USEFUL LIFE OF BUILDINGS

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By

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1. THE LIFE OF BUILDINGS

Buildings are a part of the built environment. The built environment is constructed by humans for a variety of purposes. The life envisaged for a structure will depend on its purpose, and a broad threefold classification can be made.

1. **Monumental structures** such as churches and temples would be expected to last for even a thousand years. A Hindu temple recently constructed in North London is supposed to have a design life of 1000 years; some churches that are in use today approach that sort of age.
2. **Service structures** such as bridges and reservoirs would be expected to last for at least around 100 to 200 years.
3. **Sheltering structures** such as offices and dwellings are rarely expected to last of rover 100 years. It is such structures, also called buildings, that this report focuses on.

The following sociological, economic and cultural factors have an impact on what the useful (or service) life of buildings could be.

1. The function of the building – The changing needs of various owners, and indeed the changing face of the city or area in which the building is located, may cause a building to be obsolete even before it ceases to be serviceable. For example, an owner may wish to have a high rise building in place of a low rise one; or, the nature of the locality may change from a commercial one to a residential or leisure-related one.
2. The investment made – In the face of the above proneness to change, most investors or builders will not want to pay for a building with an excessive service life. It should be noted that service structures (which have longer useful life) are generally financed by the State.
3. Avoiding new planning regulations – Owners sometimes try to use an existing building over and above its service life, because demolition and reconstruction may force them to comply with new planning regulations, such as street reservations or even minimum heights of construction. Continuation of a structure beyond its service life will generally require significant refurbishment and repair costs.
4. Heritage considerations – Once a building exceeds a certain lifespan, the owner or even other interested parties, may with to prolong its life further, as it could be considered a national heritage. In Sri Lanka for example, no building that is over 100 years old can be demolished without the permission of the Department of Archaeology.

Aspects 1 and 2 tend to reduce the lifespans of building, while aspects 3 and 4 tend to increase them. However, only aspects 1 and 2 are applicable (i) at the start of a building and (ii) for most if not all buildings.

2. NOMINAL DESIGN LIFE

In the context of the above, the nominal design life of buildings is generally considered to be around 60 years. Note that Table 1, taken from BS 7543:1992, defines "normal life" as a minimum of 60 years, It must be emphasized that "design life" is a very imprecise entity. This is because it depends on a variety of factors, such as

(i) The quality of the original construction,
(ii) The environment in which the building is located, and
(iii) The quality and degree of maintenance carried out.

It must be appreciated that these factors can vary, not only from building to building, but even within a given building. For example, (i) The quality of the substructure, superstructure and even roof structure in a building may vary if different subcontractors were responsible for them; (ii) the environment a building is subjected to will vary from external elements to internal elements and also from seaward side to landward side (if it is near the coast); and (iii) different building elements may receive different degrees of maintenance, depending on their inspectability.

Apart from the above variability, the different materials of construction that are used in a building will give rise to different rates, of deterioration. Hence, the useful life of a building may well exceed the nominal design life of 60 years; or in some cases fall short of it. This is depicted conceptually in Figure 1. However, the assignment of actual figures to useful life will be done after a consideration of the materials used in buildings and how they deteriorate.

3. MATERIALS USED INBUIDLINGS

3.1. Common Building Materials

The most common structural materials used in buildings are given below, together with the building elements they are employed for.

1. **Reinforced concrete** – This is probably the most common structural material used in buildings over the past 50-60 years (i.e. post World War 2). Reinforced concrete is a mixture of concrete that has been reinforced with steel. Any multi-storey building will generally have suspended floors made of reinforced concrete. In addition, most foundations would be of reinforced concrete. If the building is over 2 storeys high, it would have columns and beams made of reinforced concrete as well (unless structural steel elements have been used in their place). For buildings over 5-6 stories high, where strong wing speeds would preclude the use of lightweight roofs, reinforced concrete flat roofs would be used as well.
2. **Masonry** – Masonry is used for the walls of buildings. Masonry is made of discrete units (that can be bricks or cement:sand blocks), which are bonded together with cement:sand mortar. If a building does not exceed two storeys, the walls could serve as loadbearing elements, eliminating the need for reinforced concrete or steel columns, For taller buildings however, concrete or steel columns would be used, and the masonry would serve as an infill, in order to provide an external skin to and internal partitions for the building. Random rubble masonry is used in building foundations.
3. **Steel** – Apart from its use in reinforced concrete, steel beams and columns are sometimes used in multi-storey buildings, However, this is common only in buildings over around 60 years of age (i.e. pre World War 2), Today, it is more common to use reinforced concrete beams and columns. Sometimes steel beams and columns are encased in either concrete or masonry; otherwise they are left open, or perhaps hidden in wooden casements. Steel is also used in long span roof trusses.

4. **Timber** – Timber is used mainly in the roofs of buildings. In some old buildings (once again probably pre world War 2, and hence over 60 years of age), timber has been used in suspended floors.

Table 2 summarizes the locations in which the above structural materials are commonly found.

Apart from the above structural materials, common finishing materials are plasters (made of cement, sand and perhaps lime) for walls and floors, asbestos and clay tiles for roofs, ceramic tiles for floors (and bathroom walls), and glazing for the external envelope. From a durability point of view, one of the main functions of such finishing materials is to protect the main structural elements, especially from moisture.

3.2. Changes in Construction Technology

From a historical perspective, we can identify 1945 (around 60 years ago) as a point at which there was a shift in building materials usage – i.e. most structural steel used for beams and columns, and timer used for floors, was replaced with reinforced concrete. This dominance of reinforced concrete in buildings is clearly reflected in Table 2.

We can also identify a time around 1975 (around 30 years ago) as a point at which there were a more subtle changes in the quality of building materials, arguably changes for the worse, probably governed by economic considerations.

There was a worldwide change in cement manufacturing processes, resulting in cements that developed strengths quicker (by increasing the percentage of tricalcium silicate in cements). This meant that a given strength of concrete (normally tested at an age of 28 days) could be achieved with less cement. However, concretes were now made not only with lower cement contents, but also with lower percentages of the ingredient in cement (i.e. dicalcium silicate) that contributed to longer term strength development. This resulted in a lowering of the durability properties of the concrete.

There was also a worldwide and Sri Lankan scarcity of timber for construction, causing less durable species of timber to be used for construction. Although some of these species were chemically treated to improve durability, the efficiency of treatment was sometimes inadequate. Finally, the increasing demand for brick production caused it to become a cottage industry, with few regulatory controls. This too reduced the quality of bricks.

The passage of time (especially since 1975) has of course seen increasingly greater awareness of durability issues, and these have been reflected in codes of practice, especially in those for reinforced concrete. It could therefore be considered that the greater awareness of durability issues has compensated for the somewhat inferior materials.

One improvement in materials (once again we shall use 1975 as a rough date) has been in the availability of good quality waterproofing materials, performance enhancing admixtures for concrete and specialist repair materials (e.g. repair mortars). However, another detrimental factor with respect to durability stems from the more modern construction technology, where most of the structural elements are hidden behind ceilings and paneling, thus making inspection (and hence the early arresting or deterioration) more difficult. Connections between curtain walling and the main building are also difficult to inspect.

4. FACTORS AFFECTING DETERIORATION

4.1. Models for Deterioration Processes

Figures 2 and 3 constitute two models for representing the deterioration process. Both these models are particularly applicable to reinforced concrete, but have relevance for other materials as well. The predominance of reinforced concrete as a building material has been alluded to already (see Table 2). It would be pertinent at this stage to state a paradox regarding the use of this material from a durability point of view. One of the most attractive features of reinforced concrete is its durability over its design life (of around 60 years) without requiring much maintenance or repair; this is because of a fairly long and well defined incubation period (see Figure 2). On the other hand, reinforced concrete is probably the most difficult material for prolonging design life; this is because the degradation period (see Figure 2) is characterized by a positive feedback deterioration model (see Figure 3), largely because the main seat of deterioration – i.e. the corroding reinforcement – cannot be accessed or treated easily.

The incubation period in Figure 2 can be considered as one where a protection to a material is gradually eroded. In reinforced concrete, the concrete covering the steel (called the "cover" concrete) gives both physical and chemical protection to the reinforcement. Chemically, it provides an alkaline medium in which the steel is passivated. External agents such as carbon dioxide and chlorides can reduce this alkalinity, but it takes time for such depassivation to occur. Physically, the cover concrete is a moisture barrier. Other materials such as roof timber and masonry walls can be considered as being protected by roofing sheets and plaster respectively. The incubation period can then be interpreted as the time during which such protection is gradually lost.

The degradation period in Figure 2 is when the structural materials lose their strength and integrity. In reinforced concrete the degradation period is characterized by a positive feedback deterioration model (see Figure 3): cracking in the concrete due to corrosion allows easy access of deleterious agents into the concrete, causing greater corrosion and hence greater cracking. Deterioration of the concrete itself through sulphate attack also has a similar positive feedback nature. In the corrosion of structural steel, the corrosion products trap moisture, which in turn promote greater corrosion.

4.2. Causes for Deterioration

We shall list some common causes for the deterioration of building materials. Table 3 sets out a summary.

1. **Moisture** - This is by far the most common cause for deterioration. Almost all deterioration processes involve the physical transport of deleterious agents into the building materials and chemical or biological reactions that break down the integrity of the material. Moisture is required for almost all such actions. Hence, keeping building materials in a dry state will greatly reduce the rate of deterioration. In fact, conditions under which wetting and drying take place are the worst for the durability of building materials. If materials are always under water (e.g. in some foundations), deterioration can be very slow, because they will be starved of oxygen, which is another ingredient

required for degradation, whether the corrosion of steel or the biological (insect and fungal) attack on timber. Masonry is the material that is probably least affected by moisture, although continued exposure to moisture could soften it. Masonry of course traps a lot of moisture (i.e. it dried out very slowly) and this can affect timber, steel or reinforced concrete elements that are connected to masonry walls. Buildings can experience moisture from external sources (e.g. rainwater) as well as internal sources (e.g. toilet areas, leaks from pipes and condensation in air conditioning systems). Moisture in buildings can also impair electrical systems, thus compromising serviceability.

2. **Heat -** Heat will accelerate all deterioration processes. In addition, heat can cause expansion (and subsequent contraction when the heat source is absent). Such thermal movements can weaken materials with low tensile strengths such as masonry, and cause cracking. Heat (especially in combination with direct solar radiation) can also weaken some waterproofing materials, and cause them to lose their flexibility or even to crack.
3. **Settlement -** The settlement of building will also affect mainly masonry walls. In addition, if pipes are damaged during settlement, leakage of water will ensue, with the consequent potential for deterioration.
4. **Chemicals -** Only the common chemical agents will be discussed. Atmospheric carbon dioxide reduces the alkalinity of concrete and will lead to depassivation of steel reinforcement. Chlorides (the main source of which is from sea spray near the coastline) will also lead to such reduction in alkalinity, and also promote electrolytic corrosion processes in both reinforced concrete and steel. Sulphates (which are found in some groundwaters) can attack the concrete itself, causing cracking and weakening in foundations. Sulphates and chlorides can also get into concrete through impure mixing water.
5. **Biological -** Deterioration of timber is mainly a biological process. In particular, termite attack can be very damaging. If mosses are allowed to grow on damp building elements, they will trap further moisture, thus accelerating the deterioration processes associated with moisture (see above). Apart from this, if plants are allowed to take root in buildings, they can cause severe cracks, not only in masonry, but also in concrete.

5. HISTORICAL DATA ON SRI LANKA BUILDINGS

5.1. Case Studies of Building Deterioration

Table 4 gives a few cases of buildings on which condition reports have been carried out. They are listed in order of age when the inspection was made. The cases can be divided into three broad categories. The 7 and 12 year old buildings, which do not show any visible deterioration, fall into the first category.

In the next category are buildings of ages 25 to 30 years where distress of varying degree has occurred in reinforced concrete elements, due to chloride induced corrosion. The chloride source for both the Hotel Sunflower and Buddhist Girls" School is sea spray. It should be noted that the much greater corrosion in the latter is due to poor construction – see Section 2. For the Puttalam Cement Works, the chloride source was the groundwater used during construction, and for the Bandaranaike Wing (Colombo General Hospital), contamination from the toilets, This suggests that serious repair work may become necessary after around 30 years if reinforced concrete elements of a building are exposed to a chloride source.

In the last category are buildings that have survived for 65 to 100 years. It should be noted that the main structural elements are not of reinforced concrete in these buildings. The 100 year old building had masonry loadbearing walls and a large part of the floor was timber too - i.e. no steel at all in those areas. There was no exposure to chlorides either. Furthermore, remedial work was required mainly in the reinforced concrete slabs (whether floor or roof), especially in areas subject to moisture. The recommended remedial works in all these buildings involved waterproofing the reinforced concrete areas, because carbonation depths were in excess of cover, and a physical barrier to moisture was essential to slow down corrosion rates in the reinforcement.

5.2. Rate of Carbonation

As stated in Section 4, carbonation of the alkaline concrete removes the chemical protection that it affords to the reinforcement, and depassivates the steel. When the carbonation front reaches the steel reinforcement (i.e. depth of carbonation exceeds the cover), then we can consider that the incubation period is over and that the degradation period will commence (see Figure 2).

Figure 5 gives depths of carbonation with the square root of time for concrete in a dry state – the rate of carbonation in wet concrete is slower. The data is fitted fairly well with a straight line. However, it indicates that a 20 mm depth of carbonation will occur in around 20 years and a 30 mm depth in around 35 years. Most of the buildings investigated had grade 20concrete. It should be noted that most reinforced concrete slabs have covers of around 20 mm, while beams and slabs around 30 mm.

Where corrosion from carbonation alone is concerned (i.e. in the absence of a chloride source), the higher rate of carbonation for dry concrete (as depicted in Figure 5) in the incubation period will be compensated by a slower rate of corrosion (because of the absence of moisture) in the degradation period. For wet concrete, the rate of carbonation will be slower, but once the carbonation front reaches the reinforcement the corrosion will be swift.

6. ESTIMATING USEFUL LIFE

based on the considerations above, Table 5 attempts to assign useful life values for buildings having various combinations of main (structural) materials and environments. The base case is taken as reinforced concrete, because that will probably be the most common building material today. The predominance of structural steel and timber is likely to be seen only in older (pre 1945) buildings. As argued in Section 3.2, no difference need be made between newer and older buildings for estimating useful life, certainly for buildings constructed since 1945.

It must be appreciated that Table 5 is only a very rough guideline. As also stated in Section 1, a building will have different materials of differing qualities in a variety of microenvironments. Poor quality of construction could reduce useful life by up to 20 years; this would depend on the combination of material and environment.

The Table 5 values for useful life imply a reasonable level of maintenance, although a wet environment implies that the quality of maintenance has been lower than if a dry environment had been provided. Major refurbishments in each of the Table 5 categories could increase useful life by half the corresponding period of useful life per refurbishment. However, it is unlikely that useful life would be extended beyond twice the values quoted in Table 5, unless of course the building acquires a historical value that justifies large refurbishment costs.

It should also be noted that Table 4 does not give all possible combinations of materials and environments, since it is difficult to generalize. An experienced professional would need to make a judgment in such situations, based on the specific context. Although set in a U.K. context, BS 7453:1992, "Guide to Durability of buildings and building elements, products and components" can provide valuable guidance.

7. APPRAISAL OF BUILDINGS

7.1. Assessment of Durability

Appraisals of buildings can take place at various stages in their lives. A post-construction appraisal may be carried out in case there has been doubt regarding quality control tests performed in the course of construction. A mid-life appraisal could be carried out in order to ascertain the level of maintenance input required to ensure that the building reaches its design life. Appraisal can also be done at the end of design life, in order to justify demolition of the building, or indeed to consider how much refurbishment is required to extend its useful life beyond its design life. Structural appraisal, estimation of residual life and determination of remedial measures must be carried out by a qualified and experienced structural engineer. Assistance can be obtained from a comprehensive guide to appraisal published by the Institution of Structural Engineers, U.K. (1996) titled "Appraisal of existing structures, 2nd edition". Experience in the Sri Lankan context must however supplement such guides.

Appraisals can assess various properties of buildings and elements, the two most pertinent ones being strength and durability. Strength reflects the ability of a structure to carry present and future loads, while durability refers to a duration over which the structure will be serviceable. Durability is of course a time related phenomenon, and can strictly be measured only after a building has finished its useful life. In this context, historical examples of buildings performance are very valuable, such as the list in Table 4. It is largely such data that allow us to generate useful life "estimators" such as Table 5. The differentiation between different types of materials and environments is very important; they will give rise to different estimates for useful life.

7.2. Durability Indices

Another way of assessing durability is to measure properties that inhibit or promote deterioration processes. In some cases such properties can be used to predict service life. The depth of carbonation is a good example. If the depth of carbonation in a reinforced concrete element is known, established relationships such as the one in Figure 4 can be used to predict how soon the carbonation front will penetrate the cover concrete and reach the steel reinforcement, thus ending the "incubation" period (see Figure 2).

However, in practice, most of these durability indices are used to judge whether repair or refurbishment is required. It should be noted that repair can be of two forms, namely (i) strengthening or restoring the structural element and/or (ii) removing the cause of deterioration (e.g. moisture barriers, thermal insulation, ground improvement to reduce settlement etc.). Some examples of durability indices are given in Table 6; most of these refer to reinforced concrete. This is because, as stated before, reinforced concrete is the most common building material today, and also because (although if required the least maintenance) it experiences the greatest durability problems in the long term (see Section 4.1).

Apart from the above quantitative indices, visual inspections can also yield a lot of information regarding the condition of building materials. Examples of this are (i) type, extent, staining and development of cracks in reinforced concrete and masonry, (ii) extent of corrosion in structural steel and reinforcement and (iii) degree of decay in timber. In this context, if there is little or no access to the main structural elements (because of finishes and paneling etc.), judgments regarding durability will be less accurate.

8. CONCLUSIONS

Table 5 sets out rough estimates of the useful life of buildings, made of a variety of materials in different environments. These estimates range from 30 years for reinforced concrete buildings in a wet, aggressive environment to 100 years for masonry and timber buildings in a dry, non-aggressive environment. The useful life estimates in Table 5 can be extended up to a maximum of double their values, through major refurbishments. the above estimates are based in part on historical data as indicated in Table 4.

Most buildings today (and probably since 1945) are constructed of reinforced concrete. Although this material requires the least maintenance of all common building materials, prolonging its useful life beyond its notional design life of 60 years is the most difficult. Among the various causes for deterioration in buildings, moisture is the most common and harmful; keeping buildings dry will prolong their life.

Buildings can be appraised in order to obtain various indices of durability. While some of these can be used to predict service life, in practice they are used mainly to decide on remedial measures.

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Table 1 - Categories of Design Life for Buildings (from BS 7543:1992)

Category	Description	Building Life	Examples
1	Temporary	Up to 10 yrs	Site huts; temporary exhibition buildings
2	Short life	Min. 10 yrs	Temporary classrooms; warehouses
3	Medium Life	Min. 30 yrs	Industrial buildings; housing refurbishment
4	Normal life	Min. 60 yrs	Health, housing and educational buildings
5	Long life	Min. 120 yrs	Civic and high quality buildings

Table 2 - Main Structural Materials and their Common Locations in Buildings

Material	Foundation	Walls	Columns & Beams	Floors	Roof
Reinforced Concrete	✓		✓	✓	✓
Masonry	✓	✓			
Steel			✓*		✓
Timber				✓*	✓

* - usage common pre-1945

Table 3 - Causes and Mechanisms of Deterioration

Material	Moisture	Heat	Settlement	Chemicals	Biological
Reinforced Concrete	corrosion, ingress of chemicals			CO_2, chlorides, sulphates	plant roots
Masonry	softening	movement cracking	movement cracking		plant roots
Steel	corrosion			chlorides	
Timber	biological attack				termite attack

Table 4 - Some Case Studies of Building Deterioration

Building	**Year & Age (yrs)**	**Building Type**	**Deterioration**	**Recommended Remedial action**
Smart Shirts Factory, Katunayake	1998 (7)	R.C.frame*	Not apparent	None
Tourist Board Building, Colombo 4	1994 (12)	R.C.frame*	Not apparent	Little or none
Hotel Sunflower, Negombo	1999 (25)	R.C.frame*	Some corrosion (Close to coast)	Patch repairs
Buddhist Girls' School, Mt. Lavinia	2002 (c.25)	R.C.frame*	Columns and sunshades badly corroded (Close to coast;poor quality)	Columns jacketed with fresh concrete;sunshades replaced with timber ones
Puttalam Cement Works	1998 (c.28)	R.C.frame*	Some buildings badly corroded; high chloride levels	Cutting back beyond r/f and repair with specialist mortar
Bandaranaike Wing, Colombo General Hospital	1988 (30)	R.C.frame*	Severe corrosion in toilet area slabs; high chloride levels	Toilet area slabs replaced
Baur's Tenemants, Grandpass Road	2001 (65)	Steel frame; R.C. slabs and roof	R.C. roof badly corroded; also open corridor and toile slabs	Waterproofing and repair of slabs; false roof over R.C.roof
Angoda Mental hospital	1997 (72)	Steels frame, R.C. slabs	Toilet area slabs badly corroded; plant growth on walls	Waterproofing and repair of toilet and corridor slabs
Institute of Aesthetic Studies, Colombo 7	1999 (c.100)	Masonry; timber floor; R.C.roof	All reinforced concrete components corroded	Waterproofing and repair of roof; replacing some R.C. with timber

* - Reinforced concrete framed building (with reinforced concrete slabs as well)

Table 5 - Useful Life Estimator

Case	Main Material	Environment	Useful Life (years)
Base Case	Reinforced concrete	dry[3], non-aggressive	60
Variations in Material	Structural steel[1]	dry[3], non-aggressive	80
	Masonry and/or Timber[2]	dry[3], non-aggressive	100
Variations in Environment	Reinforced concrete	wet[4], non-aggressive	40
	Reinforced concrete	wet[4], aggressive[5]	30

[1] - The steel should be readily inspectable and accessible for routine maintenance

[2] - This indicates that there is sparing use of steel that is subject to corrosion

[3] - This indicates that the main materials are protected against moisture, either by coverings (e.g. roofing sheets) or coatings (e.g. plasters)

[4] - A wet environment indicates poor maintenance (e.g. leaking roofs or cracked plaster)

[5] - The most pertinent aggressive environment for any steel in buildings is a chloride environment; sulphates can also attack the concrete itself.

Note (a): Poor quality construction could reduce useful life by up to 20 years; this would depend on the combination of material and environment.

Note (b): The above values for useful life imply a reasonable level of maintenance. Major refurbishments in each of the above categories could increase useful life by half the corresponding period of useful life per refurbishment. However, it is unlikely that useful life would be extended beyond twice the values quoted above.

Note (c): The above table does not give all possible combinations of materials and environments, since it is difficult to generalize. An experienced professional would need to make a judgment in such situations, based on the specific context.

Table 6 - Durability Indices

Index	Material	Test Method	Interpretation
Depth of Carbonation	Reinforced Concrete	Spray freshly drilled/broken surface of concrete with a phenolphthalein solution; areas that remain colourless (as opposed to turning pink) have been carbonated.	If depth of carbonation is greater than cover, then incubation period is over; degradation rate can be reduced by keeping concrete dry. If depth is less than cover, Figure 4 can be used to estimate time to the end of incubation period.
Chloride Level	Reinforced concrete	Take drillings of concrete, if necessary at different depths[1], digest in nitric acid, and precipitate C1^{-} using silver nitrate.	If C1^{-}% by weight of concrete is: up to 0.05% - low risk; 0.05 to 0.15% - medium risk; above 0.15% - high risk of corrosion.
Sulphate Level	Concrete	Take drillings of concrete, if necessary at different depths[1], and perform chemical analysis to obtain SO_3 content.	If SO_3% by weight of cement is: up to 4% - satisfactory; above 4% - unsatisfactory with respect to sulphate attack.
Half Cell Potential	Reinforced Concrete	Use Half Cell Potential Meter ($Cu/CuSO_4$ or Ag/AgC1 half cell) to ascertain potential between reinforcement and surface of concrete.	If $Cu/CuSO_4$ potential is: above +5 mV - low risk; 350 mV to 5 mV - uncertain risk; below - 350 mV - high risk of corrosion.
Resitivity	Reinforced Concrete	Use 4-probe Resistivity Meter on the concrete surface (after removing any plaster), to measure concrete resistivity .	If resistivity is above 20 Ω–m – low risk; 10 Ω–m to 20 Ω–m – moderate risk; 5 Ω–m to 10 Ω–m – high risk; below 5Ω–m – very high risk of corrosion, once steel has been depassivated.
Moisture Content	Timber	Use Moisture Meter on timber surface to obtain moisture content	If moisture content is up to 20% - satisfactory; 20 to 25% - marginally acceptable; over 25% - unsatisfactory.

[1] _ Readings at different depth will indicate whether the harmful chemical entering from without, or has been incorporated within, during construction

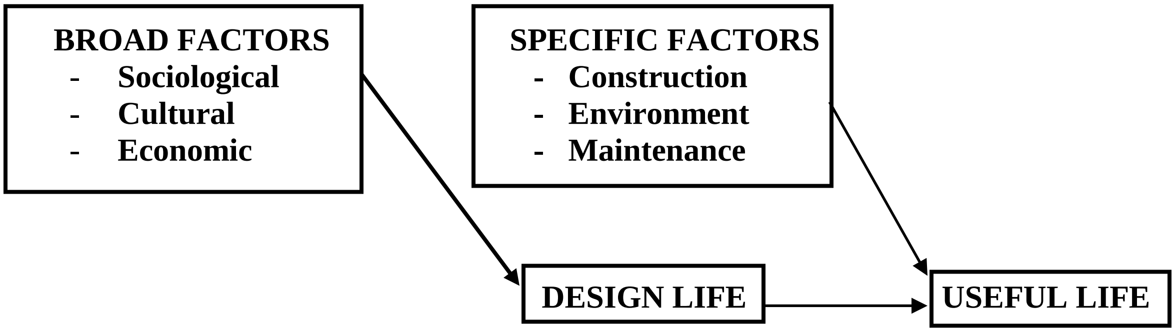

Figure 1 - Factors affecting Design Life and Useful Life of buildings

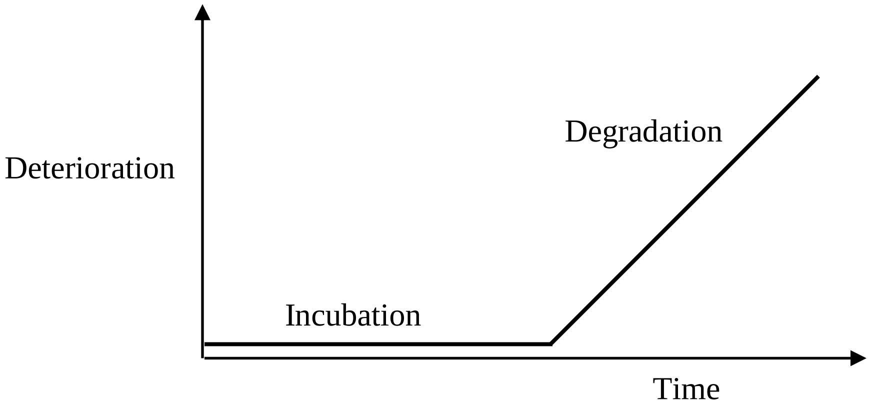

Figure 2–Two stage model of deterioration, particularly apposite for reinforced concrete

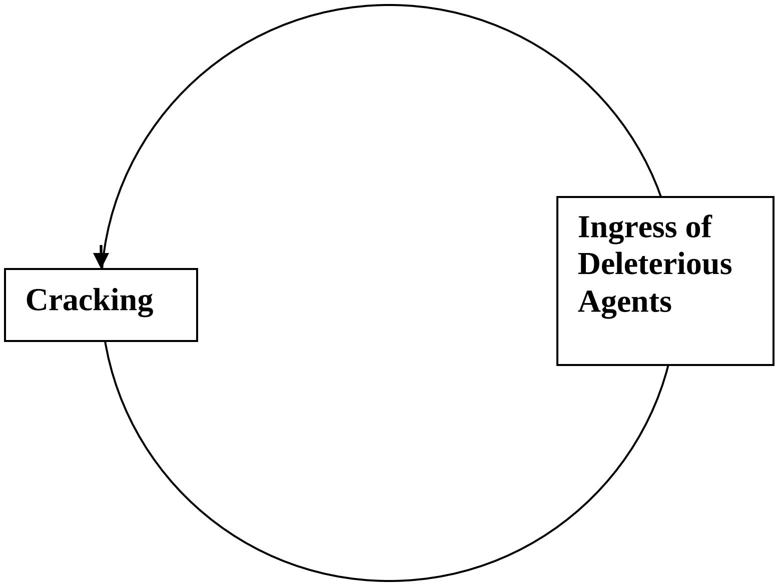

Figure 3 - Positive feedback loop for degradation of materials, e.g. reinforced concrete

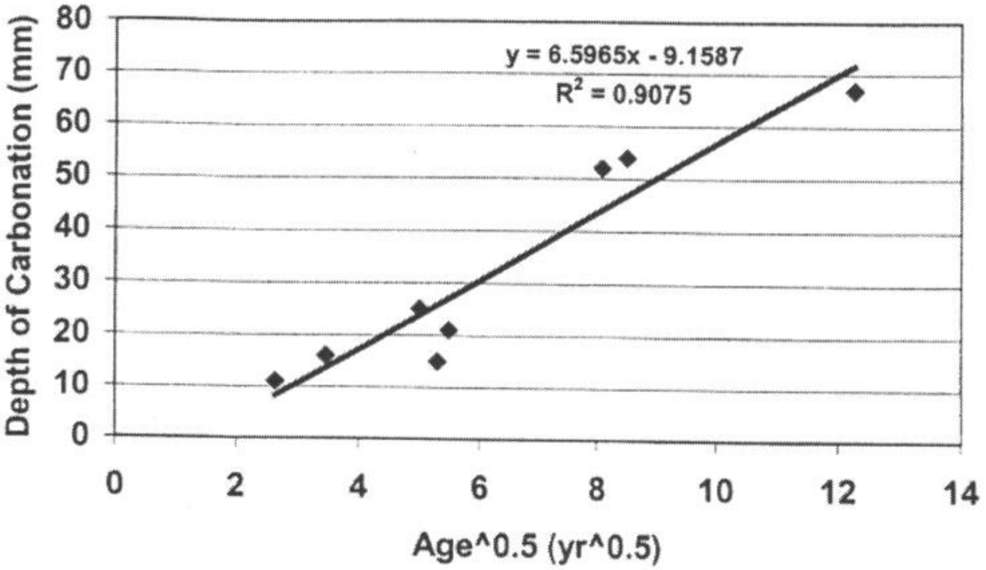

Figure 4 – Variation of depth of carbonation with square root of time