one for each stage of the life cycle. The slope at the top of each column comprises, in reality, a sequence of small steps. The degree to which the capacity exceed the load in Figures 3 to 6 is merely notional and is intended for illustrative purposes only.

5.1 Stage 1: Initial concept and preliminary design response to market

The marketing strategy for the target consumer group determines or suggests a look for the project. Recently in the Vancouver Market this has been a California or Arizona look. Typically this look has complex architectural features, flat roofs, parapet walls, exterior walkways and columns, balconies for every apartment, and stucco cladding. The absence of overhangs is also typical, but this is due, in part, to Vancouver zoning bylaws which include some overhangs in the built area.

Stage 1 is a critical time in the design of the envelope. If the developer chooses a “heritage” look with generous overhangs then the loads on the wall systems will be low and the total capacity, even with a lower cost wall will be high.

Figure 3 illustrates a theoretical condition for a true heritage stucco-clad building, many of which are still performing well in Vancouver after 60 years. It has been suggested that these had a greater inherent level of deflection, drainage, drying and durability than modern buildings. These buildings certainly had far fewer water-trapping features and penetrations.

If the design is based on a no-overhang, California look, the probability of failure will be greatly elevated unless further steps are taken to add deflection at the surface of the wall. This will still be possible if the target market is high-end and can accommodate a drained cavity wall such as strapped cedar siding or brick veneer. However if it is low-end, as has been the case for most construction in the past 12 years, then a lower-cost cladding such as conventional stucco or vinyl will be chosen. The reliance is then fully on the cladding and envelope system to deflect the full load of rainfall. For conventional stucco, drainage and drying will be minimal. The overall capacity will therefore be low (Figure 4). This is the type of construction which has suffered from moisture leakage and deterioration within 5 years of completion. Most of these buildings have had the cladding removed, the decayed framing replaced with treated wood (increasing decay resistance), a vented cavity constructed (increasing drainage and drying) and flashing added or remodeled (increasing deflection). The cladding may be replaced with stucco on a more rigid paper-backed lath, or with vinyl siding. This system is intended to provide sufficient capacity to deliver the desired service life for the building (Figure 4).

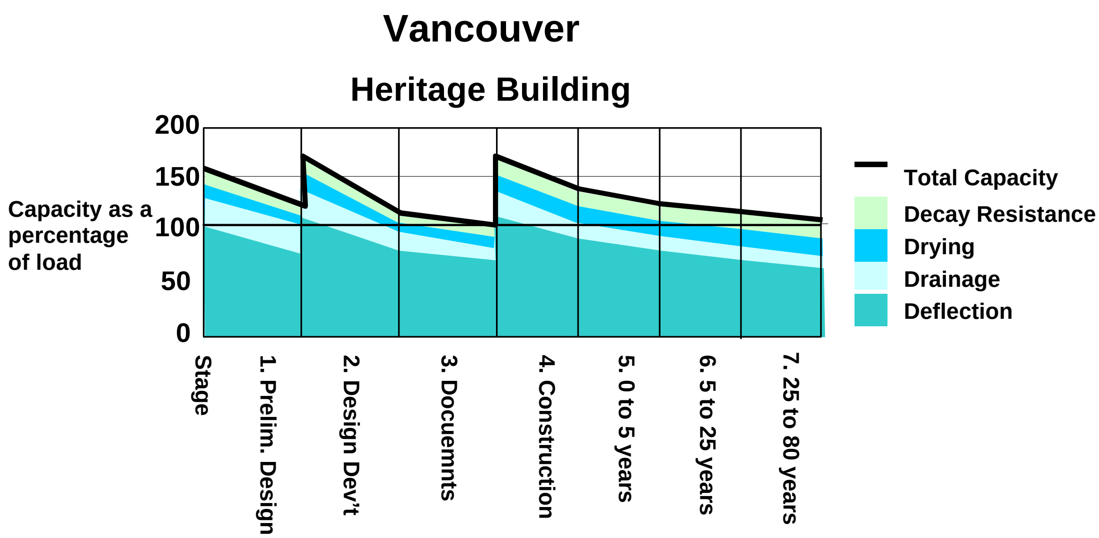

Fig. 3:Moiture load/capacity balance

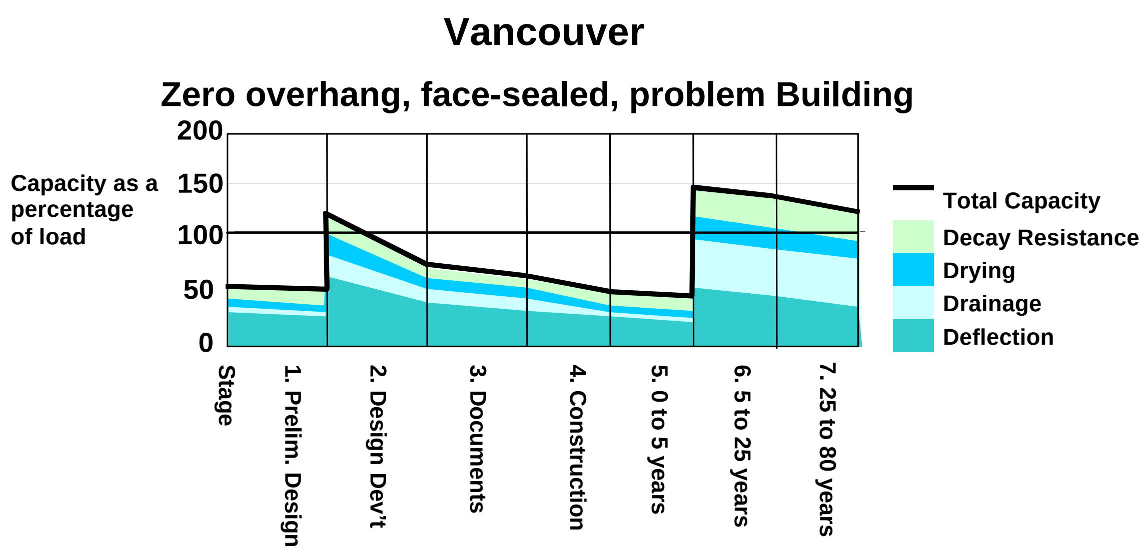

Fig. 4: Moisture load/capacity balance

In areas such as Arizona, where the rainfall is much lower, the conventional stucco building may well have provided the desired service life without such major problems and consequent repairs (Figure 5).

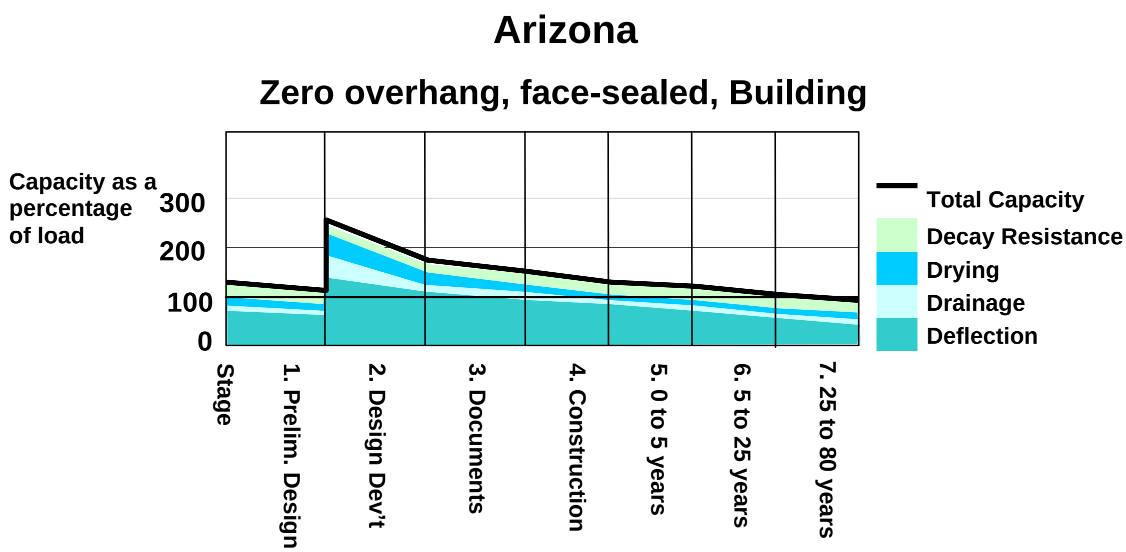

Fig. 5: Moisture load/capacity balance

5.2 Stage 2: Design development

If the California-look development is in a high end market and the design team recognizes the risks of zero deflection then they could choose to introduce a high performance cladding system, with high capacity drainage and high efficiency drying.

To illustrate how this might affect the probability of failure these factors are entered as excess moisture management capacity (Figure 6). At this stage the building has not reached the stage of working drawings and the extent and quality of the detailing is not known. Theoretically the building's load/capacity balance is greater than 100 and the likelihood of failure has been reduced to zero. Unfortunately the process does not stop here with a perfect design.

5.3 Stage 3: Construction documents

Continuing with the example of the California-look, zero overhang high-end rain-screen stucco, the design moves through the process into working drawings. At this point the design could be fully detailed and specified with all the right materials and arrangements shown on the contract documents. If this is the case the load/capacity balance does not change. If on the other hand the design is minimally documented and the specifications are not well coordinated leading to incompatible or incorrect materials choices, the design is compromised and the capacity is reduced. This is shown by a drop in capacity within the column for stage 3 in Figure 6.

The wall has lost some of the critical design intent in the drainage system and is now back into the high probability of failure category. This may seem to be pessimistic however experience in the field survey (Morrison Hershfield 1996) has shown that failure to carry through the original design intent was a common cause of failure. Incomplete, incorrect or no design details were often accompanied by poor construction.

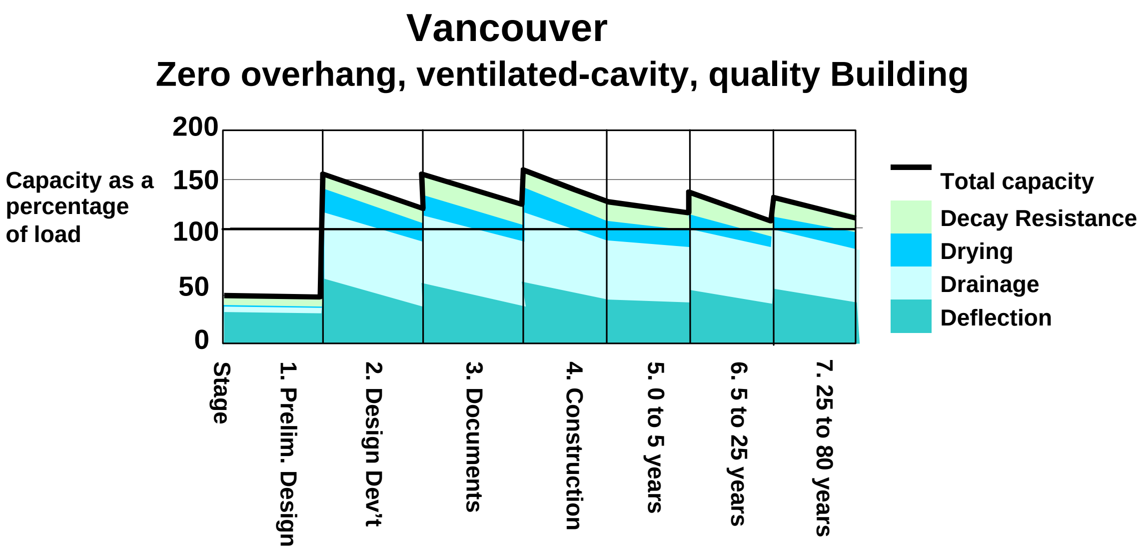

Fig. 6: Moisture load/capacity balance

5.4 Stage 4: Construction

During the construction stage the capacity of each moisture management tool may be enhanced by improvements in design introduced by a knowledgeable site superintendent or craftsman. This stage also has the potential for the greatest degree of deviation from the original design intent. The multiple nature of the trades working on the envelope and the impetus to control and cut costs during construction means that the reliability of the moisture management system is always degraded during the construction phase. This is shown as a drop in capacity for all four moisture management mechanisms in Figure 6. Obvious leaks and discontinuities in the moisture management system will often be corrected within the first 12 months of operation however the hidden moisture management system in most concealed-barrier and drained-cavity walls means that 98% of the system cannot be easily observed or repaired. In the Vancouver case low volumes of water entering the wall over a long period of time led to the demise of numerous wall systems within three to ten years. If the envelope has insufficient capacity to deal with the load, the building will likely fail within the first five years.

5.5 Stage 5: Initial occupation to five years

During the first five years, shrinkage and settlement may cause disruption of the moisture management systems. Aging and weathering of materials may lead to further reductions in capacity, for example, differential thermal properties of adjacent materials may cause cracks to open up. Deterioration of caulking may also reduce the capacity for deflection at joints between materials, indicated as a further drop in deflection capacity in Figure 6.

5.6 Stage 6: Five years to 25-year mortgage period

Planned maintenance activities at the five-year mark may restore some of the lost capacity in the deflection systems (Figure 6). It is highly unlikely that drainage, drying or decay resistance of framing members can be improved without major structural modifications. However, small-dimension exterior wood components may be remedially treated with brush-applied liquids and larger members may have soluble preservative rods inserted into drilled holes.

Aging and weathering over the 5 to 25 year period will cause further deterioration in moisture management systems, but major repairs should not be required (Figure 6).

5.7 Stage 7: Twenty-five years to life expectancy of 80 years

Between 25 and 80 years, it may be necessary to replace the cladding on a building. At that time, it may be possible to introduce additional drainage and drying capacity, if required. However, with attention to moisture management at an earlier stage this should not be necessary (Figure 6). There is also limited opportunity to provide increased decay resistance, but application of surface-applied preservatives to framing will not provide the same level of decay resistance as an initial pressure treatment.

6 Towards a mathematical model for the load/capacity balance

If the load, in terms of annual rainfall, is assumed to remain constant, the probability of success of the building envelope is a function of the excess of capacity over load. The total capacity is the sum of the capacities provided by the four moisture-management strategies: deflection, drainage, drying and decay resistance. However, since the intended capacity is typically reduced by imperfect design and construction, it is necessary to include a capacity reduction term related to the probability of perfection and the impact of imperfection. Each stage when an attempt is made to add additional capacity with each moisture management strategy will have a value for the capacity reduction term and the effective capacity will be the intended capacity multiplied by the capacity reduction term. A mathematical model based on these principles is under consideration. While such a model may well be too cumbersome for general application, it does serve to illustrate the numerous occasions where attention to detail, or the lack of it, can positively or negatively impact the success of a building envelope.

If such a model can be fully developed, the performance of the building envelope system can be predicted for the life of the building. In the design phase this becomes a heads-up warning for the designer, the owner and the builder. For the builder in the construction phase it becomes a quality tracking system for performance management of the sub-trades. In the property management phase it becomes a planning tool for the setting of maintenance schedules and the development of contingency reserves.

The objective of the BERC program is to support the development and continuous improvement of the Best Practice Guides and Quality Assurance Protocols through research into the factors which affect the moisture management strategies defined in the four D's.

7 Conclusions

Design, construction and operation of wood buildings for durability succeed through consideration of the 4 Ds of moisture management, relative to the probability of perfection and the effect of time on long-term performance of moisture management systems.

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