Chapter 14

Development of a Powered Outdoor Sealant Fatigue Test Apparatus

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This chapter describes a new cyclic fatigue test apparatus (CFTA) developed at the USDA Forest Service, Forest Products Laboratory. The new CFTA is computer controlled and powered by electric linear actuators. Computer control allows the CFTA to subject specimens to specific strain/time profiles or replicate input strain data in real time from thermal and/or moisture driven cyclic movement of materials such as metals, glass, ceramics, and wood. The CFTA was designed for outdoor sealant testing but is readily adaptable for testing other materials.

BACKGROUND

Sealants and caulking compounds are used to prevent moisture intrusion into the structure and living space of residential and commercial buildings. This is necessary to maintain safe, comfortable living conditions for occupants and to prevent water damage to building structures.

In outdoor use, sealants and caulking compounds are subjected to physical strains caused by the expansion and contraction of building materials as temperature and relative humidity change. These strains include axial and shear components that depend on the specific application and installation details. Sealants and caulking compounds are also exposed to environmental stressors including ultraviolet light, temperature changes, moisture (as rain or water vapor), air pollution, and acid rain.

The sealants presently being evaluated were provided by industry partners and are similar to commercially available building sealants and caulking compounds except that their formulations have been modified to accelerate failure. The chemistry type (such as silicone, urethane) and exact formulation of the test sealants is unknown to the experimenters. The present goal is to develop generally applicable test and analysis methodologies, not to evaluate specific sealant formulations. The purpose of testing sealants is to acquire data for accurately Predicting their service lives. Ideally, tests could be completed in much less time than the actu-

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al service life. These accelerated test results would be used by manufacturers for accelerated product improvement and by contractors and consumers for appropriate product selection.

Predicting service life from accelerated test data requires an analysis that is independent of time. A cumulative dose/damage model relates the sum of incremental doses of factors such as mechanical strain, ultraviolet radiation, moisture, and temperature and their interactions to the cumulative damage or degradation of the sealant. In such a model, *time to failure is replaced by dose to failure or, ideally, as quantjfiable dose to quantifiable degradation.* Damage is quantified as the measurable change of some material property of the sealant. Preferably, the damage can be measured without significantly altering the specimen and with minimal interruption of the ongoing test. Determination of precisely which material property of sealants best satisfies the aforementioned requirements is the goal of ongoing research.

Ultimately our goal is to use the information from outdoor material response and weather data to develop appropriate accelerated tests and cumulative dose/damage models to predict service life in less than real time with accuracy, precision, and repeatability.

Outdoor Cyclic Fatigue Testing of Sealants

Traditional methods for testing sealants consist of placing specimens outdoors and visually evaluating them periodically to determine their service life. If the sealant is expected to undergo cyclic fatigue, the exposure test should include cyclic fatigue. Methods for cyclic fatigue testing of sealants have included several techniques for inducing cyclic strain. Previous outdoor fatigue testing has relied on the mechanical expansion/contraction of a large monolith (usually metal or plastic) to mechanically strain specimens. These monoliths (engines) were placed in series or in parallel with sealant specimens and directly imposed strain on specimens by responding to the environment. These apparatuses were typically set up to react to solar radiation and ambient temperature. For example, Onuoha[1] used unplasticized polyvinyl chloride (PVC) pipe to produce fatigue in one-part polyurethane and polyurethane-hybrid sealants. Racks have also been built using dissimilar materials such as wood and aluminum[2] concrete and aluminum[3] and steel and aluminum[4] to develop fatigue stresses.

All the methods described above depend on visual inspection for surface defects and delamination to determine the degradation of specimens. Degradation occurred through the combined stress caused by mechanical deformation, ultraviolet (UV) radiation, heat, and moisture, but there was no record kept of the amount of each of these stressors; nor was the actual movement of the specimens recorded during the tests.

Wood Engine Approach

The Forest Products Laboratory (FPL) Sealants Durability team developed wood engines that used the swelling/shrinking with moisture content of wood blocks to strain specimens.[5-7] These engines swelled and shrank as they absorbed and desorbed moisture with precipitation and changes in relative humidity, which directly imposed mechanical strain on specimens. Specimens were instrumented to continuously monitor force and deflection. The force and deflection were then used to calculate and record the stress and strain on each of the specimens. A weather station located at the test site gives temperature, precipitation, relative humidity (RH), and wind velocity; and a UV radiometer gives UV radiation at 18 different wavelengths. This information was continuously recorded along with the specimen response.

Because dimensional change of the engines was directly transferred to the specimens, the specimens had to be placed in the same environment as the engines. This makes it difficult to perform designed experiments that require some stressors to be "turned off" for some specimens. Unfortunately, engines that are either thermal or moisture driven (primarily wood and plastic) are subject to variability between engines because no two wood blocks or plastic tubes are exactly the same. Wood and plastic engines also tend to change as they age. This makes exact replication of experiments virtually impossible, not only between test apparatuses but also within the same apparatus when multiple engines are used. Another disadvantage of this type of test apparatus is the difficulty of ensuring that the strain imposed on the specimens is of a specific amplitude about a prescribed mean value (zero in present experiments). Though the amplitude is determined by the size of the engines, material variability limits the precision with which the amplitude can be controlled. In order to center the strain at about zero, specimens must be pre-strained at the time of installation to match the instantaneous state of the engines. Further, the mean dimensions of the engines change with seasonal variations in weather. Physical adjustment of the specimens is required to correct asymmetric strain.

Advantages of a Computer Controlled Powered Cyclic Fatigue Test Apparatus

In July 2003, a new technique was proposed to design and build an outdoor cyclic fatigue, test apparatus (CFTA) that could be computer controlled. This would require using precisely controllable motors in place of wood, plastic, or metal engines, designing new hardware and electronic controls, and developing control software. The advantages offered by a computer-controlled CFTA are consistency from one test to another and almost uniform strain among specimens on the same apparatus. The strain uniformity is limited only by the physical compliance of the CFTA, which can be minimized with proper design and corrected for after the compliance has been determined.

A computer-controlled CFTA can be programmed to receive input from the thermal response of a metal or plastic, or a moisture response from wood. The CFTA can be programmed to produce strain in the same or opposite direction of thermally/moisture driven expansion/contraction, and a gain factor may be set with software. The CFTA also can be commanded to move in an arbitrary manner determined by the programmer. This allows a specific strain history to be repeated at other times or replicated by another CFTA at a different location, such as in a controlled laboratory environment.

A computer-controlled CFTA may be programmed to execute a specific strain versus time profile at a particular time or when environmental conditions are within specified limits. This can serve as an in situ experiment that measures a material property of the specimen that is associated with the amount of damage sustained by the specimen. Such periodic testing could be used to acquire data needed to determine dose/damage relationships.

A computer-controlled CFTA mimicking a reactive engine can prevent excessive strain amplitude with software limits. Thermal and moisture-driven apparatuses must be designed conservatively with relatively small wood engines to avoid specimen strains exceeding ±25%. A computer-controlled CFTA may be programmed to react more aggressively while relying on software to limit strain to ±25% during extreme conditions. Computer-controlled CFTAs can compensate for asymmetric strain profiles with programmable zero offsets. Current wood engine apparatuses require physical adjustment of the specimens to correct this problem.

DEVELOPMENT

Requirements

The first step in designing the computer-controlled CFTA was to develop a set of requirements.

(1) The motors must be powerful enough to drive 10 to 20 specimens on one CFTA.
(2) The apparatus must be rigid enough to ensure near equal strain on all specimens.
(3) The CFTA must be reliable when exposed to the weather.
(4) The CFTA must accurately impose strain on the specimens.
(5) CFTA must be free of accumulated error.
(6) CFTA design must facilitate simple mounting/dismounting of specimens.
(7) Cost must be minimized.
(8) Design and prototype must be completed and working in less than three months. This demands using as much "off-the-shelf" hardware as possible to minimize fabrication time.

Mechanical Design

A two-beam parallel design was selected. In this design, the CFTA consists of two horizontal beams, one above the other, connected by linear actuators at each end (Figure 1). The upper beam is fixed and the lower beam is driven up or down by the linear actuators. Specimens are placed between the beams parallel to the linear actuators. The entire apparatus may be tilted upward as much as 90° to maximize exposure to sunlight.

Each apparatus utilized 1.8-m beams in order to accommodate 20 specimens as well as actuators and positioning instrumentation. To ensure consistent strain across the CFTA, the upper and lower beams had to be stiff enough to minimize deflection under load. Standard aluminum I-beams were selected such that deflected would be less than 0.635 mm or 5% strain at maximum load, which would occur only beyond the designed test limit of ±25% strain and only with relatively stiff specimens.

To ensure smooth linear motion, the lower beam was designed with wheels that run in tracks secured to the upper beam. This constrained the lower beam to move vertically and maintain parallelism between the beams.

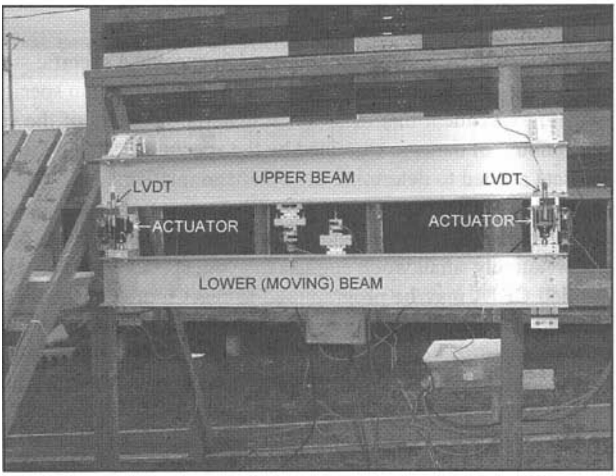

Figure 1—Computer-controlled cyclic fatigue test apparatus at FPL test site near Madison, WI. CFTA is shown mounted vertically but may be set in any position from vertical to horizontal. Two specimens are mounted on the apparatus.

Electronic Design

A survey of available technology revealed that off-the-shelf linear actuators, each consisting of a stepper motor and lead screw, offered sufficient force and precision for a sealant CFTA. Each actuator has a capacity of 2.22 kN (500 lbf) with a resolution of 0.0127 mm/step (0.0005 in./step) or 0.1% strain/step (with a standard 12.7 mm [0.5 in.] square by 51 mm [2.0 in.] long sealant specimen). The linear actuators have 25.4 mm (1.0 in.) of travel.

The linear actuators are controlled, through drivers, using a personal computer. The drivers convert low current command pulses from the computer into high current pulses to the actuators causing them to move the desired number of steps.

Limit switches are mounted on the CFTA to interrupt power if the CFTA moves too far. This will prevent damage to the CFTA or specimens in the case of a computer error or spurious signal. The limit switches constitute a physical backup to the software control limits.

Instrumentation

The CFTA prototype has two linear variable differential transformers (LVDTs) for measuring the position of the lower beam *(Figure 1)*. This position is used to calculate specimen strains. Currently there is one LVDT at each end of the CFTA, but another LVDT will be installed at the center in the near future. This will allow measurement of beam deflection under load. Software will be modified to correct specimen strain measurements for beam deflection.

Control

The CFTA is presently configured to mimic the thermal expansion of a black aluminum bar *(Figure 2)*. The aluminum bar could be easily replaced with a wood block to mimic a moisture-content-driven test apparatus, or with any other material or combination of materi-

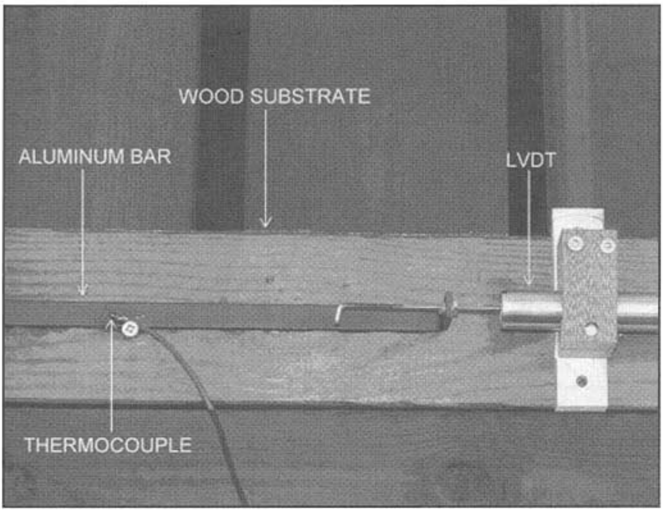

Figure 2—Detail showing free end of aluminum bar and LVDT relative displacement sensor used as thermally driven input for the cyclic fatigue test apparatus.

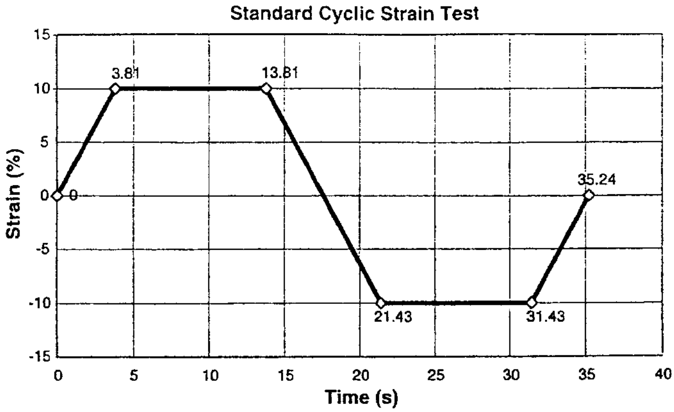

Figure 3-Sample strain profile, which my be used for in situ tests.

als. The approximately 76-cm (30-in.) bar is mounted outdoors with one end fixed and the other end attached to an LVDT that measures the thermal expansion of the bar. The aluminum bar is moutned to sealed pressure-treated board. The thermal coefficient of expansion of the wood is an order of magnitude less than that of aluminum. A computer program records this displacement, scales it, offsets it, and outputs the result of the CFTA control program. The CFTA control program compares the scaled, offset bar displacement wit the current position of the CFTA and generates apporpriate step movement commands to eqaulize the two. Commands are subsequently sent to the drivers, causing the linear actuators to step the cor-

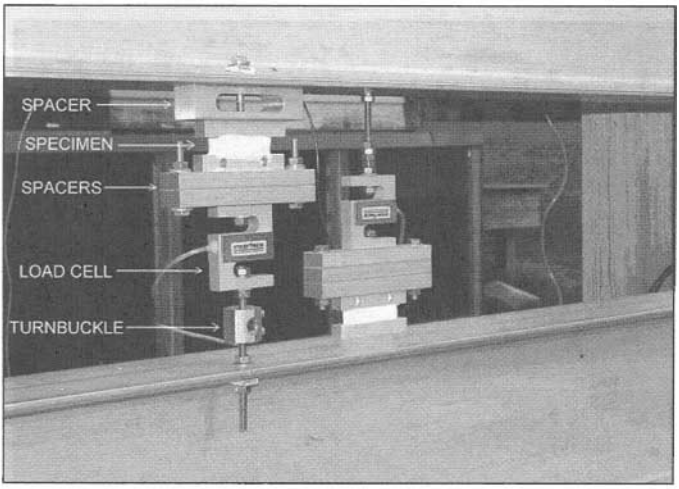

Figure 4-Two specimens mounted in the cyclic fatigue test apparatus, showing load cells in series with specimens. Note spacer above front row specimen and that back row specimens is mounted directly to lower (moving) beam; this is to mimimize shading of the specimens.

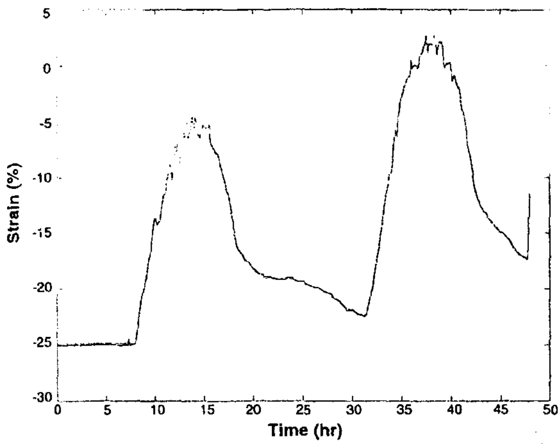

Figure 5—Strain vs. time for two specimens mounted in the cyclicfatigue test apparatus driven by thermal expansion ofa black aluminum bar. The strain is primarily negative (compression) during this interval.

rect number of times. The program will not command the actuators to move if the movement would exceed preset displacement limits. The frequency of this process is programmable.

Although the prototype CFTA uses displacement information from an LVDT, any type of transducer could be substituted. The software gain factor could be changed as needed to make the CFTA react to any physical quantity that can be measured with a transducer.

The control program can also be set up to read from a data file to repeat a previous strain history or perform a specific strain profile such as an in situ test *(Figure 3)*. This profile consists of a constant rate ramp (20 mm/min.) to 10% tensile strain, a 10-s hold. constant rate ramp down to 10% compressive strain, 10-s hold, and a constant rate ramp back to the starting point. Degradation of specimens may be detected and quantified by repeating this test, under similar environmental conditions, over a period of months, and recording the material load response. Any change in specimen load response will be correlated with dosage of mechanical deformation, UV, heat/cold, and moisture.

Figure 4 shows two specimens mounted on the CFTA. Each specimen is mounted in series with a load cell that measures force on the specimen. A data acquisition program reads load

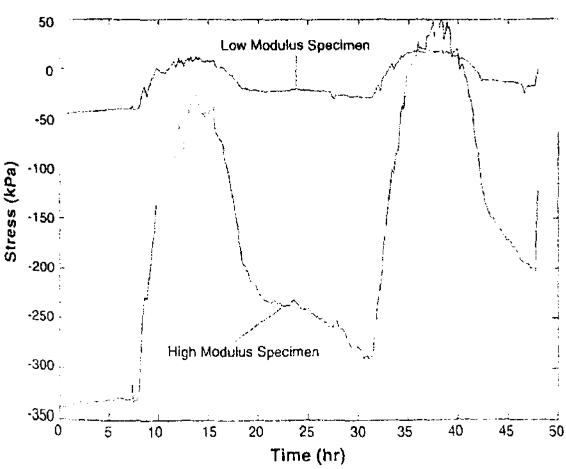

Figure 6-Stress vs. time for two specimens mounted in the cyclicfatigue test apparatus driven by thermal expansion ofa black aluminum bar. The difference in elastic moduli of the specimens is clearly evident by the difference in magnitude of the stresses for a given strain. The stress is mostly negative, indicating compression ofthe specimens.

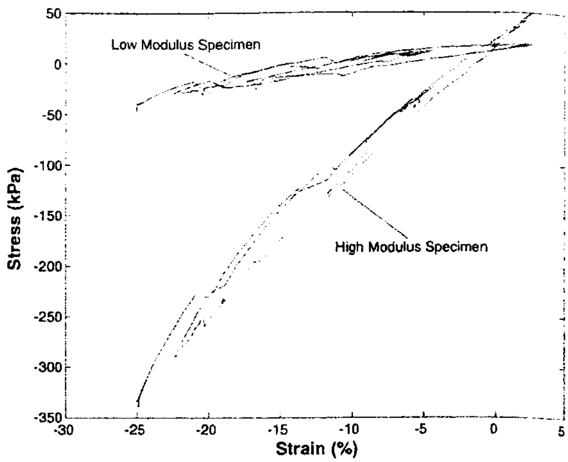

Figure 7—Stress vs. strain for two specimens mounted in the cyclic fatigue test apparatus. The difference in elastic moduli of the specimens is clearly evident by the greater slope of the stiffer specimen.

cell and LVDT voltages and computes stress and strain. A plotting program creates graphs of stress, strain, and environmental conditions for analysis.

OPERATION/TESTING

Data/Results

Force and displacement data for two sealant specimens has been recorded. The specimens were selected to draw attention to the difference in material response of sealant specimens with relatively low and high elastic moduli. Strain versus time is shown for the specimens as the CFTA mimics the expansion and contraction of an aluminum bar *(Figure 5).* Strain is similar for the two specimens because the CFTA is powerful enough to impose displacement on the specimens.

Stresses differ significantly between the two specimens: one with a low modulus and one with a high modulus *(Figure 6).* Although the shape of the stress curves is similar, the magnitude of the stress is much greater for the stiffer specimen.

The difference in elastic moduli between the two specimens appears as a difference in slope on the plot of stress versus strain *(Figure 7).* The stiffer specimen exhibits a higher slope. The fact that the curves form a loop instead of a line indicates the presence of hysteresis effects.

CONCLUSION

Predicting service life from accelerated test data requires an analysis that is independent of time–a cumulative dose/damage model. In such a model, *time to failure* is replaced by *dose to failure.* Mechanical and environmental stressors become the dose. Damage is quantified as the value of some material property of the specimen that changes as the specimen sustains damage and can be measured without significantly altering the specimen. Preferably, the material property can be measured with minimal interruption of the ongoing test. Precisely which material property of sealants best satisfies the aforementioned requirements is the goal of ongoing research.

Designed experiments where similar sealant specimens are subjected to different combinations of stressors can reveal which stressors are important, which are negligible, and which are significant in combination. Further, more refined experiments will allow determination of dose/damage relationships and development of dose/damage models that can be used to predict service life from accelerated test data.

SUMMARY

The computer-controlled powered sealant cyclic fatigue test apparatus (CFTA) is a versatile machine, which can mimic mechanical strain caused by any type of moisture, thermal, or combination of moisture/thermal material response. This new CFTA can also subject specimens to arbitrary strain profiles to determine changes in materials response as the test proceeds. The design permits operation in controlled environments, duplicating the outdoor mechanical strains, as part of a designed experiment. This designed experiment will be used to determine which environmental stressors and interactions are important to the degradation of sealants and estimate dose/damage relationships. This will allow construction of cumulative dose/damage models to be used for service life prediction from accelerated test data.

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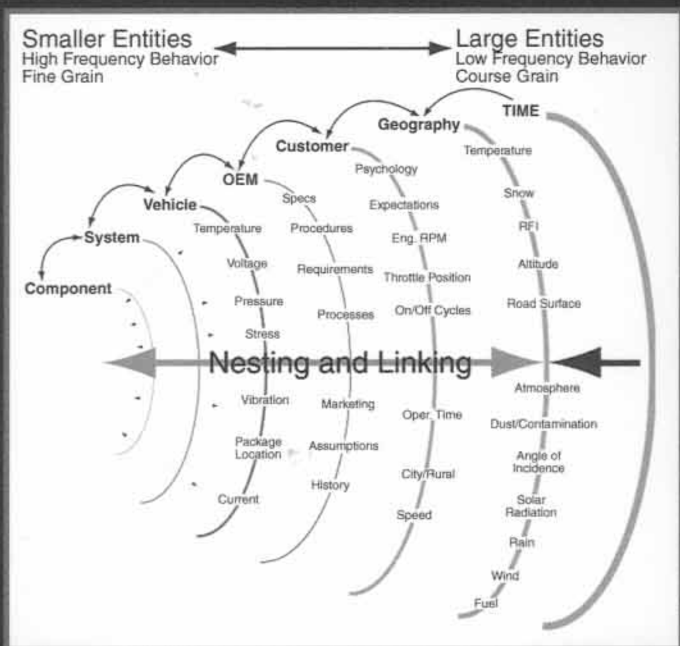
Service Life Prediction

Challenging the Status Quo



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