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Installing Sealants for Long Service Life

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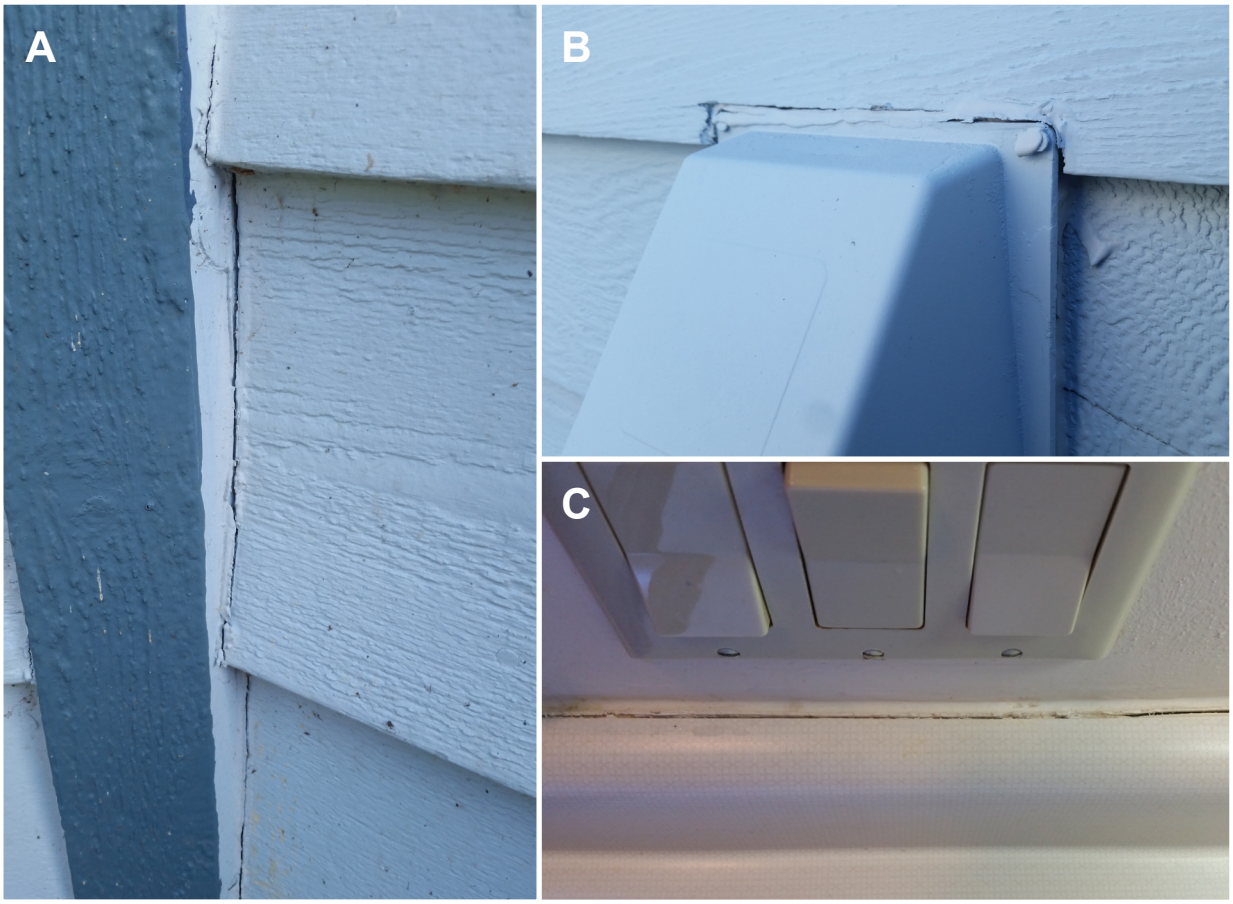

Proper sealant installation and selection are essential for long-term durability.

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Abstract

Sealants are critical components of building construction. They must prevent air and water leaks in the building envelope to prevent moisture damage and maintain comfort and energy efficiency. Simultaneously, they must absorb relative motion between the building components as materials expand and contract due to changes in environmental conditions. Repairing failed sealant is an expensive, labor-intensive operation. Common understanding is that sealants fail under tension as they age and stiffen. Experiments at the Forest Products Laboratory using outdoor exposure with movement, laboratory tests, and finite element models with butt joints showed that compression results in significantly higher loads than tension and that the stress is concentrated at the bondline. The amount of tension and compression deformation experienced by a sealant in service depends on both the overall movement of the building joint and the state of the gap when the sealant was installed. Sealants installed when the gap is decreased (typically summer) will experience mostly tension, and sealants installed when the gap is increased (typically winter) will experience mostly compression. Therefore, sealant installation temperature sets the strain profile the sealants will experience and likely has a significant impact on durability. Methods for minimizing the resulting stress are provided.

Keywords: building sealant, installation condition, backer rod, surface tooling, cyclic strain testing, high compression loads, finite element analysis

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On the cover: Failed sealants in a typical home.
A: A poorly designed joint—Sealant in a 90° corner without a bond breaker cannot accommodate movement. Other contributing factors may include low sealant flexibility and poor surface preparation. Sealants rated for large movement are recommended (for example, ±50% in ASTM C719).
B: Sealant bond failure and tearing within sealant at dryer vent—The sealant does not have enough flexibility and failed within 3 years. C: The sealant debonded from kitchen counter backsplash within 1 year of installation. The sealant failed because it became quite stiff upon curing.

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Introduction

Surveys completed in the late 20th century estimated that 55% of sealant installations exhibited failed seals within 10 years (Hutchinson et al. 1999), indicating that design and installation practices could be greatly improved. Sealants fail when they experience loads that exceed either the strength of the sealant itself (cohesive failure) or the strength of the sealant–substrate bond (adhesive failure). In service, sealants are stretched and compressed as the joint moves in response to environmental conditions. Typically, joints are compressed as the building materials expand during warmer weather, and the sealant is stretched as the building materials contract during cooler weather. As sealants are stretched and squeezed by building movement, they experience tension and compression loads parallel to the motion and shear loads at the bond line.

Sealants do not react to tension and compression in the same way. As a sealant bead is stretched, it thins in the direction perpendicular to the elongation. This phenomenon is called "necking" and decreases the cross-sectional area of the sealant. Necking effectively decreases the stiffness of the sealant and makes the sealant behave like a softer spring. The net effect is that the load necessary for continued elongation plateaus, or stops increasing. Sealants react to compression in a very different way. As the sealant bead is compressed, it tries to squeeze out of the joint. The middle of the bead expands, but the edges that are bonded to the substrate cannot deform without breaking the adhesive bond. This sets up concentrated and high-intensity shear loads at the bondlines. As a result, compression can generate significantly higher reaction loads than tension. Figure 1 shows a sealant test specimen bulging under compression, with arrows pointing to areas of shear stress concentrations. Failures are most commonly observed in these same areas. The appearance of these failures may be very similar to that of tensile failure. Because failure can be observed only in tension, it is easy to erroneously conclude that a compressive failure was caused by tensile stress.

This study was intended to identify causes of failure and to suggest methods for improving sealant reliability. Commercially available silicone and polyurethane sealants were subjected to simulated joint movement during 44 months of outdoor exposure in Madison, Wisconsin, USA. During the exposure, changes in mechanical properties were measured and failures observed.

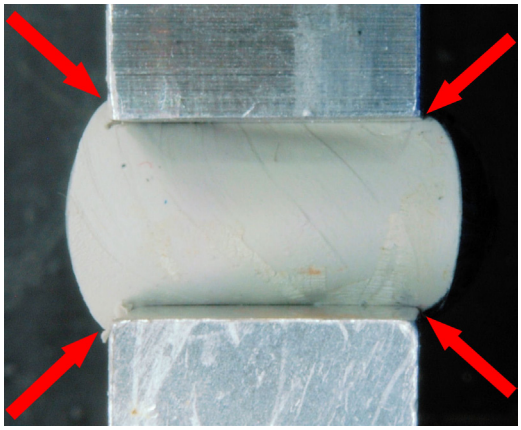

Figure 1. Untooled (vertical front and back face at installation) silicone sealant specimen compressed 40% showing characteristic bulging. This causes severe shear stresses at the edges of the bondlines (arrows).

Additionally, laboratory tests were performed and finite element modeling conducted to further investigate observations from outdoor testing.

Experimental

Outdoor Testing

A study was conducted to correlate environmental stress factors, including solar radiation, temperature, relative humidity, and imposed deformation, on sealant butt joint test specimens with changes in physical properties and performance of the sealants. The experimental apparatus simulated a building butt joint that contracted and expanded with changes in ambient temperature. The test apparatus was located outdoors near Madison, Wisconsin, USA, and consisted of an electromechanical load–displacement frame. The instrument and weekly stiffness measurement procedure are detailed by Schueneman et al. (2012). Briefly, the stiffness of the sealants was measured as follows: The instrument automatically halted strain cycling and then imposed a stress relaxation period where the load for each specimen was captured at a fixed time and used to calculate stiffness using an apparent modulus approach. Sealant specimens were 50.8-mm-long by 12.7-mm-high by 12.7-mm-wide (2- by 1/2- by 1/2-in.) rectangular sealant beads between anodized aluminum bars, as specified by ASTM C719-93. The apparatus was designed to impose

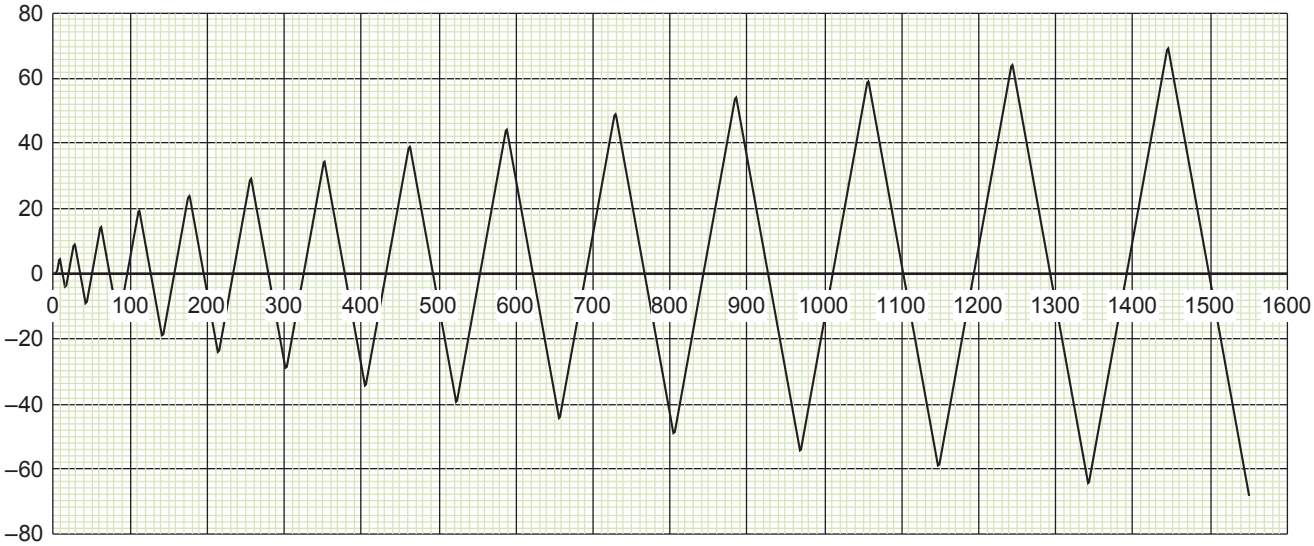

Figure 2. Plot of displacement (percentage of undeformed width) as a function of time (s) for cyclic deformation laboratory test of silicone sealant.

±25% deformation on the specimens as the temperature varied from –18 to 38 °C (0 to 100 °F) with the neutral point at 10 °C (50 °F). Sealant specimens were mounted in the apparatus so that four specimens cycled between 25% elongation and 25% compression, simulating a neutral installation; four specimens were biased toward compression and cycled between 5% elongation and 45% compression, simulating a winter installation; and four specimens were biased toward tension and cycled between 45% elongation and 5% compression, simulating a summer installation. Half the specimens were commercial grade silicone sealant and half were commercial grade polyurethane. The silicone sealant was rated for 40% extension and 40% compression. The polyurethane sealant was rated for 100% extension and 50% compression. Additional static sealant specimens were exposed to the weather without movement. One-third of these static specimens were fixed at 12.5% compression, one-third at 12.5% elongation, and one-third undeformed.

Laboratory Testing

Additional laboratory experiments were conducted to determine tension and compression loads during cyclic extension and compression of sealants and to evaluate if compression alone can cause failure. The first test consisted of alternately imposing tension and compression on a sealant specimen in a materials testing machine. Deformation of the specimen as a percentage of nominal width plotted as a function of time is shown in Figure 2. The strain rate was held constant, and the magnitude of the imposed deformation increased with each cycle. The test was stopped when loads reached the limit of the test apparatus.

A second laboratory test was conducted to demonstrate compression loading in relation to sealant failure. This test cycled a silicone sealant specimen between 20% extension and 70% compression. The sealant was rated for ±40% joint movement. The specimen was first extended to 20% and inspected. No failure was observed. The specimen was then compressed 70% and returned to 20% extension for inspection. This was repeated for a total of 10 times.

Finite Element Analysis

Finite element analysis (FEA) models were created using LISA 8.0 software to calculate load distribution in sealant specimens under various strains. The models were two-dimensional simulations of a cross section of sealant bead. The models included square cross-section specimens, used here in outdoor and laboratory testing, and cross sections with concave faces, simulating properly tooled sealant beads installed over round backer rods. The models do not take into account viscous dissipation, which is significant in sealants, as evidenced by their rapid stress relaxation. Instead, the FEA models represent instantaneous loads, which in reality will gradually decrease over time yet remain proportional to the load that was initially applied.

Results and Discussion

Outdoor Test Results

After 44 months of outdoor testing, none of the sealant specimens failed. During the test, the actual maximum deformations recorded were 35% elongation and 36% compression. That imposed as much as 55% elongation on the tension-biased specimens and as much as 56% compression on the compression-biased specimens. The neutral and compression-biased silicone specimens decreased in stiffness by 36% during the exposure, with the most rapid loss occurring for the specimens biased in compression (winter installation). The specimens with

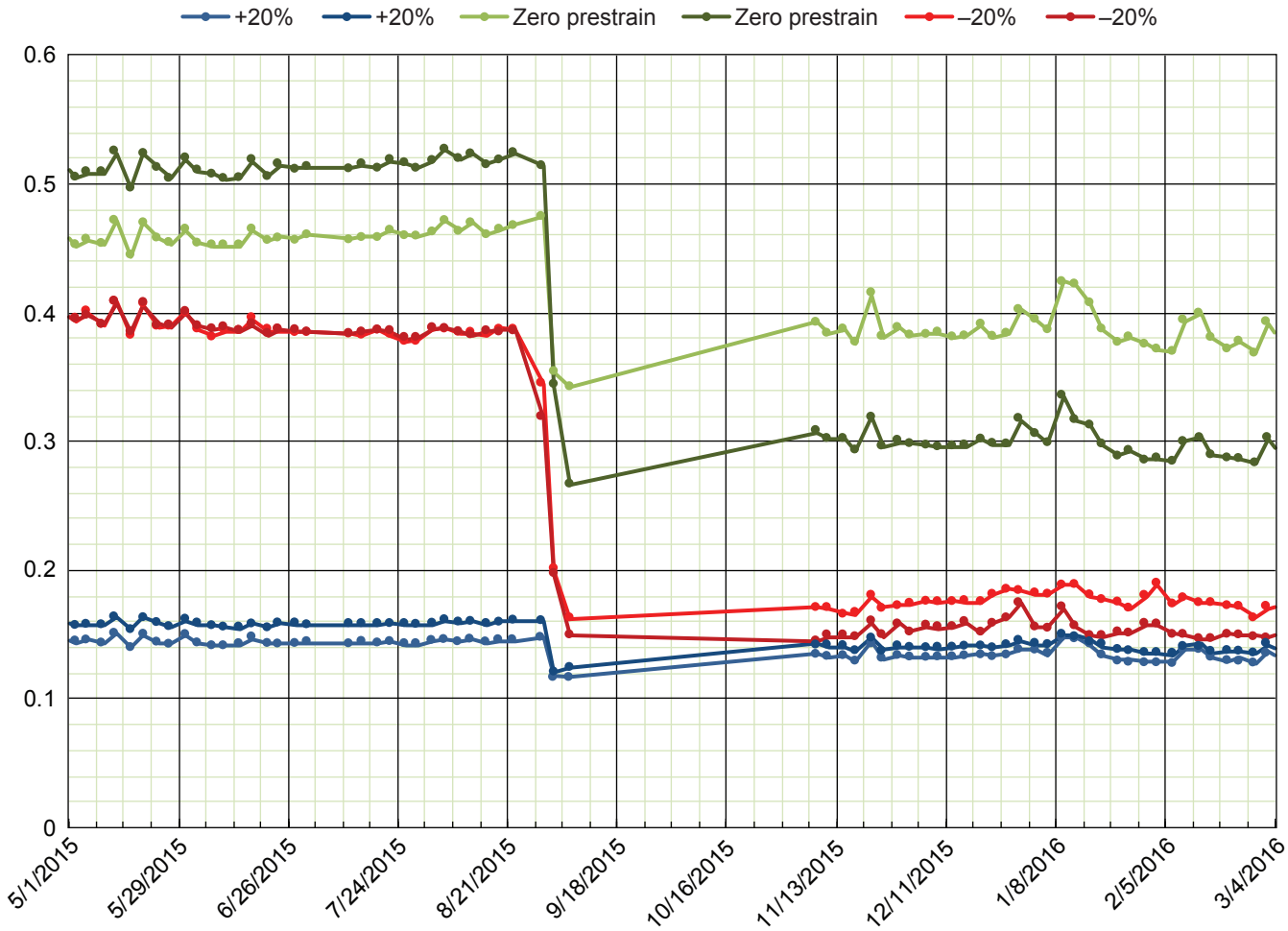

Figure 3. Plot of the stiffness (MPa) of silicone sealant specimens' before and after excessive deformation subsequent to sensor failure, showing two replicate specimens for each condition (+20% tension, neutral, and –20% compression (in red)).

little overall loss in stiffness were those biased in tension (summer installation). The dynamically tested urethane and all the static specimens underwent no significant change in stiffness even though the urethane had surface erosion and micro-cracking.

During the 45th month of exposure, a sensor failure caused the test apparatus to exceed the design limits and move to 50% extension and 45% compression. That incident imposed 70% elongation on the tension-biased specimens and 65% compression on the compression-biased specimens. After the overstrain event, the neutral and compression-biased silicone specimens exhibited a significant decrease in measured stiffness. Stiffness measured 100 s after application of strain is shown in Figure 3. The overstrain event caused a sudden drop in modulus in all silicone and polyurethane specimens with compression bias. Subsequent visual inspection showed partial debonding of these sealant specimens from their substrates. The survival of the tension-biased specimens is taken as further evidence that tension bias (summer installation) is less harmful than compression bias (winter installation).

Tension versus compression bias strongly affected the change in stiffness of the silicone specimens. Figure 4 shows a plot of load versus joint movement during a 1-month period in the spring for specimens installed in compression, neutral (unbiased), and tensile bias. The compression-biased specimens experienced deformation from 48% compression to 2% elongation, the neutral specimens experienced deformation from 28% compression to 22% elongation, and the tensile-biased specimens experienced deformation from 8% compression to 42% elongation. The plot clearly illustrates that the loads resulting from compression are much higher than from tension. Loads resulting from 40% compression are approximately three times as high as loads resulting from 40% elongation. These experiments indicated that compression results in a more severe loading environment than tension for the tested building sealants when compared at equivalent strains. Our outdoor testing data generally show that loads on sealant joints were approximately three times higher in compression than in elongation, at similar percentage deformation. This was true with both polyurethane and silicone sealants.

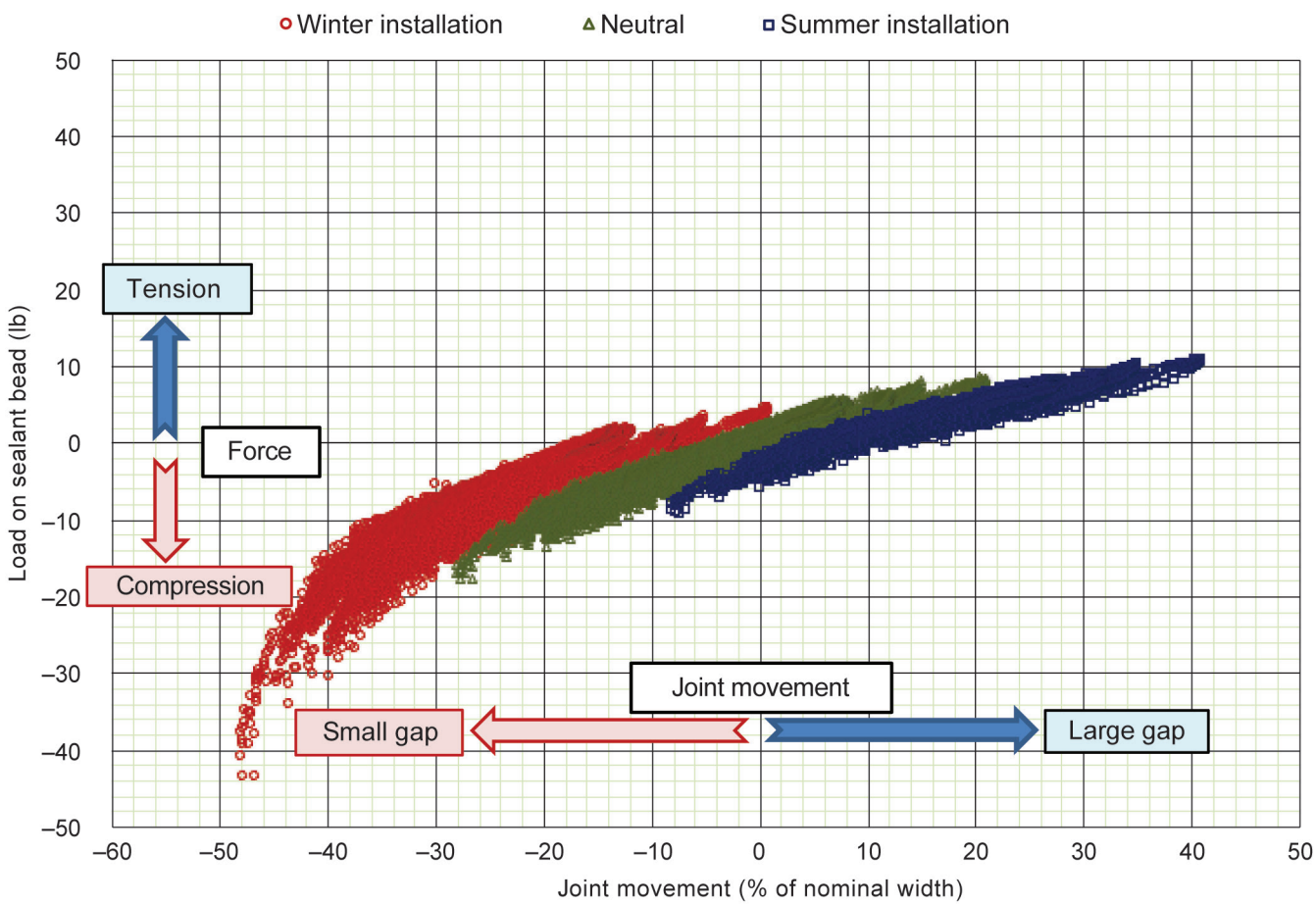

Figure 4. Plot of load on polyurethane sealant test specimens as a function of joint movement during 1-month cyclic deformation during outdoor exposure. Note that loads in compression are much greater than loads in tension.

Laboratory Test Results

The higher loads induced by compression were further investigated in the laboratory by exposing sealants to alternating compression and tension loading with magnitude increases after each cycle. Figure 5 shows the plot of load versus joint movement for these tests. The results clearly reveal that compression induces significantly higher loads than tension. The formation of a neck during tensile loading resulted in a plateau at low strains that was generally maintained even at high tensile extensions. Note that sealants will vary in their load versus strain response, including at what tensile strain they reach a load. The severity of compression loading is demonstrated by observing that the load at 65% compression was more than eight times that at 65% extension. The test had to be stopped before reaching 70% compression to prevent exceeding the load capacity of the test apparatus. At the manufacturer's stated limit of ±40% deformation, compressive load was three times as high as tensile load. This is in close agreement with the data obtained from the outdoor cyclic deformation tests.

A possible consequence of the high loads and joint movement seen in Figure 5 is damage to the sealant or bond. High-quality modern sealants can withstand significant elongation without failure. The silicone sealant in our test was rated for 40% elongation, but withstood 70% elongation without failure. The polyurethane sealant was rated for 100% elongation and also withstood 70%. Compression is different. The silicone sealant was rated for 40% compression and debonded from the substrate when subjected to 45% compression. The polyurethane sealant was rated for 50% compression and debonded from the substrate when subjected to 70% compression.

To separate any contribution of tensile loading toward failure, these tests were repeated with a constant cycling of the specimens between 70% compression and 20% tension. The testing paused at 20% tension to allow for visual examination of the bond. Cohesive failure of the sealant was observed along all edges of the bondlines (Fig. 6). Damage increased with each repeated cycle. Failure or damage took the form of a crack starting at the sealant–substrate interface and propagating toward the center of the specimen. The failure mode is cohesive, with a thin layer of sealant remaining adhered to the aluminum substrate after failure.

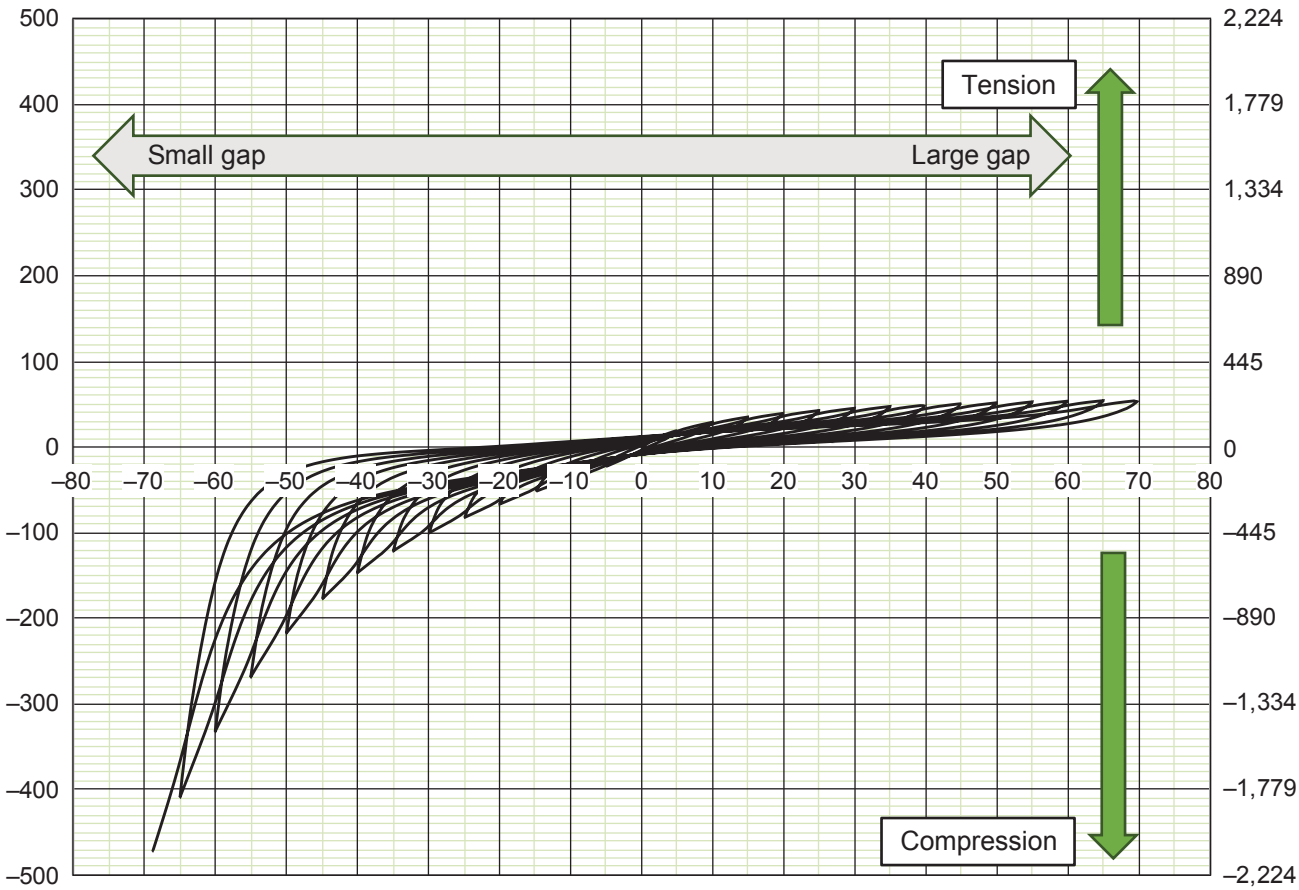

Figure 5. Plot of load (lb on left, N on right) versus deformation (percentage of nominal gap width) for cyclic deformation laboratory test. Load at 40% compression was three times higher than at 40% tension.

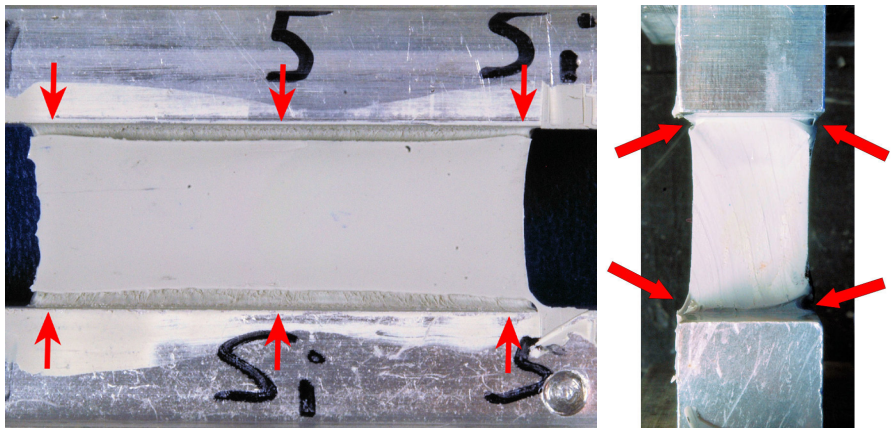

Figure 6. Damage along the bondlines (arrows) of a silicone sealant specimen after 10 cycles of 20% extension and 70% compression. Both images are shown with an extension of 40% to highlight the damage. View from side (left) and end (right).

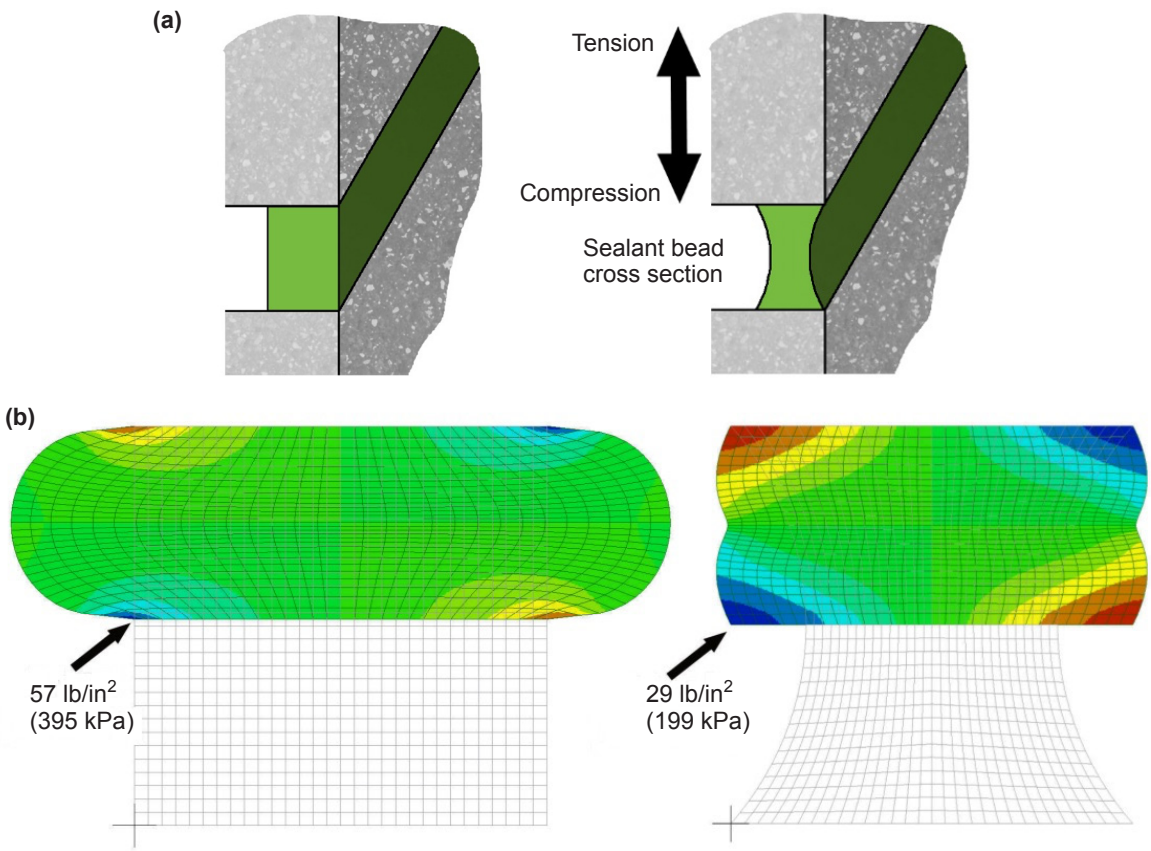

Figure 7. (a) Cross-sectional diagram of two sealant beads. Untooled rectangular bead (left) and a properly tooled concave hourglass-shaped bead (right). (b) Comparison of finite element analysis results for untooled (left) and tooled (right) silicone sealant beads under 50% compression. View is looking end-on to a sealant bead compressed vertically. Gray mesh shows the undeformed bead shape. Tooling reduced the maximum stress by almost 50%.

Based on these test results, sealants should be installed to avoid excessive compressive deformation. Compression induces shear forces in the bondline that can result in failure at or near the bondline. Once a failure begins, subsequent expansion of the joint can peel the sealant bead away from the substrate, leaving gaps that will allow air and water intrusion. In cold climates, water that fills the gaps may freeze and expand, causing additional cracking of the sealant.

Finite Element Models

Finite element analysis was used to generate models of sealant beads under joint movement to further investigate the compression failure mode. Here we modeled the response of the sealant from the point of view of the cross section perpendicular to the long axis of the sealed joint (Fig. 7a). Figure 7b shows models of the stress field resulting from 50% compression of a silicone sealant bead without (left) and with (right) tooled faces. The untooled bead is similar to the square cross-section used in the outdoor exposure and is depicted in its undeformed stated below the stress field as a grid. Similarly, the tooled bead on the right is depicted as an hourglass-shaped grid that resulted from the backer rod and shaping of the surface of the uncured bead with a tool or gloved finger. The stress field of the deformed rectangular bead (left) shows bowed ends, in agreement with the test specimens used here. The stresses are well distributed across the sealant except for highly concentrated loads at the edges. The tooled bead (right) has lower stress concentration at the corner, and the stress is evenly distributed to the faces of the bead. The color scales for both model beads run maximum to minimum separately and thus cannot be directly compared. However, looking at maximum loads in the same corners, the rectangular bead with flat surfaces has almost double the load as the hourglass-shaped bead with tooled surfaces, a clear demonstration of the importance of tooling.

Finite element analysis was further used to examine the effect of installation condition on the strain a tooled sealant bead would experience during a service year. Figure 8 shows an example of how the state of the joint at time of installation affects the deformation (as a percentage of as-installed bead width) experienced by the sealant in service. The basis of these models is a hypothetical joint designed to move ±25%. The FEA images on the left-hand side represent the situation in which the sealant bead was

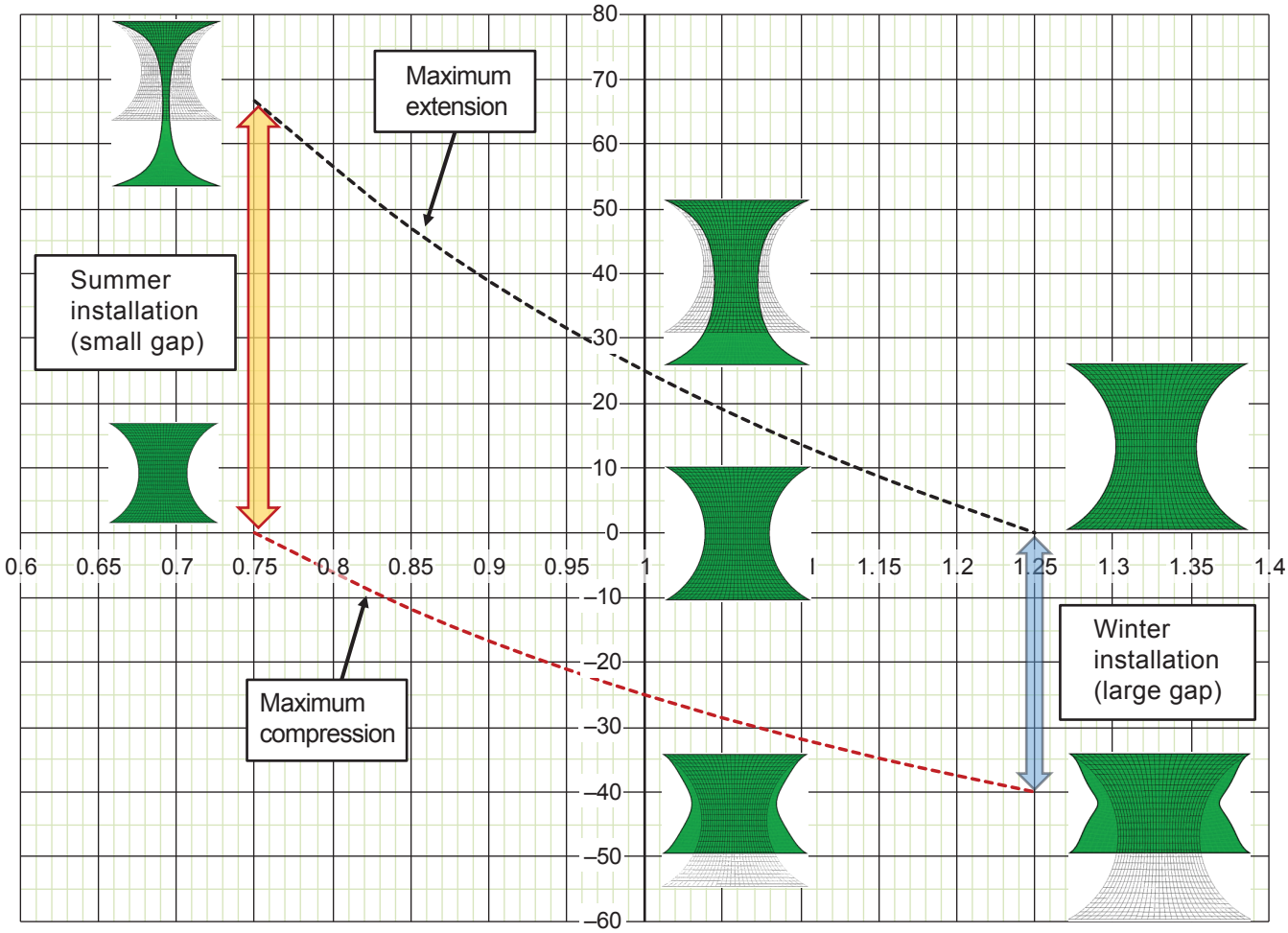

Figure 8. Range of deformation (percentage of as-installed bead width) for sealants installed in joints designed for ±25% movement. The horizontal axis represents the ratio of the joint gap width to its neutral (spring–fall) width at the time of installation. Sealants installed in cold weather (right side) see mostly compression, whereas those installed in warm weather (left side) see mostly tension. Sealant bead cross sections representing the extremes of deformation for (left to right) summer, spring–fall, and winter installation are also shown with grids representing their undeformed shapes. Pictured deformations are exaggerated for clarity.

installed during warm weather when the joint gap was compressed 20% from its neutral gap width, at or near its minimum gap width. The middle FEA images represent a sealant bead installed during spring or fall when the joint gap width was at the midpoint of its design movement. The right-hand side FEA images represent a sealant bead installed during cold weather when the joint gap width was opened 20% from its neutral width, at or near its maximum gap width. The rows (FEA models top to bottom) represent what each sealant experiences as the joints expand and contract with seasonal temperature changes during the year.

The displacement values from the FEA models are also plotted in Figure 8 as continuous lines versus the gap's variation from the neutral position. The upper dashed line is the maximum elongation of the sealant bead and the lower dashed line is the maximum compression of the sealant bead. The center of the plot, (1, ± 25%), represents installation at the point of average gap and the sealant cycles symmetrically with equal amounts of tension and compression. The right side of the plot, (1.25, 0/–40%) represents sealant installed when the structure is cold and joint gaps are expanded. Even though the joint is designed for ±25% movement, the sealant experiences a range from 0 tension to 40% compression. The left side of the plot, (0.75, +67%/0) represents sealant installed when the structure is hot and the joint gaps are compressed. The sealant experiences 67% tension but 0 compression. Note that ideally, installed sealant beads are twice as long parallel to the motion as perpendicular to the motion, so sealants installed in large gaps require greater depth as well as width.

Sealants installed during the summer experience the highest strains, or percentage change in size, compared with any other installation period. This is a favorable condition because this high strain is all tension, which

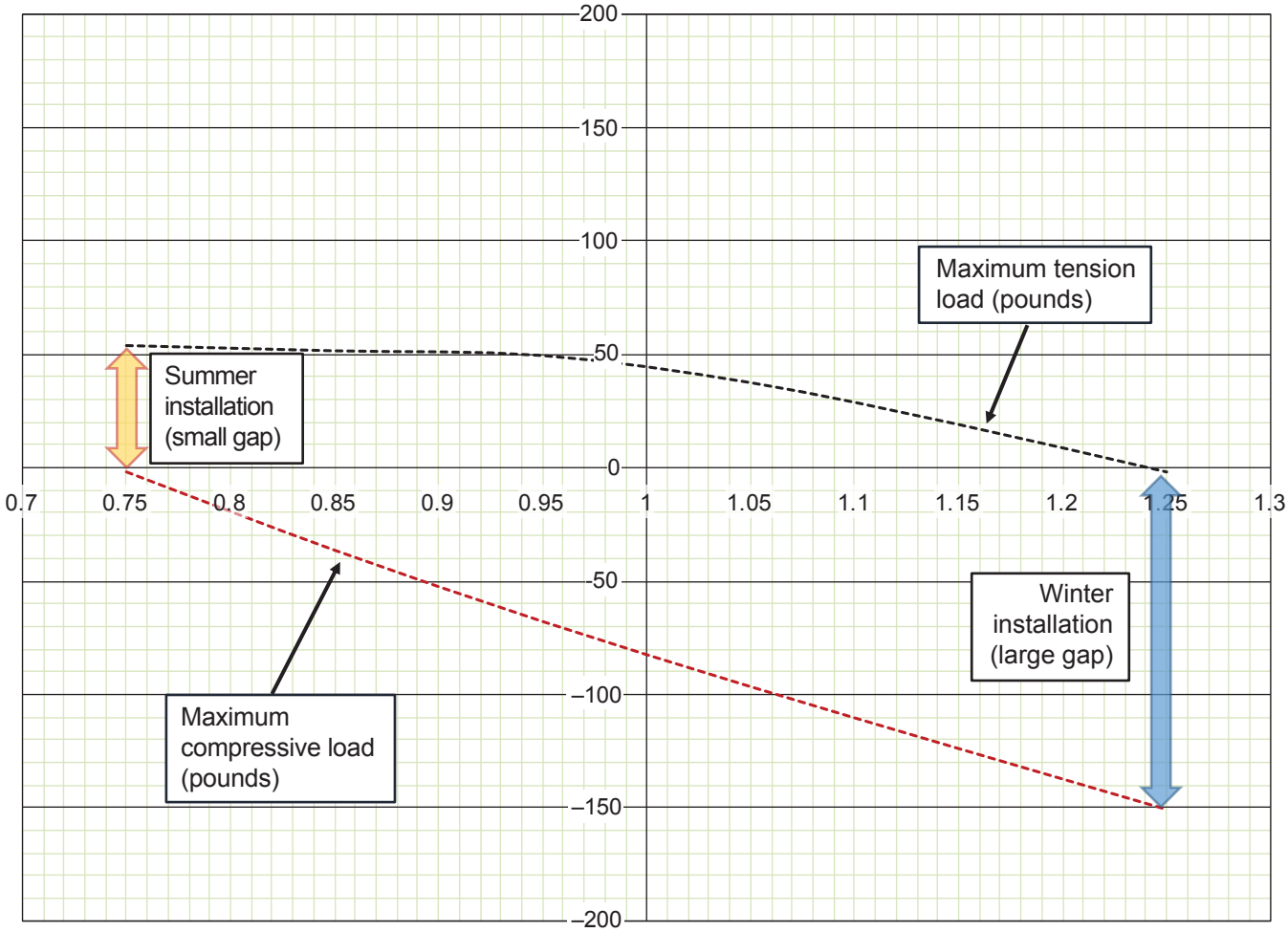

Figure 9. Predicted seasonal range of loads (lb) experienced by a silicone sealant in a joint designed for ±25% movement as a function of gap width at installation (ratio of actual gap width to neutral gap width).

results in significantly lower loads than the compression a winter installation experiences. The loads resulting from the installation conditions shown in Figure 8 are plotted in Figure 9. Here the highly favorable condition of low overall loads produced by summer installation can be observed on the left-hand side of the plot. Only tensile loads are experienced by sealants installed at the highest summer temperatures. Moving from left to right, as installation conditions move to cooler temperatures, the tensile loads maintain a plateaued maximum value due to necking, whereas the compressive loads grow linearly. Once the neutral (spring/fall) temperature is approached the maximum tensile loads drop linearly until they reach zero at the minimum installation temperature where the compressive loads are maximized. Our measurements on the sealants tested here indicate the maximum compressive loads are three times higher than the maximum tensile loads, even though the compressive deformation is less.

Conclusions

Outdoor aging of sealants with movement demonstrated that neutral and compression-biased silicone specimens decreased in stiffness by 36% during exposure, with the most rapid loss occurring for the specimens biased in compression (winter installation). The specimens with little overall loss in stiffness were those biased in tension (summer installation). The dynamically tested urethane did not change in stiffness even though it had surface erosion and micro-cracking. Sealants exposed to the same outdoor environment without movement had no significant change in stiffness even though the changes in their surfaces were the same. An overstrain event caused by sensor failure damaged all but the tension-biased specimens and ended the testing at 44 months. Tension bias induced by summer installation demonstrated a protective effect on sealants with regard to cyclic aging damage and overstrain due to the overall lower loads compared with compression. Cyclic aging was found to be necessary to induce property changes in the sealants that would otherwise be missed by static outdoor exposure.

Laboratory testing further investigated the effects of compression versus tension loading. Compressive strain applied to sealants caused significantly higher loads than tension. Tensile loads plateaued at moderate strains due to the formation of a neck. Under compression, the sealant bulged out of the joint, resulting in loads three to eight times higher than tension. Sealants subjected to compression in excess of the manufacturer's recommended limit failed where similarly strained specimens under tension did not. Compressive failures occurred without any tension applied to the sealant specimens, countering the commonly held notion that tension is required for sealants to crack.

Finite element analysis revealed that untooled rectangular beads have more load concentration at the bond edges, with load values approximately double that of sealant beads with front and back tooled surfaces. Tooling sealants to the preferred hourglass cross section significantly reduces loads under compression and facilitates the formation of a neck in tension. The FEA models also demonstrated that installation temperature locks in the sealant's exposure strain level and compression–tension asymmetry. Installation in the summer results in sealants predominately in tension, with overall lower loads. Winter installation creates the opposite situation of primarily compression and may lead to over straining or loading sealants, resulting in premature damage and possibly failure.

Note that in some circumstances, the direction of substrate movement may be opposite of that described here, but the results and findings presented here are still relevant because the application of tension or compression is the important factor, not necessarily the temperature.

Recommendations

Because installations of sealants will not likely occur exactly at the time when the joint gaps are at the midpoint of the building's seasonal expansion and contraction, most installations will experience unbalanced movement. It is important to ensure that the movement capabilities of the sealant exceed the actual movement of the building with respect to installation and cure temperature. Thus, it is important to ensure that installation is in accordance with the manufacturer's instructions and consult an architect, structural engineer, or ASTM C1472 for required sealant movement rating. Ensure that the movement rating according to ASTM C1472 on the sealant label is sufficient for the expected movement. Durability may be improved by increasing the size of the gap relative to the expected movement, resulting in less percentage deformation of the sealant bead and decreased reaction loads.

Because joints expand as building materials contract with decreasing ambient temperature, it is especially important to plan for sealant compression if the sealant is installed when the building structure is cold, as in winter. Sealant installed in joints while the joints are near their widest will experience mostly compression, and therefore higher shear forces on the bondline.

Ensuring an hourglass cross section, by using a backer rod and tooling the surface, is highly recommended because it will significantly reduce the loads experienced by the sealant. In this work we assumed that some things were done well. These include ensuring that the back side of the sealant can move freely by using a flexible backer rod, not a stiff material, and that proper surface preparation was performed to ensure a proper bond to the substrate. A proper bond can be tested in the field by applying sealant to test pieces of the substrate, curing it, and then testing its strength after the joint has been soaked in water for a few hours. Further information on sealant installation is provided by Carll (2006), ASTM (2014, 2016), and Dow Corning Americas (2011).

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