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Estimating The Service Life Of Jointing Products And Systems Application Of A Crack Growth Model To Different Climates

MA Lacasse* S M Cornick* & N Shephard†
***Institute for Research in Construction, National Research Council Canada, †Dow Corning Corporation, Midland, USA**

Summary: **Models for service life estimation of jointing systems and products are potentially useful for comparisons among the relative performance of different products in specific systems, similar comparison of products in different climates, or for helping establish requirements for maintenance and refurbishment of building envelopes. Although generic methods for developing service life estimates exist in literature, no practical and verifiable models have yet been developed for jointing products. However, notional models for products have been proposed based on damage functions related to fatigue rupture and crack growth and provide a basis for further work. This paper reports on the use of a crack growth model to assess crack development over time when subjected to different types of climates. The effects of installation temperature and relative humidity on potential crack growth in joints located in various cities are considered. Estimates of expected service life are provided in relation to specific performance criteria.**

Keywords. Climate, crack growth model, damage function, jointing systems, sealant, service life model

1 INTRODUCTION

Wolf [2000a, b] states that service life models for jointing products and systems have yet to be developed despite the fact that deterioration models for sealant products do exist. Indeed there is an evident lack of information that relates deterioration induced from laboratory testing to that observed in field inspections. Systematic approaches to service life prediction for building materials and components are available from both RILEM [Masters & Brandt 1989] and ASTM [1996] technical documents. As well, these proposed methods are both consistent with the requirements outlined by Wolf [2000a] and are readily applicable to addressing the apparent lack of mathematical connection between laboratory and field exposure results.

Both documents recommend that service life prediction be based on a comparison between the performance over time of degradation functions derived from either short-term or accelerated tests and that of long-term exposure tests. This generic approach (Figure 1), adapted to jointing systems [Lacasse & Cornick 2001] suggests that a service life or performance over time model incorporates information derived from both deterioration or damage models, as well as life models derived from in-situ inspections on real joints in buildings.

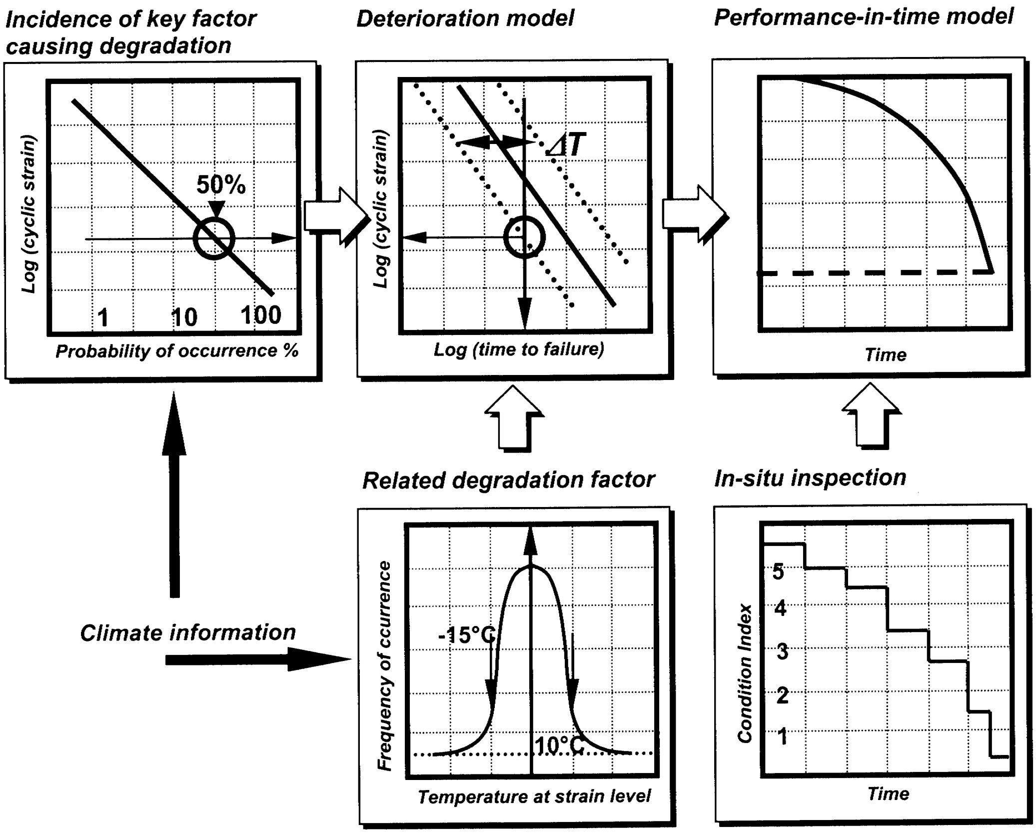

Figure 1 - Approach to service–life prediction showing relation between degradation models and performance in time functions as adapted from RILEM [Masters and Brandt 1989] and ASTM [1996]

Short-term tests are based on an understanding of in-use conditions and as well, knowledge of the most significant factors causing degradation. Long-term exposure tests, on the other hand, are typically undertaken in field or outdoor conditions in which climatic and related environmental effects can only be monitored but not controlled, as expected when undertaking studies in a laboratory setting. In these instances, evaluation of the long-term degradation effects on products may be determined from inspection of products used in buildings or from field trials on joints of test buildings or outdoor exposure rigs that simulate joint movement of real buildings.

Degradation models for sealants materials based on accelerated tests have either focused on the deterioration induced by rupture in the bulk of the sealant, as proposed by Lacasse et al. [1995, 1996, 1998] or the loss in adhesion to an aluminium substrate, as advanced by Shephard [1995]. Studies have also been conducted by Lacasse et al. [1994] to determine the fatigue characteristics and related mechanism of deterioration of silicone sealant in relation to fundamental studies on fatigue of rubber compounds. However none of the results from these models have used to investigate the likely behaviour of products in different climates nor been used to help estimate service life of jointing systems.

Work undertaken by Shephard [1995] was used to simulate crack growth between a one-part acetoxy-cured silicone sealant and aluminum substrate of a butt-jointed system in both Wittman, AZ and Miami, FL. The rate of crack growth along the joint interface, $\dot{a}$, is given in the equation below from which the rates of growth at different temperatures and relative humidities could be estimated.

$$\dot{a} = \left(\frac{G}{k} \right)^{1/n} \bullet \frac{1}{a_T \bullet a_{RH}}$$

in which:

$\dot{a}$ = Crack growth rate (m/s)

G = Strain energy release rate = $\int_{X_0}^{X} (mx + b)dx$

k = Constant = 1161.7

n = Constant = 0.184

a_T = Temperature dependent shift factor (log a_T = 6841T-20.81)

a_{RH} = Relative humidity (RH) dependent shift factor (log a_{RH} = 9.253 – 0.266RH + 0.0016RH^2)

x = Displacement of joint = 1.7•a•? T ; a = coefficient of thermal linear expansion, aluminium

m = 236040T + 1.07 x 10^8

b = -437T + 24827

This relationship was shown to be valid for temperatures ranging between 5 and 90°C and relative humidity varying between 37 and 85%. The critical crack size for joint failure to occur was not established, however, the contrasting rates of crack growth and the climatic conditions necessary for growth to occur highlight the significance of climatic variables in establishing damage patterns. Shephard [1995] noted that the speed of crack growth greatly increased when the temperature fell below sealant application temperature and the relative humidity remained above 35%. It was suggested that climates that have wide annual changes in temperature and maintain moderate levels of humidity during cold months are likely to have the largest crack growth.

In this paper the crack growth model developed by Shepherd [1995] will be used as a basis to assess the relative importance of climatic factors to influence crack growth in particular climates located in Phoenix, Miami, Singapore, Ottawa and Winnipeg. The effect of other variables will be determined including that of installation temperature and change of modulus over time. Finally, on the basis of this model, estimates of time to failure are made as it relates to specific failure criteria. These results are limited by and relate exclusively to a given joint length, configuration and size and the physical properties of a "model unoptimized" silicone sealant product adhered to an aluminium substrate.

2 APPLICATION OF A CRACK GROWTH MODEL

The crack growth model requires information regarding the installation temperature, and ambient climatic conditions at a given location including temperature and relative humidity. The model was applied to various climatic conditions as described in detail below. The assumptions regarding joint details, in particular the joint type, size and configuration and panel material are required to calculate the expected movement due to thermal effects and the strain energy induced in the sealant upon movement of the joint.

2.1 Quantifying in-service conditions – climatic effects

Although the key environmental factors causing degradation in sealant products are well known [Wolf 2000a, b] (i.e. spectral radiation; moisture; temperature; joint movements) the vital item required to help insure the usefulness of prediction (estimation) models is quantifying the intensities of these climatic factors and their likelihood of occurrence

For the purposes of this study, simulations were carried out for the specific locations shown in Table 1. The locations were chosen such that the results from simulation could readily be compared in terms of contrasting climate variables. Specifically, hot-dry climates such as those of Wittman or Phoenix could be compared to the hot-wet climates of either Miami or Singapore, or indeed the cold-wet or cold-dry climates of Ottawa and Winnipeg respectively. The climate classifications were taken from Russo [1971]. The climatic information was obtained from Environment Canada, for Ottawa and Winnipeg, NOAA (National Oceanic and Atmospheric Administration) for Wittmann, Miami and Pheonix, and the WMO, for Singapore. The information consisted of hourly data for a given location over a specific year. Examples of the data are plotted in Figures 2 and 3 below. Hourly temperatures are shown Figure 2a for Miami, FL (1994), whereas the corresponding hourly relative humidity for the same location is given in Figure 2b. Similarly, hourly temperatures and relative humidities for Phoenix, AZ (1994) are provided in Figures 3a and 3b respectively. The values shown in Table 1 for the various climate variables were derived from the hourly data. The extent to which these are close to climate normals has not been provided.

Table 1 – Climatic profiles for different locations

Location	Climate*	Average annual climate variables				
		Avg. T (°C)	Avg. Min. T (°C)	Avg. Max. T (°C)	Avg. % RH	Avg. rain (mm)
Wittman (AZ)	Hot-Dry	20.6	12.2	28.9	N/A	230
Phoenix (AZ)	Hot-Dry	22.5	15.2	29.8	36	194
Miami (FL)	Hot-Wet	24.4	20.6	28.2	73	1420
Singapore (SG)	Hot-Wet	27.1	23.4	30.7	83	2413
Ottawa (ON)	Cold-Wet	6.0	1.2	10.7	69	700
Winnipeg (MN)	Cold-Dry	2.4	-3.4	8.1	72	404

* As classified in Russo [1971] Hot: Average annual T > 15 °C; Cold: Average annual T < 15 °C; Wet: Average annual rainfall > 500-mm; Dry: Average annual rainfall < 500-mm

In comparing the hourly temperatures profiles of Miami and Phoenix it can be seen (Figures 2a; 3a) that the variation in temperatures over the year is particularly more pronounced in Phoenix even though the difference in average annual temperatures is less than 2 °C. The contrast between 'wet' and 'dry' climates is evident from comparison of the relative humidity profiles (Figures 2b; 3b) and values of annual rainfall (1420-mm vs. 194-mm) of either climate.

2.2 Assumptions concerning the joint configuration and product

The fictitious joint is a 2-m long vertical butt joint located on an exterior wall and sheltered from direct sunlight and rain. The assumption of sheltering precludes the need to correct for surface temperatures of the sealant given ambient conditions. In other words, the increase in temperature of the sealant due to the effects of exposure to direct solar radiation need not be considered. The butt joint is located between aluminium panels of 1.7-m width. The joint is 12.7-m wide by 12.6-mm deep. The thermally induced joint movement, d, is simply calculated assuming that the panels are fixed to the structure at their mid-points; hence d = 1.7•a•? T, where a is the coefficient of linear thermal expansion of aluminium (23.2 x 10^{-6} mm/mm °C) and ? T is the temperature differential causing movement.

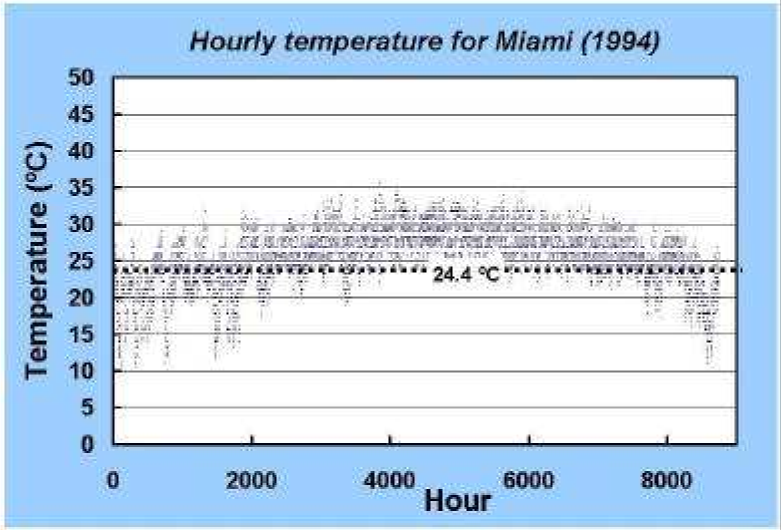

Figure 2a – Hourly temperatures in Miami (1994)

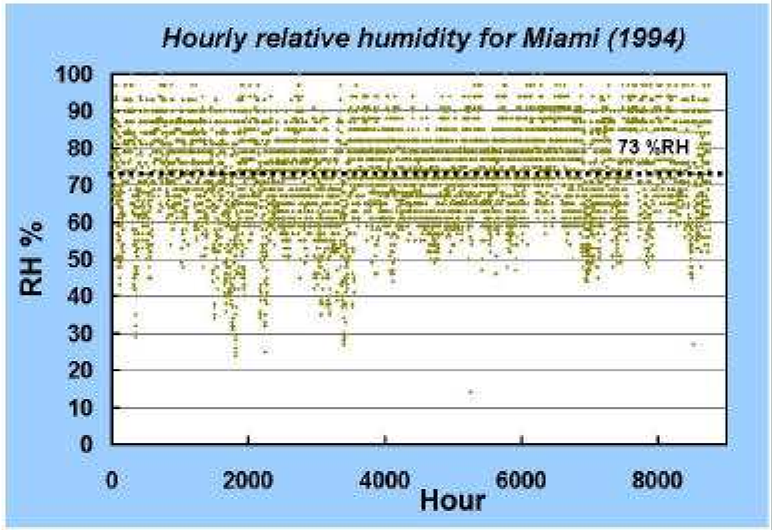

Figure 2b – Hourly relative humidity in Miami (1994)

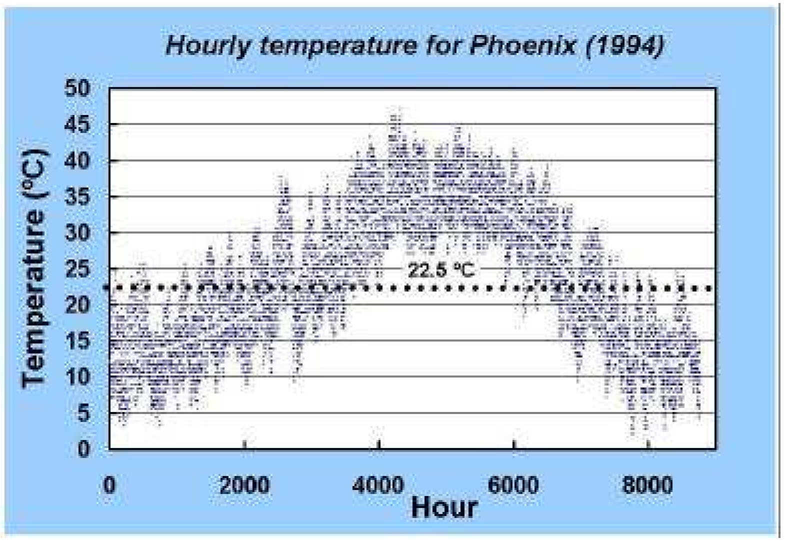

Figure 3a – Hourly temperatures in Phoenix (1994)

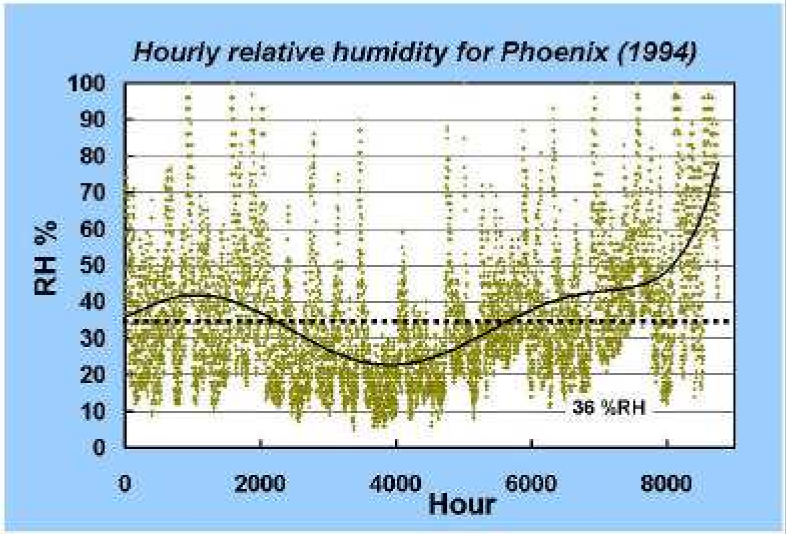

Figure 3b – Hourly relative humidity in Phoenix (1994)

The sealant considered was an acetoxy-based one-part moisture curing silicone product that was assumed to cure at 30°C. Strain energy calculations were not taken into consideration when ambient local temperatures exceeded the installation temperature give that in these conditions, the joint is in compression and crack growth is assumed to occur only when in tension. This is a reasonable assumption so long as the compressive strains are less than 50% or the sealant cross section is hourglass shaped.

2.3 Variables investigated

Four items were investigated using the crack growth model to simulate sealant deterioration: the nature of crack growth in nominally similar as well as dissimilar climates; the significance of the installation temperature on crack growth development in the various climates investigated; the possibility of estimating time to failure for given failure criteria; and, emulating the effects of ageing through increases in modulus.

3 RESULTS

3.1 Comparison of crack growth in different climates

Depicted in Figure 4 is the crack length development over a period of one year (8760 hours) for a joint product located in Wittman (AZ) and Miami (FL). The assumed installation temperature was 30°C and is above the average annual temperatures of either location. This implies that crack growth is arrested (horizontal portion of plot) for most of the year and growth is thus limited to those months in which hourly temperatures are typically well below the 30°C range. Note as well, that the rates of growth either preceding or following that portion showing arrested growth are nominally the same.

The model also suggests that the expected annual crack growth in Miami may be up to ca. 5 times less significant than that of Wittman. The differences are almost entirely attributable to the magnitude of differences in temperature between either the climate during the ‘colder’ months of the year.

The expected consequences of these simulated phenomena in regard to longevity of the seal are apparent although no pronouncements can be made unless criteria for failure or loss in performance are first established.

The annual crack growth profiles derived from model simulations for locations having hot-wet climates is provided in Figure 5 from simulations of crack growth in Singapore and Miami. It is evident that the relative overall annual crack growth in Miami (ca. 0.425-mm) is significantly greater than that of Singapore (ca. 0.003-mm Singapore), about 2 orders of magnitude difference.

Whereas the growth in Miami appears to be dominated by seasonal effects with growth occurring primarily in the colder months, growth in Singapore is reasonably steady over the year (see inset) indicating that diurnal variations in both temperature and relative humidity are causing the growth effects.

Although both climates are classified as being ‘hot-wet’ there is nonetheless an evident difference in the manner in which the model responds to climate loads. When considering that the difference between the average annual temperature in Singapore (27.1°C; 83% RH) and Miami (24.4°C; 73% RH) is 2.7°C and that the difference in terms of relative humidity is ca. 10% the model appears reasonably useful in being able to readily discern between nominally similar climates. The spread between the average maximum temperature in Singapore is 7.4°C about the same as that which occurs in Miami (7.6°C)

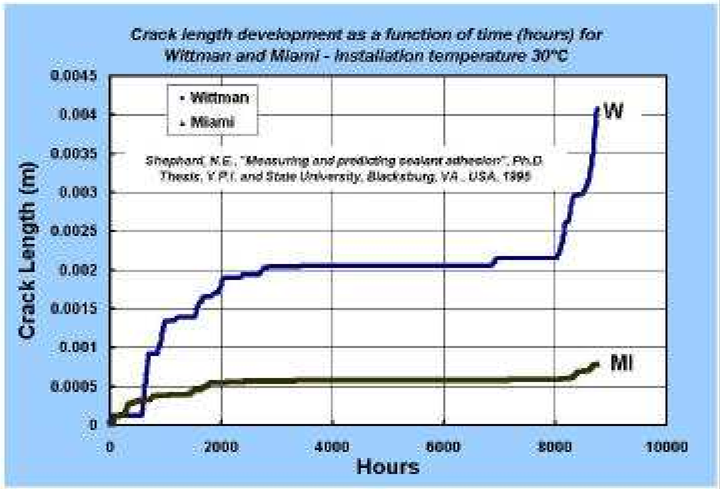

Figure 4 – Simulated hourly crack growth of product over 1 year (8760 hours) in Wittman (hot-dry) and Miami (hot-wet) climates installed at 30 °C.

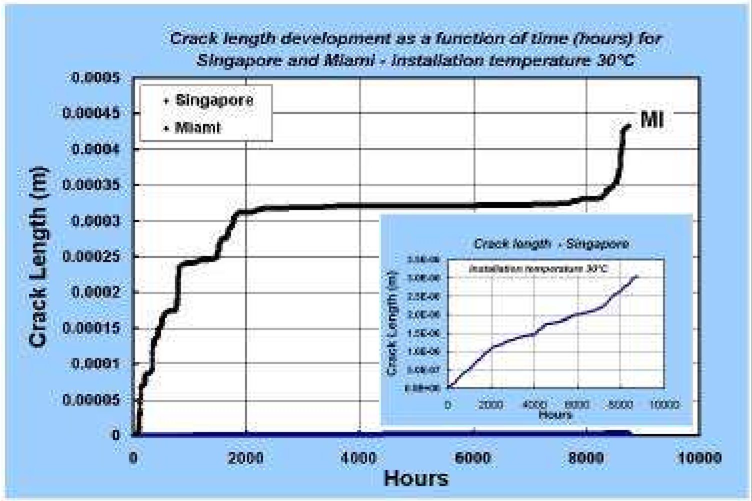

Figure 5 – Simulated hourly crack growth of product over 1 year (8760 hours) in Singapore and Miami climates installed at 30 °C. Both climates are 'hot-wet'. Inset shows hourly crack growth in Singapore over 1 year.

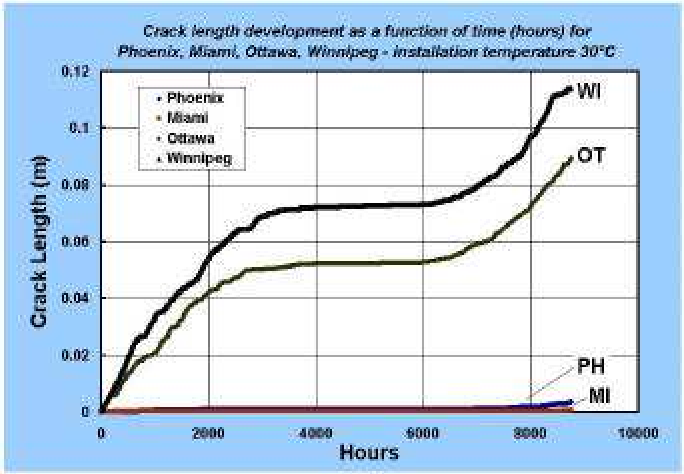

Figure 6 – Simulated hourly crack growth of product over 1 year (8760 hours) in Phoenix (hot-dry), Miami (hot-wet), Ottawa (cold-wet) and Winnipeg (cold-dry) climates installed at 30 °C.

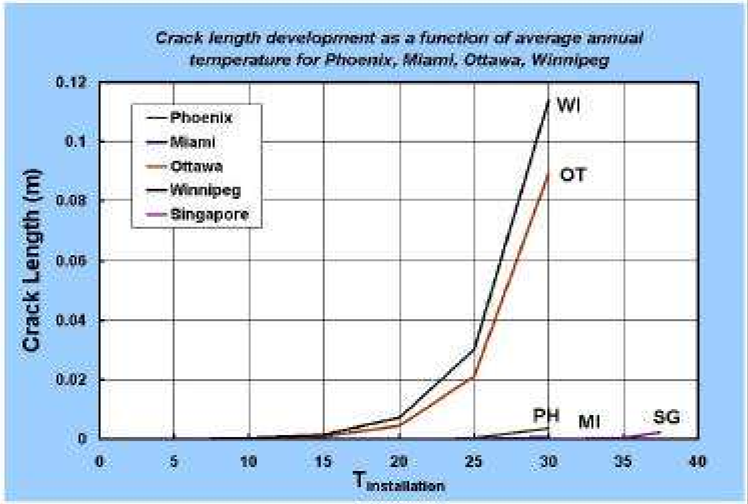

Figure 7 – Simulated total annual crack length development for various locations in relation to installation temperature

Shown in Figure 6 are the simulated crack growth profiles of jointing systems located in hot-wet (Miami), hot-dry (Phoenix), cold-wet (Ottawa) and cold-dry (Winnipeg) climates. Phoenix is physically in close proximity to Wittman hence the climate variables are similar and the comparison between Phoenix and Miami is similar to that shown in Figure 4 for Wittman and Miami. Shown in this figure are simulations undertaken for Ottawa and Winnipeg, both characterized as generally cold climates (Table 1), the climate in Winnipeg being cooler (average annual temperature - 2.4°C) than that of Ottawa (6.0°C) and also dryer (404-mm avg. annual rain vs. 700-mm).

The crack growth profiles for these two locations offer significantly greater annual crack growth in comparison to either of the values obtained for Phoenix and Miami; ca. 90-mm and 115-mm for Ottawa and Winnipeg respectively as compared to 0.425-mm for Miami. The period of growth in the cooler months is both more significant and longer lasting. More significant because the growth rate during the colder months is greater and longer lasting, evidently because the period of 'dormancy', (period during which growth rate is comparatively less) is shorter as compared to that of, e.g., Miami.

3.2 Significance of installation temperature in the development of crack growth

The rate of simulated crack growth is largely dependent on the temperature of installation. This occurs because it is assumed that when ambient temperatures fall below the installation temperature the joint widens in response to contractions of adjacent panels. Hence the product is in tension and this effect is increasingly pronounced in relation to the temperature difference that exists at installation and ambient conditions. Clearly then, if the jointing product is installed at 30°C, the most pronounced effects will occur where there exists the greatest difference between the average annual temperatures and installation temperature as is the case for both Ottawa and Winnipeg.

This is illustrated in Figure 7 that shows the significance of the installation temperature on the simulated annual crack length development for the five locations. Total crack lengths after one simulated year are plotted as a function of installation temperature for Phoenix, Miami, Ottawa, Winnipeg, and Singapore. It shows that the significant crack lengths developed in both Ottawa and Winnipeg as compared to the other locations (Phoenix, Miami, Singapore) is directly attributable to the temperature of installation. Simply put, installation at temperatures higher than the average annual temperature for a given location, as is the case for Winnipeg and Ottawa, produces greater simulated annual crack length development as compared to those locations where the installation temperature is closer to that of the average annual temperature (i.e. Phoenix, Miami and Singapore). It also shows that the annual crack growth diminished quite significantly for both Winnipeg and Ottawa as the installation temperature approaches the average annual temperature at these locations. This observation is in keeping with good installation practice that suggests undertaking sealing operations as close as possible to the average annual temperature such that the joint can thereafter operate equally in compression as in tension. Figure 7 also illustrates that there is an increased risk of failure when joints are installed at temperatures well in excess of their average annual value.

If products were installed at the average annual temperature of the location, what would be the magnitude of the annual crack development at the different locations? This is shown in Figure 8 in which the simulations were conducted for each of the locations at an installation temperature reflecting the respective average annual temperatures of the location with the exception of Winnipeg. In this instance, installation was assumed to be 5°C since this is typically the lowest permitted temperature at which products are installed.

The results indicate that the magnitude of the crack growth over the year is reduced in all cases in comparison to those values obtained when products are installed at 30°C. Values for Miami, Ottawa and Winnipeg are in the same order of magnitude, ranging from ca. 0.015-mm (Miami) to ca. 0.04-mm (Winnipeg), whereas Phoenix is shown to exhibit crack growth of up to ca. 0.11-mm. Hence of the locations investigated, interestingly Phoenix is comparatively the most severe climate, having about 2-3 times more growth over the year (0.11-mm) as compared to, e.g. Winnipeg (ca. 0.04-mm).

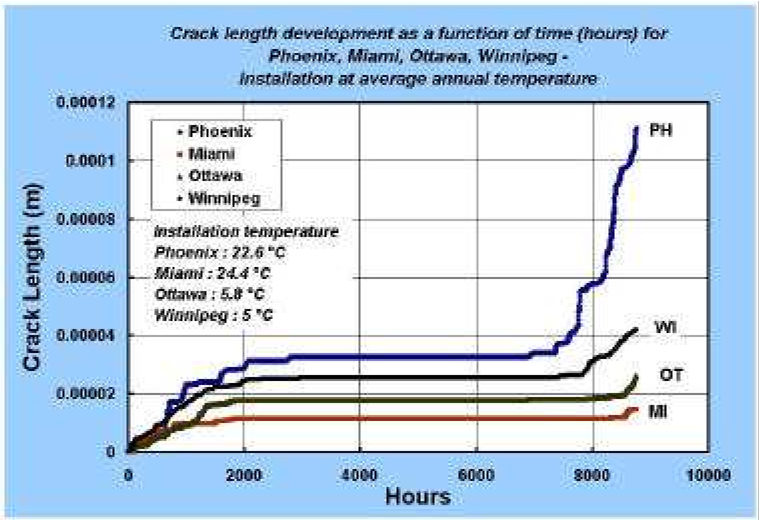

Figure 8 - Simulated hourly crack growth profiles for Phoenix, Miami, Ottawa and Winnipeg for products installed at average annual temperature

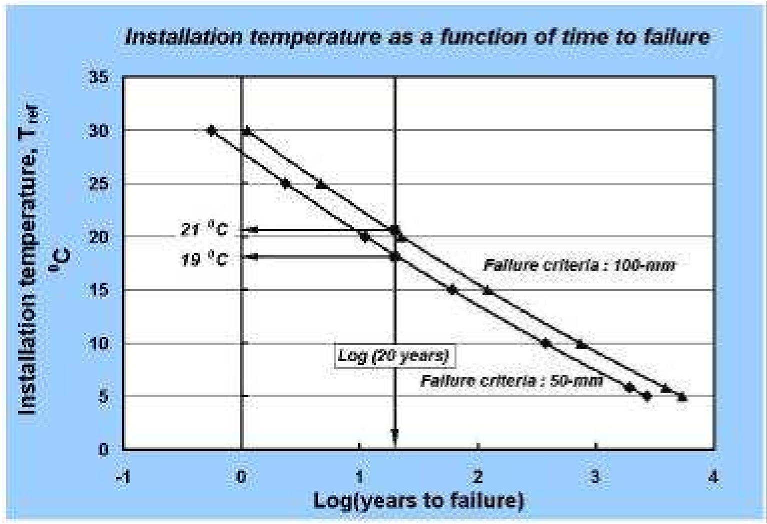

Figure 9 – Time to failure for given installation temperatures and failure criteria (50-mm and 100-mm) for a product installed in Ottawa

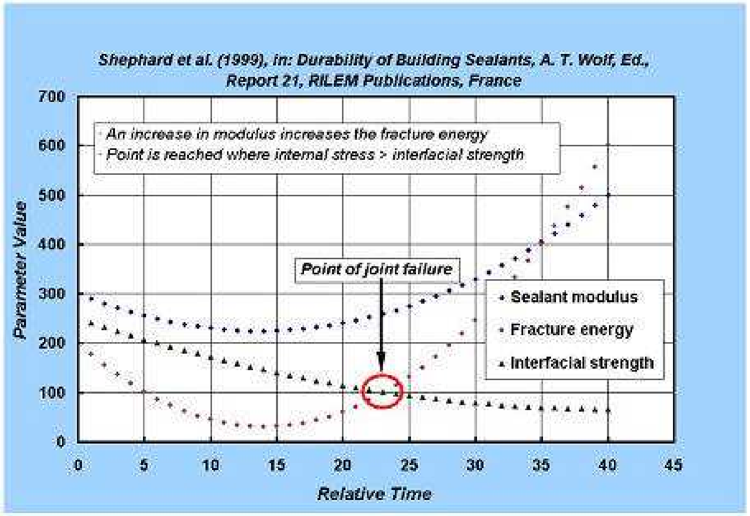

Figure 10 - Relative changes in applied fracture energy and interfacial strength [Shephard 1999]

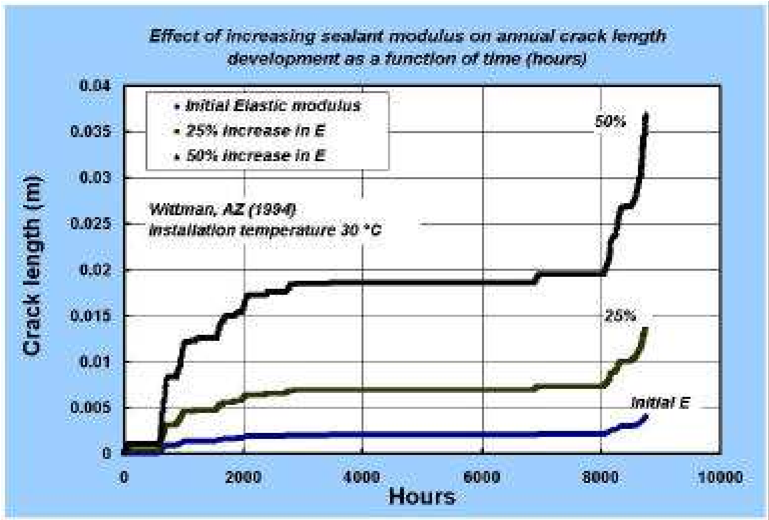

Figure 11 –Simulated hourly crack growth over a year in Wittman for a butt joint having increases in modulus of 25 and 50% [Shephard 1999]

3.3 Estimates for time to failure

It has been shown that significant crack growth can develop over a period of a year if installation is undertaken at temperatures well in excess of the average annual value (Figure 7). As well, these effects are seen to diminish significantly if the installation temperature is close to that of the average annual value. For example, in Ottawa the annual value for crack growth derived from simulation was shown to be 0.03-mm. Estimates for the service life of a joint can be made on the basis of this crack growth model provided criteria for loss in performance is established. For example, the service-life of a 2-m joint may be reached when along this length a crack of, e.g., 50 or 100-mm is detected. Given that the average annual crack length can be determined from simulation, a projection can then be made as to when a certain length of crack will appear, assuming that in each subsequent year, climatic conditions are essentially the same.

The results of this annual progression for a joint installed in Ottawa (Avg. An. T = 6.0°C) at various temperatures are provided in Figure 9. Two plots are shown that provide estimates of service life in terms of the log (years to failure) where the failure criteria is the development of either a 50 or
100-mm length of crack. A service-life of 20 years is highlighted because this value is one that is often ascribed to high-performance sealant products.

The results from simulation suggest that if the products are installed at the average annual temperature of a given location (in this case Ottawa), they may last indefinitely however, if installed at higher temperatures, e.g. ca. 20°C, the service life is likely to diminish.

3.4 Effect of change in modulus over time

Necessarily, a number of different factors other than crack development contribute to the deterioration of jointing seals. Products typically harden as they age as manifested by the increase in modulus over time. As shown in Figure 10 [Shephard 1999], increases in modulus directly affect the fracture energy. Once the modulus starts to increase there is then a corresponding increase in the fracture energy to which the interfacial strength of the adhesive bonds is likewise affected. Joint failure essentially occurs when internal stresses, brought about by higher fracture energies, exceed the interfacial strength of the adhesive bond.

To illustrate this aging effect in an indirect manner, aging is reproduced by increases in modulus and thereafter, crack growth was simulated on a joint installed at 30°C in Wittman, as shown in Figure 11 [Shephard 1999]. The profiles show crack growth of the product having the initial elastic modulus increased by 25 and 50 % respectively; increases in crack growth evidently occur over the year due to the increases in modulus. It appears that growth profiles nominally increase from 0.4-mm to 14-mm for a 25% increase in modulus to 38-mm for a 50% increase. These results simply emphasize the significance of modulus changes to that of crack growth development.

4 SUMMARY

A crack growth model has been used to study the development of crack profiles for a specific joint type and configuration and sealant product in different climates. It is particularly sensitive to variations in temperature and less so to changes in relative humidity. As such it is able to discern the apparent crack growth development of nominally similar climates and as swell, to readily differentiate between the effects brought about in dissimilar climates. It can be used to assess the relative significance of installation temperature at given locations and as well could form the basis for the development of a service life model provided results from the simulations are compared to those derived from controlled field (outdoor) tests. As well, the method can be applied to other sealant products and sealant–substrate combinations to determine their comparative crack growth characteristics.

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