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THE DURABILITY OF BUILDINGS

By R. F. Legget[1] and N. B. Hutcheon[1]

Synopsis

The durability of buildings is a subject of timely importance in view of current changes in building types. The meaning of the term is explored. This leads to the suggestion that it is the question, "How much durability do you want in a building?" that must be faced by the designer. Correspondingly, it is demonstrated that the durability of a building is really the durability of its components. The interrelation of building components can only usefully be considered in relation to the climatic environment, interior and exterior, in which the building is to serve, and this suggests some of the limitations of testing for durability.

"The Durability of Buildings" is a challenging title. That the subject is timely will be generally admitted. The relatively sudden widespread acceptance, in North America, of curtain wall construction for a wide variety of building types, and in locations all over the continent, is in itself warrant for a critical review, at this time, of what is meant by the durability of buildings. Such a review may be expected to provide answers to some of the questions inevitably associated with the subject, of which perhaps the one most relevant to this meeting is what testing procedures, if any, can usefully be considered as an aid to the prediction of durability. The subject is one with which the authors are in almost daily contact, in their task of guiding and directing the development of building research in Canada. They therefore welcome the interest of ASTM Committee E-6 on Methods of Testing Building Constructions, in durability and the holding of this symposium which can provide a useful forum for a sharing of thinking on this complex subject.

It may be useful, at the outset, to be reminded of some of the extremes between which the more practical aspects of the durability of buildings will find context. There are, for example, buildings in the Old World that are still in use after more than two thousand years of service. On the other hand, most of the imposing structures to be seen at any of the major special Fairs or Exhibitions, which are now so well accepted a part of the international commercial scene, are designed to serve for no more than a year or two. One of the authors has a vivid recollection of visiting, about 1927, the new building for the Bank of England in the City of London, and of being told by the consulting engineer that every feature of the structure was designed to last for a thousand years. Temporary

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buildings, on the other hand, are a commonplace and especially so in time of emergency such as war. The fact that many so-called temporary buildings sometimes outlast more permanent structures merely serves to emphasize the real complexity of what is meant by the expression, the durability of buildings.

DEFINITIONS OF TERMS

Definition of terms can provide a starting point. There is little doubt as to what is meant by a building, an enclosure designed to provide protection from the elements for its contents and occupants. To define durability, however, is not so easy. Webster is not very helpful in merely suggesting that durability is the state or quality of being durable. Durable, in turn, is defined as "able to endure or continue in a particular condition; lasting; not perishable or changeable; not wearing out or decaying soon. . . ."[2] As Canadians, the authors hoped that their own standard dictionary (the Shorter Oxford) might have proved to be more useful but in this they were disappointed, "the quality of being durable" appearing again, durable being defined as "capable of continuing in existence; persistent; permanent; able to withstand change, decay or wear. . . ."[3] Although possibly suitable for ordinary philological purposes, these explanations are of little assistance when applied to buildings. They suggest that possibly the word "durability" has been borrowed from the language of every day and has been applied to technical matters in a precise way never originally intended.

There is a chapter in the British Standard Code of Practice (CP3—Chapter IX: 1950)[4] that deals with durability as one of the functional requirements of buildings. Although containing interesting information, to which later reference will be made, it does not give an exact description of its own subject, its "official" definition being "The quality of maintaining a satisfactory appearance and satisfactory performance of required functions." Use of the word "satisfactory" in this context really raises more questions than it answers.

By coincidence, a publication has appeared while this paper was in course of preparation that does attempt a broader definition of the subject now under review. This is the Report of the Committee on Building Legislation in Scotland,[5] recently submitted to the British Parliament. This unusually valuable report states that "from the point of view of the building as a whole, durability is the product of a large number of factors—the type and quality of materials chosen, the way in which they are used, the fitness of the design for the use to which the building is put, the stability of the site on which it is erected, the degree of exposure to which it is subjected and other factors. It is perhaps misleading, therefore, to treat durability as an isolated function when it is the product of many." This reflects the thinking of the authors. The quotation may therefore serve as a useful introduction to a consideration of the many factors that must be reviewed if the durability of buildings is to be a meaningful expression.

BUILDING FUNCTIONS

Any new building is conceived, designed, and constructed with a specific function in view. The intended function

[2] Webster's New International Dictionary of the English Language, 2nd Edition, Springfield, Merriam (1953).

[3] Shorter Oxford English Dictionary on Historical Principles, 3rd Edition, Clarendon Press, Oxford, England (1944).

[4] British Standard Code of Practice: CP3—Chapter IX, "Durability," British Standards Institution, London, England (1950).

[5] Report of the Committee on Building Legislation in Scotland, H. M. Stationery Office, Edinburgh, Scotland, p. 42 (1957).

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of a building may change either through functional obsolescence or because of change of ownership. All building officials know well the problems that arise from such "change of occupancy"; one of these may well be the possible effect of the change upon the ultimate durability of the structure. Since any change in function is almost always unknown and unpredictable when a building is designed, little is to be gained by extending this review of durability to include for such cases; suffice to say that the principles to be elaborated herein can and should be applied as a part of the study that must always be made before any change of the occupancy of a building is either proposed or approved.

The designer of any building must not only know exactly its intended function but must also have in view, at least to some degree, a general idea of the intended life of the structure. In many cases, this factor will have some bearing upon details of design and upon the selection of materials. When this is the case, the influence of durability upon design becomes obvious. The fact that the intended useful lives of buildings may vary widely will show that a designer must know how much durability is desired. And the more one studies the matter, the clearer does it become that the durability of buildings is essentially a relative matter and in no way an absolute. "The Service Life of Buildings" could, therefore, quite properly have been the title of this symposium since, with ordinary materials now in general use, all buildings are durable for some length of time. For how long will they be durable is the very practical question facing the owner or the user; for how long should they be durable is the rather more difficult question, the answer to which must be implicit in the designer's drawings and specifications.

SOME ECONOMIC CONSIDERATIONS

In extreme cases, when the greatest length of life possible is desired, as in the case of monuments and monumental type buildings, economic considerations will be of subsidiary importance only. But in the case of the vast majority of buildings today, economics are not only of major importance but are frequently the main determinant of design. Costs, therefore, will usually dictate desirable durability. Capital cost comes immediately to mind but real, or annual, costs are more significant. Annual costs will include the interest on the capital outlay, sinking fund payments based on an agreed period for amortization, the maintenance charges necessary in order to keep the building in its intended condition, and the sum of all operating costs including taxes, cleaning and heating (and possibly air conditioning) expense. It can be seen that each major component of the annual cost of a building will be affected by durability.

It must be pointed out that there may be some occasions when capital cost rather than annual cost can be the determinant of design. Short-sighted financial policy on the part of owners is one such possibility but one not worthy of attention at this meeting. In Great Britain today, however, the national taxation policy is such that a good case can be made for keeping the initial capital cost of British buildings low, even at the expense of higher annual costs. This is perhaps reflected in the fact that, according to figures released by the Ministry of Works for 1956, 327,000 men out of 1,186,000 employed in the British construction industry were engaged in building maintenance.[6]

Taking the more orthodox approach,

[6] "Design and Durability of Buildings," RIBA Conference Papers on Finance, *Journal*, Royal Inst. Building Administration, London Vol. 64, June, July and Aug., 1957.

however, it is usually economically desirable in building design to have the sum of the several components of annual cost be a minimum, alternative designs and the use of alternative components being compared with this in view. Ideally, the building and its equipment should realize not only this minimum annual cost, but be deteriorated to the minimum acceptable level on the day after the amortization period expires. Foolish though such a picture may seem to be, it is ideally correct. It underlines the vital importance of durability in the process of design. Such a criterion places the greatest emphasis on the evaluation of durability in the design stage. Since it is not yet possible to predict accurately the rate of deterioration under a given set of conditions, buildings are usually found to deteriorate differently in different parts. It must be recognized that different occupancies may indicate different levels of deterioration for minimum acceptability so that a building which is completely "worn out" for one type of occupancy may still be salable and acceptable for other occupancies. This factor in the changing occupancies in the hearts of cities will at once be recognized, although it is often combined with a great many other factors.

DURABILITY OF BUILDING PARTS

Modern architectural developments, in which only the structural framework of a building need be thought of as "permanent", confirm the view that durability is something which cannot be a feature of a building as a whole but is something which, even in its broadest aspects, varies for its different parts. This view is confirmed when thought is given to amortization periods. However short be the intended life of a building, the useful life of the materials used for its structural skeleton—wood, steel, or reinforced concrete, when properly protected—will not vary from the relatively long period which experience has demonstrated. The durability of buildings can, therefore, be considered only on a discrete basis. The British report to which reference has already been made[5] suggests the following as a subdivision, and lists different service lives for each item:

Foundations, structure, floors, and roof;
Internal (nonstructural) walls and partitions;
Roof covering;
Interior wall and ceiling finishes;
Exterior finishes;
Interior decoration; and
Exterior decoration.

To this list must be added, for modern buildings, the electrical and mechanical equipment necessary for the operation of the building, the useful service life and cost of maintenance of which can usually be estimated a good deal more accurately than most of the other items.

The list is suggestive only, but the necessity for some such subdivision of a building becomes clear in comparative studies of building design, just as soon as one turns to the estimation of maintenance costs. There is so wide a divergence in useful life between a well-built monolithic reinforced-concrete foundation and, say, the painted decoration applied to interior partitions, that the expression "durability of the building" ceases to have any concise meaning. It is, however, in the estimation of the maintenance measures that must be applied to ensure that all parts of the building can be maintained in an acceptable service condition at the lowest possible cost, that the skill of the designer must come into play. And it is exactly in this field that a serious lack of information will be found, a lack to which this symposium will be directing attention and which future activity on the part of ASTM Committee E-6 may help to remedy.

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Here arise some of the crucial questions as between higher initial capital costs or alternatively higher maintenance costs during the life of the building. Curtain wall construction raises these questions to an acute degree. Admitting lower capital cost as compared to earlier masonry wall construction, allowance has to be made for the annual cost of cleaning, with some allowance made for possible breakage when glass is the main curtain material. Estimates must be made of the useful life of new materials so used for external finishing, the "form of buildings" (a much neglected subject in the opinion of the authors) being an associated feature with an undoubted influence upon durability, especially of the critically important joints. When it is recalled that annual operating costs will similarly be affected by any change in exterior wall type, for example, heating and cooling costs will increase when glass is widely used, it will be clear that the judicious selection of a curtain wall design is not the straightforward and simple choice that some advertisements would have one believe.

Function, Environment, and Durability

The discussion thus far has led to the view that the durability of a building is peculiarly related to the ability of building components to maintain satisfactory performance of required functions. An examination of these functions and of the conditions under which they may have to be maintained may therefore next be made.

One of the main functions of a building is to enclose and divide space in such a way that some or all of the physical environmental conditions inside the enclosed spaces can be regulated within acceptable limits. Buildings are normally used to make possible the control of the physical environment within the enclosed spaces, but they may at times be used also to contain or control substances, organisms, or radiation which might otherwise become a nuisance or a hazard in the space outside them. Buildings are invariably required to carry the structural loads resulting from occupancy, although this function is secondary and not fundamental since these same loads might also be carried by structures, designed for this limited purpose, which would not be classed as buildings. They usually provide also a wide range of facilities for the particular activities associated with their occupancy, as well as for the production and maintenance of the desired environmental conditions.

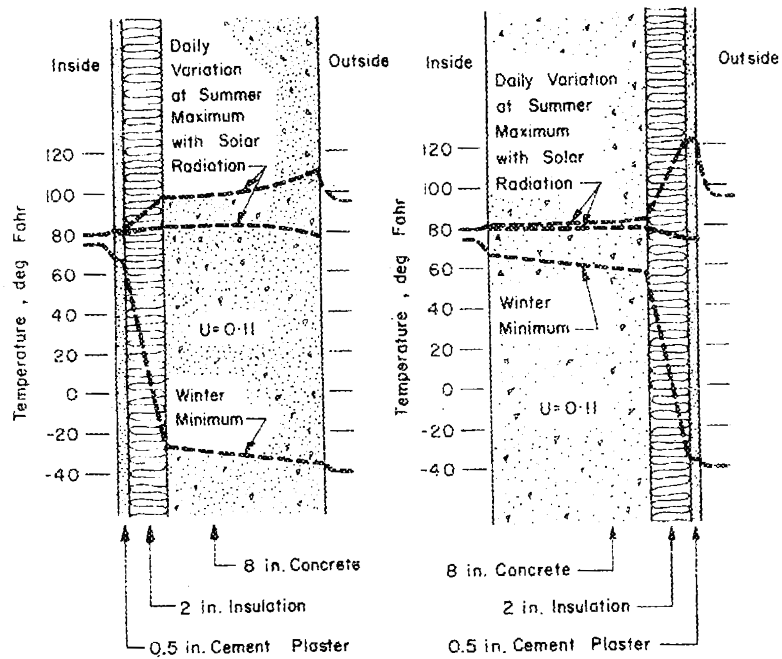
The function, or service, required of a building component in place may be related to one or more of the following properties:

1. Strength, or ability to carry load,
2. Stiffness,
3. Appearance, including surface finish and color,
4. Shape, and
5. A variety of physical and chemical properties including the ability to absorb, transmit, or restrain the passage of light, heat, vapors, gases, liquids, or particulate matter.

The durability of any component, regarding this as the quality of maintaining satisfactory performance of function, is therefore related to environmental and other factors which may have a deteriorating or degrading effect upon those properties which are essential to that function.

Environment Imposed on Components

A building is really necessary only when differences in environment are to be maintained between one space and another. In temperate climates, buildings may consist of little more than a roof to shed the rain and to provide protection from the sun; in more extreme climates much greater service may be demanded of them. Consider as extreme examples buildings in Honolulu, the equable temperature of which is such that buildings are really only shelters from the sun and the rain; and, on the other hand, buildings in northern Canada in which inside temperatures of about 70 F must be maintained with winter temperatures outside ranging to −40 or even −50 F. These indoor and outdoor environments, and particularly the differences between them, not only determine in large measure the properties which many building components must have, but they also determine the environments in which they must exist and function.



(*a*) Insulated on the inside. (*b*) Insulated on the outside.

FIG. 1.—Yearly Temperature Range Throughout a Concrete Wall for Air Temperature Range −40 to 95 F.

Even the ways in which materials are combined to form components can have a very marked effect upon the conditions to which they will be exposed. It will readily be recognized that a material used as the interior finish of an exterior wall will be exposed to the indoor environment and that, if used as the exterior covering, the conditions to which it is exposed will be more nearly those of the outside environment. In general, indoor environments will be rather closely regulated while outdoor environments will vary through rather wide limits, and they will usually be more severe insofar as degradation of materials is concerned.

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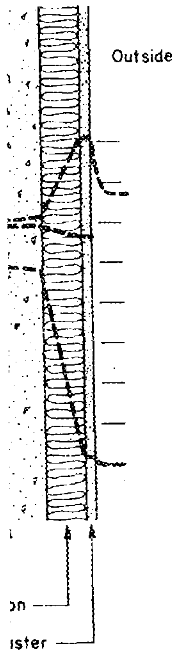

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of a material is influenced by a change in the way in which it is combined with other materials to form a building component, and this is particularly true in the case of exterior walls and roofs. The limiting temperatures throughout an insulated wall, for the extreme winter and summer conditions to be found in many parts of Canada, are shown in Figs. 1(*a*) and (*b*). The two curves shown for summer represent the range of temperature throughout a summer day. In Fig. 1(*a*) insulation is shown on the inside of the wall. The maximum range of temperature in the concrete from winter to summer is 148 F. This temperature change represents a dimensional change of $1\frac{1}{4}$ in. per 100 ft, and its equivalent in strain would correspond to a stress of 2600 psi for a concrete having a modulus of elasticity of 2.5×10^6 psi. When the insulation is placed on the outside, however, Fig. 1(*b*), the temperature change from winter to summer is greatly reduced, to about 18 F. The monolithic concrete in the case of these two walls constitutes the main structural membrane, which must not only possess strength and rigidity, but it ought also to show little tendency to expand and contract, so as to avoid "self-loading" in combination with the other main structural elements of the building. Despite this, it is frequently placed in the position in which it is exposed not only to the most severe range of temperature possible, but also to the other effects (such as wetting and drying) which result from the outdoor climate.

Even more startling differences than those shown for temperatures can be shown for moisture contents by varying the order in which materials having widely differing moisture transmission properties are placed in an exterior wall. This arises because of the phenomenon of condensation which is capable of producing severe wetting conditions within a wall even when no wetting occurs at either face. An impermeable paint film, for example, placed on the outside of a brick wall can trap water vapor flowing through the wall to the outside and cause it to be condensed, thus saturating the brick immediately behind the paint film. If frozen in this condition, the brick may be caused to spall, thus ridding itself of the offending paint film. Other examples of a similar nature could be given in connection with the positioning of vapor barrier membranes within walls. Not only is it possible to vary the "durability" which will be shown by a material by varying its location within a component, but it is also possible to change its environment and therefore the "durability" it will exhibit by rearranging or replacing other materials within the component.

DETERIORATING FACTORS

The causes of the deterioration of materials used in buildings as listed in the British Code of Practice[5] include the following:

(*a*) Atmospheric and climatic action,
(*b*) Wetting and drying effects,
(*c*) Soil and ground water action,
(*d*) Rodent, insect, bacterial, fungal and plant action,
(*e*) Water supply (effect on installations),
(*f*) Electrolytic action,
(*g*) Contact or association of incompatible materials,
(*h*) Specific chemical action or chemical changes in materials,
(*i*) Wear,
(*j*) Impact and vibration,
(*k*) Action of cleaning and cleansing agents,
(*l*) Action of domestic or industrial wastes, and
(*m*) Accidental causes, including fires lightning and floods.

Atmospheric and climatic action are further broken down as follows:

Agency	Effects
Frost	Direct damage to many porous materials exposed in a wet condition.
Changes in temperature	Expansion or shrinkage, leading to cracking.
Sunlight	Deterioration of some organic materials (for example paint, rubber, and asphalt).
Wind	Direct damage to structures. Erosive effects.
Rain	Erosive effects.
Normal atmospheric gases	Oxidation of metals (corrosion, including rushing).
Sulfur dioxide in air	Damage to building stone, metals and some types of paint.

EFFECT OF SELF-LOADING

There is one other most important deteriorating effect which, although it relates to loading and stress in a material, is frequently omitted from direct consideration in design. It may, for want of a better name, be called "self-loading", and it involves the internal loading or stressing of components or parts of components when they tend to expand or contract. As they do so, this may also impose loads and strains on related parts. Steelwork expanding with a rise in temperature may result in the stressing of attached materials until they crack. Expanding concrete may fracture adjoining brickwork. Moisture or temperature change may cause a plaster base material to expand, thus cracking the plaster. Temperature gradients through a wall may produce a tendency to warp which, if restrained by the adjacent structure, may cause cracking on the side of lower temperature. Self-loading in tension is usually more serious than in compression, frequently leading to cracking since most nonmetallic building materials are much weaker in tension than in compression.

Tendencies to expand or contract arise principally from differences and changes in temperature and in moisture content, but may be caused by a variety of other physical and chemical actions. Self-loading short of fracture may, when repeated often enough under cyclical conditions, lead to deterioration. If fracture is produced, this may prevent the material from performing its proper function, but more often makes it possible for other deteriorating effects to occur, such as those produced by water entering cracks. Self-loading, therefore, must be considered in all investigations of durability and yet it is far too frequently overlooked. Most materials exhibit tendencies to dimensional change, from one cause or another. The approach to the ideal, that is dimensional stability, must be regarded as a most important attribute for almost all materials as used in construction and one closely allied with durability.

DIMENSIONAL STABILITY OF MATERIALS

The development of means of improving the dimensional stability of materials and of developing new materials possessing this characteristic to a greater degree is an important challenge in building research. Unfortunately, all too often the new materials being offered today are less satisfactory in this regard than those which they tend to replace. There is needed, also, more knowledge of the dimensional changes that can occur in materials, along with improvements in design which, recognizing the imperfect nature of practical materials, will provide ways of minimizing the ill effects that can arise. Many of these ill effects now regarded as degradations can be reduced or eliminated by making changes in

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ASSESSMENT OF DURABILITY

Nothing that has been said has minimized in any way the importance of durability as a quality or property, nor the great need to be able to measure or to assess it. It must, however, now be clear that the durability of a building as a whole cannot usefully be measured or even assessed. The most that can be done in a practical way is to attempt to measure or assess the durability or service life of components of a building. Even this cannot be done without great difficulty. There are several major problems. The first of these is the great difficulty in fully establishing the exact conditions that will be imposed by environment and function on any given component. Unless this can be done, even the durability of the component cannot readily be evaluated. Since the conditions to be considered and the ways in which they vary in practice may make it impossible or impractical to investigate all the possibilities for deterioration, it is usually necessary, although admittedly dangerous, to select a limited number of combinations of conditions for study. This is done on the assumption, or the hope, that if the component is sufficiently durable under these limited conditions it will be sufficiently durable in actual use. Some factor of safety may be introduced by adopting assumed conditions that are believed to be somewhat more severe than those actually to be encountered.

The conditions determining the "demand" on the material having been established, another major difficulty is then encountered. The deteriorating effects of the conditions established as a basis for evaluation cannot be predicted adequately, and so it becomes necessary to resort to methods of test in which certain specified conditions are established and the deteriorating effects measured directly. This, however, is unsatisfactory since the time over which such observations ought to be made is the proposed life of the building. It becomes necessary, therefore, to adopt much more severe conditions than those to be experienced in practice in order to get accelerated effects. Establishment of the applicability of the results of accelerated testing to performance in actual use is difficult indeed. Finally, there is the staggering problem posed by the large number of combinations of individual materials and elements which go to make up building components, so that in theory almost every new combination may have to be tested.

Accelerated laboratory testing is clearly not the final answer to the problem of predicting service life, yet it may be that it will always find substantial use. There are undoubtedly many limited cases in which the establishment of a suitable set of test conditions and the application in practice of the results obtained present no real difficulty. There are other cases in which, with no suitable alternative, the admitted weaknesses of the method may have to be overlooked.

Study of the performance of components in service in actual buildings is also important. The minimum interval involved in acquiring such information is usually of the order of the service life being studied. Even when this is as short as four years, as in the case of paint films, it is still a serious limitation to direct evaluation. Despite this, almost all valid experience relating to durability has been accumulated on the basis of field experience. In the last analysis it provides the final basis for evaluating any of the more rapid means of predicting service life. Such studies must be pursued on a long-time basis, at least for those materials and constructions that are probably going to be used over a sufficiently long time to make studies worthwhile.

The ability to evaluate service life must ultimately be based on adequate knowledge of the phenomena involved in the interaction of the materials and components with one another and with the environments in which they must perform. Only in this way can the virtually infinite number of separate combinations of materials and conditions be dealt with. Methods must be found, eventually, to predict not only the conditions of service that are most likely to be imposed in any given application, but also the effects that they will produce.

CONCLUSIONS

If it serves no other purpose, this paper will at least show the complexities that surround the stated subject, the durability of buildings, a topic superficially so simple and straightforward. In view of the many complicating factors that have been mentioned, it may be useful to conclude by stating briefly the more important of the authors' considered opinions on the subject under review.

1. There is no such thing as the durability of a building, the durability of the major components of a building being inevitably different.

2. The relative durability of building components is a matter which has not received, and still does not receive, the attention which it deserves and demands from the designers of buildings.

3. Continued use of the vague and indefinite word "durability" should be avoided in discussions of building science, the term "service life" being preferable.

4. The time element involved in service life, being of the order of the life of the building, imposes great difficulties in evaluation.

5. Understanding of the phenomena involved in the interaction of a component with its service environment must be promoted for use not only in design but in establishing the methods by which deterioration of materials in service can be assessed.

6. Studies of degradation in actual buildings must be promoted, since these provide the only way of assessing the validity of accelerated laboratory testing and other methods of predicting service life, and

7. The challenge presented to ASTM in the evaluation of the service life of building components is great. Accelerated test methods must be found, but these will be much more difficult to establish than the test methods thus far developed for the determination of the physical properties of materials when judged separately, rather than in combination as building components.