On Life Expectancy of Built-Up Roofing*

R.L. Bonafont
Ruberoid Building Products

ABSTRACT

The concept of life expectancy in the context of built-up roofing is discussed. A simplified mathematical model is used to determine the characteristic fatigue endurance envelopes for selected built-up specifications. The major technical benefit afforded by the use of polyester-reinforced roofing is a marked increase in life expectancy and/or a greater tolerance to amplitude of substrate joint movements. Both life expectancy and joint movement capability contribute to the durability of the roof covering.

INTRODUCTION

Perhaps the question most frequently posed these days concerns the life expectancy of a roof covering. Basically, the inquirer seeks a simple response in the belief that the question is straightforward and can be answered. He expects the answer to be expressed as a span of time, as though time were a kind of property that could be measured in advance. The question presupposes that, after the stated period has elapsed, something happens to the roof covering to cause fitness for purpose to be irretrievably compromised, and to require some action on the part of the building owner to renew the roof covering.

The reality is much more complex than the inquirer supposes. But the question is important and merits consideration. This paper attempts to explore and discuss some aspects of the matter.

It is interesting that the word *life* is employed in the context of roof covering. The common use of the word in connection with roof coverings suggests some muted analogy with human life. This is fortunate, because by humanizing roof coverings, one may, where appropriate, borrow notions drawn from human experience itself.

LIFE SPAN

Life span is a property belonging to an individual taken from a population. It is the interval of time that separates the events of birth and death for that individual. Life expectancy is a statistical concept that emerges from the organization of life span data, a kind of average life span for the population in question.

While there is no great problem in defining the moment of birth, whether it be for human beings or roof coverings, the same cannot be said for the terminal event of death. Even in the case of human beings, this now presents a problem in light of the new-found ability to transplant organs from one body to another.

In the case of roof coverings, the definition of system death presents particular difficulties. Exactly when a roof covering is deemed to have reached the end of its useful life often rests on subjective judgment, or on accounting considerations not necessarily related to a precise physical state of disorder in the covering. Impending roof covering death can usually be delayed almost indefinitely by timely maintenance, though admittedly at some cost. The death of a roof covering is therefore much more a matter of economics than it is a specific physical manifestation.

There is premature death by misadventure and death through normal wear and tear or simple old age. A particular roof covering may be prematurely destroyed by an exceptionally severe storm or by some accident. However, the question of life expectancy is probably intended to relate more specifically to the ability to survive an aging process or, alternatively, the capacity to ensure natural deterioration as a consequence of exposure to no more than is normal and expected.

The statistical concept of life expectancy in no way ensures a fixed period that is always and inevitably reached and never exceeded for a particular individual. It is strictly a probabilistic statement saying that as many deaths are likely to occur before as are likely to occur after the quoted expectancy.

While most people will not be confused by the meaning of life expectancy as applied to human beings, the meaning will generally be less obvious when applied to roof coverings. The building owner will tend to see any statement on the life expectancy of his roof covering as something contractual, which, if not fulfilled to the letter, will justify a claim against somebody. The temptation will be for the owner, in that case, to see himself as the victim of some tort rather than of bad luck. While the building owner will accept as inevitable the everyday risks of life, he will, in all probability, dismiss the idea that uncertainty affects materials as much as it does human beings. And the law, more often than not, will support his view if tested in court. This understandable attitude on the part of the building owner therefore inhibits all but academic discussion of the subject.

Life expectancy should not be confused with the notion of a guarantee. The point is that a statement on life expectancy is necessarily wide of the mark in a small proportion of cases. Apart from anything else, such a statement could never be about a particular roof covering. At best, it would be a statement about a population of roof coverings belonging to a specified type with common features, and all exposed to some plausible, yet arbitrary, service life regimen. The spread of life spans for a given type of roofing system comes from the small variations or tolerances in dimensions and properties, and from the vagaries and vicissitudes of exposure to the elements.

Perhaps it may be said that the life span depends on two factors. In the first place, the system must be born healthy, with all parts present in their right places and fit for purpose. In the case of the roof covering, this requires the design to be sound and buildable and the workmanship to be satisfactory. In the second place, life itself must not be too unkind, without serious accidents or misadventures, so that the system may have the opportunity to pass into

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old age and thus approach the expected life span.

The design process must clearly anticipate and reasonably provide against the unlikely, yet possible, misadventure, such as the infrequent and severe windstorm. But the design must also provide for an adequate normal life span in the absence of misadventure, where the conditions of exposure are normal and in no sense exceptional. However, all design processes are probabilistic. The role of the safety factor, sometimes called the *factor of ignorance,* is to reduce risk, though it can never eliminate it altogether.

If progress is to be made with the concept of the life span of a roof covering, it is necessary to define the concept in somewhat narrow terms to simplify an otherwise complicated matter. This paper therefore restricts itself to the calculable life of a given ideal built-up roof covering. It is assumed that the design, materials and workmanship have no congenital defect at the outset. The covering is considered to be exposed to a regimen that is in no way exceptional and that the known effects of aging will have the opportunity of manifesting themselves. The service life span will end when the covering first reaches a point of general mechanical exhaustion or failure by fatigue such that fitness for purpose is compromised.

BUILT-UP ROOFING MEMBRANE

A bituminous roofing felt is essentially a prefabricated layer of reinforced bitumen. The built-up membrane consists of an assembly of two or more superimposed layers of roofing felt bedded and bonded together, usually with hot-applied bitumen, to form an impermeable composite membrane. In effect, the membrane is a sensibly flat plate or slab of reinforced bitumen, with as many layers of reinforcement as there are layers of roofing felt in its buildup.

The role of the bitumen is (1) to make the membrane impermeable and (2) to provide a means of assembly by bonding. The role of the reinforcement is (1) to enable a layer of bitumen to be preformed in a factory and conveniently installed on site, and (2) to distribute and carry the membrane stresses induced by building movements and other forms of loading applied to or generated within the membrane. The built-up roof covering is therefore a kind of load-bearing structure whose fitness for purpose depends critically upon conserving the continuity of the enveloping bitumen matrix.

Bitumen is itself inherently durable, provided it is protected from direct exposure to sunlight and not subject to mechanical attrition. Bitumen will harden progressively as a consequence of oxygen absorbed from the surrounding air and from loss of volatiles. Even so, it conserves its adhesive and waterproofing properties, as evidenced by its use from antiquity to the present day. However, a bituminous layer will not act as a waterproof barrier if fissures are permitted to develop through the total thickness of the bituminous matrix. It is known that bitumen, in common with other materials, can suffer from fatigue weakening if exposed to repeated loading or deformation cycles. It is furthermore known that the splitting of bituminous membranes is the most frequent reason for callbacks of roof coverings that are otherwise sound in design and workmanship.[1]

It therefore seems appropriate to regard the fatigue endurance of a built-up membrane as the measure of its potential long-term performance. A notional life expectancy can then be related, if only approximately, to the number of cycles that can be endured by the membrane bonded to its substrate. More particularly, the membrane is presumed to be bonded across a joint in the substrate that is assumed to open and close on a cyclic basis in concert with temperature fluctuations.

This is not to say that the mechanism of roof covering failure is invariably the outcome of fatigue. As mentioned earlier, resistance to wind effects, to slipping down steep inclined surfaces, or to concentrated loads imposed on the covering are all matters of critical importance that bear on the choice and combination of roofing materials. But failure by progressive deterioration—as opposed to failure by poor design, inadequate workmanship or simple misadventure—is most appropriately linked to fatigue endurance and therefore to life expectancy. If nothing else, notional fatigue endurance provides a useful practical basis for comparing the capacity to endure of one membrane system with that of another.

MEMBRANE MECHANICS

Much progress has been made during the past two decades in the development of mathematical models for built-up membrane systems. The reader is referred to the many papers presented at the International Symposia on Roofs and Roofing, 1974, 1977, 1981 and 1985[2] and to other workshops and conferences held at various times in the United Kingdom, the United States and France. Suffice it to say that the built-up membrane lends itself to structural analysis. Even the complicating effect of the viscoelastic bitumen behavior can be accommodated, if required. There are some data on the properties and fatigue endurance of bitumen and for the more common types of reinforcement used in bituminous roofings. The mathematical treatment of such membranes will not be dealt with here.

When the designer settles upon a specification for the built-up roof covering, he or she selects the dimensions and properties of the membrane system, represented by the symbol P in the formula below. The designer will also influence, in part, the regimen, R, to which the membrane will be exposed. For example, the life regimen of the covering will be influenced by the type of roof construction adopted, according to whether it is a warm roof, a cold roof or an inverted roof. The performance of the chosen system arises from the interplay between P and R, but for practical purposes, the two parameters may be taken to be independent.

If the chosen membrane is now considered to be fully bonded in bitumen to a substrate incorporating a joint capable of opening and closing, two extra variables are introduced. One represents the amplitude, g, of cyclical joint movement, and the other is the number of movement cycles, n, capable of being endured by the membrane at that amplitude before total failure of the bituminous waterproofing envelope occurs.

From the mathematical model for the composite membrane one can derive a relationship of the general form

$$F(g, n, P, R) = 0 \quad (a)$$

The specifier selects P and in part influences R. The exposure regimen R is governed mainly by climatic considerations over which there is little human control once the location of the building is determined. An assumption has to be made about the independent elements of R if the function F is to show an explicit relationship between g and n. For example, one might adopt for the purpose a constant temperature equal to the average annual air temperature for the locality. One might also wish to consider the endurance of membranes for a cycle time of 24 hours. This would have the benefit of pacing the system when exposed to diurnal building movement variations, which is perhaps not all that far from reality.

The mathematical model, and the associated functional relationship, a, imposes no particular restriction on R and P, but there is clearly merit in selecting the theoretical regimen conditions to be as close as possible to those that might obtain in practice. If the modeling is used for comparative purposes, then the regimen conditions are of lesser importance; indeed, it might be of special interest to run comparisons over a range of regimens. The use of computers to calculate the relationships between g and n for specified P's and selected R's takes the tedium out of the work.

PERFORMANCE ENVELOPE

By selecting the dimensions and properties of the built-up specification of interest (P), and the temperature and substrate movement regimen (R), eq a reduces to a function linking the amplitude of joint movement, g, and the number of cycles, n, required to bring the membrane to the state of incipient fatigue failure. This state is presumed, for present purposes, to terminate the useful life span of the system.

The relationship between g and n, symbolized by $f(g,n)=0$, provides a characteristic fatigue performance curve for the chosen membrane. Each membrane will have its particular curve for a given regimen.

The notional expected life can then be determined for a given amplitude, or the amplitude for a given number of cycles. If the cycle period is 24 hours, then the number of cycles may be expressed conveniently in years.

A selection of typical specifications may be compared with a datum specification by expressing the corresponding g-factor for a given n, (say, equivalent to 20 years). In general, the relative g-factors so expressed will not be independent of the standard life, n. There will be a set of g-factors for each value of n, but the ranking of specifications will not be affected.

By plotting the points (g,n) and fitting a smooth curve through these, the equation of the curve so constructed approximates to the form

$$g.n^b = K \quad (b)$$

where b ranges from about 0.25 to 0.50, depending upon the type of reinforcement used in the roofings, and K is a constant for a given fully bonded membrane system. The units are: g in millimeters and n in years.

The expression is such that a small percentage change in g results in a much greater percentage change in n. Performance expressed in terms of life, n, is more sensitive to system tolerances than is performance expressed in terms of amplitude, g. For these reasons, relative performance is more prudently expressed by relative g-factors than by relative n-factors.

Table 1 gives the calculated values for K and b for selected fully bonded built-up roofing specifications composed of roofings complying with BS 747, class 3 glass fiber base and class 5 polyester base, for which the following typical mechanical properties are used:

3B	glass fiber	maximum elongation modulus	1 percent 300 N/mm
5U	polyester	minimum elongation modulus	20 percent 150 N/mm
5B	polyester	minimum elongation modulus	20 percent 260 N/mm

The bonding compound is taken to be an oxidized bitumen, grade 105/35. Allowance for age hardening is made by increasing the softening point by some 30 percent and reducing the penetration by 50 percent; these corrections are roughly in line with expectation. The grade of bitumen for the purpose of calculation is therefore equivalent to 137/17.

The values for K and b are calculated for a cycle of 24 hours and a constant service temperature of 10 C, which corresponds to the annual average air temperature in the United Kingdom. The practical calculation procedure for determination of points on the g-n curve are given in a previous study by the author.[3]

Specification	K	b
a. Three layers of 3B fully bonded	1.15	0.42
b. Three layers—3B+5U+3B (or 3E)	2.07	0.54
c. Two layers—3B+5B (or 5E)	1.46	0.25
d. Two layers—5U+5B (or 5E)	2.16	0.24

Table 1 Values for K and b

The amplitude, g, may now be calculated more readily for a given value of n, or the number of years, n, for a given amplitude for each system. Table 2 gives the relative amplitude of the four built-up systems for life spans of 15, 20, 30 and 50 years. The amplitude of the three-layer glass fiber system for a 20-year life is arbitrarily taken as 100 for convenience. The second column of figures in brackets lists the amplitude relative to the datum specifications taken as 100 for the given number of years in each case. The ranking order is preserved, although the relative g-values depend on the assumed life span.

Specification	15 yrs.	20 yrs	30 yrs	50 yrs
a. 3B+3B+3B (datum)	113	100 (100)	85 (100)	68 (100)
b. 3B+5U+3B	143	122 (127)	98 (115)	74 (109)
c. 3B+5B	222	207 (196)	187 (220)	164 (241)
d. 5U+5B	336	314 (297)	284 (334)	251 (369)

Table 2 Relative Joint Movement Amplitude - g

The figures in Table 2 show the benefit derived from the type and combination of roofing in the membrane in terms of increased substrate movement capability and/or improved life expectancy. Calculated life spans in excess of 50 years must be treated with some caution. Even so, the data given in Table 2 are sufficient to point out the substantial improvement in performance that can be achieved with modern roofing materials. For example, by choosing specification d in preference to specification a, one may expect to increase the life span from 20 to 50 years and simultaneously augment the joint movement capability of the membrane by some 250 percent.

CONCLUSION

- By regarding the built-up roofing membrane as a flat plate of reinforced bitumen, and by applying the laws of mechanics as appropriate, a relationship between cyclic substrate movement and cyclic membrane strain can be derived. The characteristic performance of the membrane under given conditions can then be expressed by a function, $f(g,n)=0$, which relates the amplitude of substrate movement to the corresponding fatigue endurance as expressed by the number of cycles, n. For most practical purposes it will be sufficient to take the membrane as fully bonded to the supporting substrate. Allowance for partial bonding can be made and has the effect of increasing n for a given g, but the treatment of this case is beyond the scope of this paper.
- The characteristic performance of a fully bonded membrane takes the form $g.n^b=K$, where K and b depend upon the dimensions and properties of the typical membrane and also on environmental factors, such as cycle time of substrate movement and average membrane service temperature.
- There is no simple way of reducing the set of performance curves for a selection of membranes to a corresponding set of unique ranking numbers. Membranes are best ranked according to g-values for a given life span, n, such as 20 years. It should be noted that g-values are not very sensitive to tolerances in dimensions and material properties, unlike life-span values, which are highly sensitive to small variations in membrane dimensions and properties.
- A relatively modest improvement in the g-value corresponds to a substantially greater life expectancy, as judged by considerations of fatigue endurance.
- The principal benefit afforded by roof covering specifications incorporating polyester bases is a marked increase in life expectancy and/or in tolerance to substrate movement.
- The life expectancy of a membrane is increased by one or more of the following:
  - increasing the overall thickness of the membrane by adding layers and/or using thicker products
  - reducing the average shear modulus of the bitumen by using a high penetration index or suitably modified grades of bitumen
  - increasing the modulus or stiffness in traction of the reinforcing layers by increasing the number of such superimposed layers, or
  - other measures such as the use of more stable substrates to reduce amplitude of joint movement or the use of partial bonding techniques to limit the effect of substrate movement on the membrane.
- The experience in the United Kingdom over the last 15 years or so with the greatly improved built-up roof coverings fully justifies the expectations in respect to a potentially longer life. In effect, the improved coverings offer a substantially greater margin of safety and therefore a greater capacity to endure.

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