ADVANCES IN TESTING TECHNIQUES FOR POLYMER FOAM PRODUCTS USED IN STRUCTURAL LONG-TERM APPLICATIONS

Abstract:

Structural foam products are found across a wide range of industries including the construction market.

For applications requiring long-term resistance to buckling and compression failure, conventional test methods do not appropriately identify sample geometry and techniques that capture the inherent variability of cellular structures found within large-scale parts with complicated geometries.

Test methods for identifying and quantifying the failure mechanisms of structurally foamed polymers for long-term applications are explored in this work. The effect of void size and stress concentrations are specifically investigated, and a method of utilizing the failure criteria for quality control through nondestructive testing to determine critical cell size and locations is discussed.

Introduction:

CULTEC Inc. has manufactured arch-shaped corrugated plastic chambers for the subsurface septic and stormwater markets for the past 30 years using the thermoforming process.

When CULTEC began designing and manufacturing its largest chamber to date, they chose *Structural Foam Injection Molding* as an affordable means to enter the marketplace with a product with strict dimensional and performance requirements, including resistance to long-term traffic and soil loads per AASHTO and ASTM standards.

This low pressure process requires lower cost aluminum molds and lower clamp tonnage, while maintaining high dimensional accuracy of the part. A cellular plastic part also has lower internal stresses than traditional injection molding.

Fig 1. Cellular plastic stormwater chambers

This process allows for part weight reductions of 10-30% and increased strength and stiffness due to the cellular structure and resulting increase in chamber thickness.

To ensure that the foamed chambers, as shown in Figure 1, meet performance requirements, it is critical to understand the variability inherent in the foaming process. Due to the large size and weight of the part, some gas pockets typically form at various locations (Figure 2). These pockets, if below a critical size, are not expected to substantially deteriorate the collapse strength of the part, due to the large size, high geometric stiffness from the corrugations, and distributed loading present.

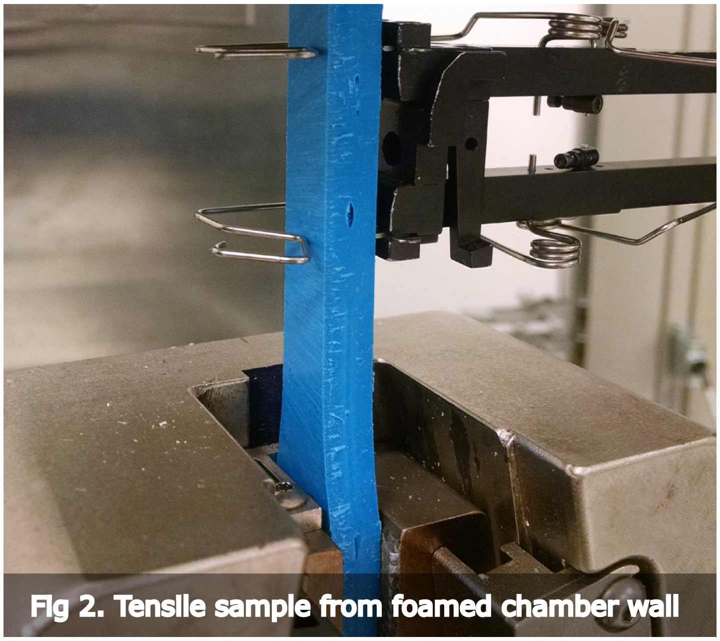

Fig 2. Tensile sample from foamed chamber wall

However, it is necessary to determine what this critical size is, so as to develop a quality assurance process that can identify any gas pockets that exceed that size in a cost effective manner on production parts.

Materials:

One impact-modified polypropylene copolymer was used for the experimental work supplied by Chase Plastics. The data sheet [1] denotes a nominal specific gravity of 0.900 g/cm^3, a nominal tensile strength of 25.5 MPa (3700 psi), and a nominal flexural modulus of 1.07 GPa (155,000 psi). The melt mass flow rate (MFR) for the resin is noted as 10 g/10min (230^{o}C, 2.16 kg) and the nominal notched izod impact strength is 6.41 J/cm (12 ftlb/in).

Literature Review:

CULTEC approached Stress Engineering Services Inc. (SES) to develop a testing and analysis approach to identify the critical void size in the foamed polypropylene stormwater chambers. Based on a literature review, no existing research adequately investigated the presence of gas pockets or voids. Previous research has focused on detailed characterization of micro scale voids (including those typically found in foamed rigid plastics), such as work completed by Turng [2] and Hwang, et. al [3]. This research has examined the mechanical properties of foamed injection molded parts (also referred to as microcellular injection molding) under various molding conditions. Of interest to CULTEC and SES are unintended, larger scale voids, and their effect on structural performance.

Testing Approach:

SES decided to adapt an accepted test method, ASTM D695-15 [4]. Solid plates of the polypropylene resin were molded at low hold pressures (similar to the actual process), however no chemical blowing agents (CBA) or injected nitrogen gas was used, unlike in the production process. This was done to allow the manufacturing of precisely known simulated gas pocket structures in an otherwise solid structure. The baseline sample size was 50.8 mm X 12.7 mm X 6.85 mm (2.0 in X 0.5 in X 0.27 in). This size was chosen to be near the maximum slenderness ratio allowed (for the solid specimen), so as to make the sample more sensitive to buckling, the behavior of interest. The thickness was chosen as it is near the actual wall thickness of the stormwater chambers in question, 7.62 mm (0.30 in.). In addition to the baseline solid sample, eight other configurations of the baseline sample size were machined to create known void patterns, as well two additional configurations which changed both the solid sample size and machined void size (See Figure 3, configurations #10 and 11).

These samples were intended to represent larger void sizes and lower aspect ratio voids respectively. All samples are described in Figure 3. Five samples each of eleven configurations were tested. Samples were tested in an MTS RT-100 load frame at the Stress Engineering Services material testing laboratory in Cincinnati, OH. The test fixture and sample during the test are shown in Figure 4.

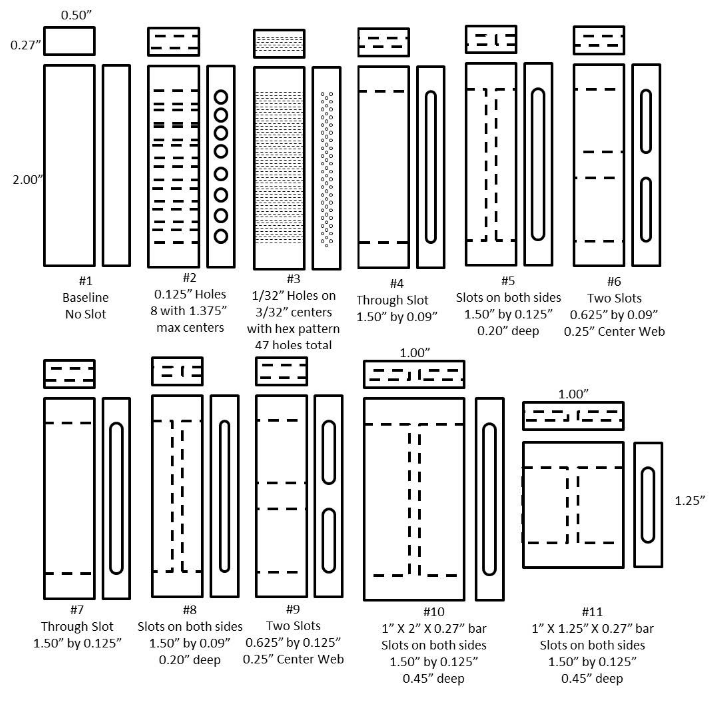

Fig 3. Compression test sample configurations

The test was performed with a crosshead speed of 0.05 in/min. Of particular interest from the test was the strain at peak load. This value indicates how far the sample was deflected before buckling occurs, after which the strength of the structure decreases rapidly.

In the real-world part, the distributed soil loading suggests that the chamber wall can remain structurally sound even with the presence of voids as long as the voids do not compromise the local buckling strength of the wall at that location. As long as the structure remains below this critical strain level, the void region continues to carry increasing load, as the excess stress (due to the missing void material) is redistributed around the void into the wall. However, if a void region reaches peak load at a much lower strain the surrounding wall, that region will buckle, requiring the surrounding material to take up much more of the load, and potentially leading to a total collapse.

The test is designed to identify what size of void can be accommodated while still maintaining a minimum strain to peak load value (determined by testing and analysis of the chamber wall). The simulated voids are expected to be conservative with regards to predicted strength and strain before peak load, as the edges of these voids are free to deform in any direction, while actual voids, with surrounding material, are more constrained with forced symmetry of their deflection.

Results:

The test configurations exhibited distinct differences in failure behavior as expected. Strain to peak load results are shown in Figure 5. This strain was calculated from crosshead deflection of the load frame and the initial measured length of each sample. Additional details including the average, range, and standard deviation for the strain at peak load for each configuration is shown in Table 1. A comparison of the nominal stress/strain curves for representative samples from each configuration is shown in Figure 6. Stress values were calculated for the original specimen cross section, and not adjusted for the material removed during machining of the test voids. Significant reductions in strain capacity before buckling were observed for all four of the configurations which had through slots, which effectively represent an infinitely long void, perpendicular to the load path. The strain at peak load was reduced by 73% for both of the 2.3 mm (0.09 in) through slots, and by 82% (single slot) and 72% (double slot) for the 3.2 mm (0.125 in) through slots.

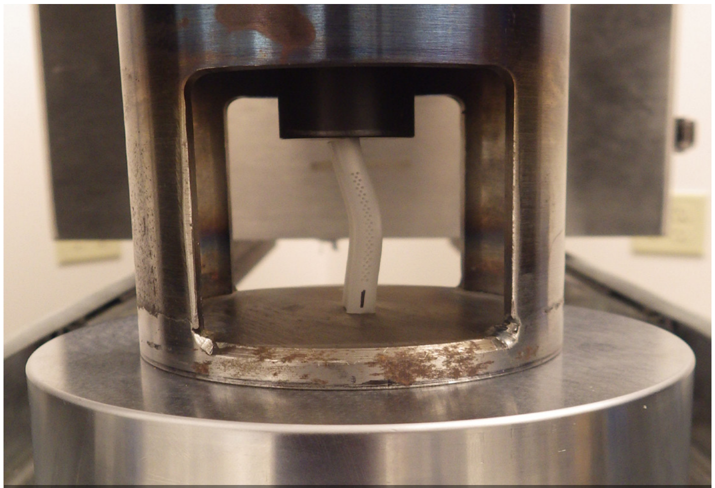

Fig 4. ASTM D695 Compression Test Setup

	Strain at Peak Load (mm/mm)		
Configuration	Average	Range	StDev
#1 Solid - Baseline	0.040	0.006	0.003
#2 8X 0.125" Holes	0.046	0.009	0.004
#3 47X 0.0313" Holes	0.043	0.009	0.004
#4 0.090x1.5" Through Slot	0.011	0.004	0.002
#5 0.090x0.2x1.5" Slots	0.035	0.014	0.006
#6 2X 0.090x.625" Through Slots	0.011	0.001	0.000
#7 0.125x1.5" Through Slot	0.007	0.001	0.001
#8 0.125x0.2x1.5" Slots	0.034	0.007	0.003
#9 2X 0.125x.625" Through Slots	0.009	0.001	0.000
#10 1x2x0.27 Bar, 0.125x0.45x1.5" Slots	0.019	0.002	0.001
#11 1x1.25x0.27 Bar, 0.125x0.45x0.75" Slots	0.031	0.008	0.004

Table 1. Strain at Peak Load Results

However, as indicated by the two samples with a remaining web between the surface layers, a very small web thickness is sufficient to prevent premature buckling, restoring most of the strain capacity of the structure. The partial depth configurations (#5 – 0.09 in slot, #8 – 0.125 in slot) exhibited average strain capacity reductions of only 13% and 15% respectively.

Only when increasing the sample width to 25.4 mm (1 in), with a remaining web of only 2.54 mm (0.10 in) did a substantial loss of strain capacity result with a partial depth slot (51.9%, configuration #10). This loss was largely reversed, however, when the simulated "void" length was reduced from 38.1 mm to 19.05 mm (1.5 in to 0.75 in), representing an approximate void size of 19.0 mm X 22.9 mm (0.75 in X 0.90 in). This configuration, #11, exhibited an average reduction in strain capacity of 23%. The approximate void size is equivalent to splitting the central web in half and moving it to the outside edges of the sample, which is more similar to real-world void geometry, but is not feasible to manufacture in a controlled manner.

The strain capacity before buckling was relatively insensitive to the through-thickness width of the slot (0.090 in vs. 0.125 in). This sensitivity is likely to be further reduced in the actual part with foamed material, as the core material that is missing in a gas pocket was already highly foamed and contributed much less stiffness than the dense surface layers. This effect also would result in a decrease in the loss of stiffness and strength for the actual part as compared to the solid wall.

Application to Analysis and Long Term Behavior:

SES is currently testing several additional test specimens under constant stress loading conditions. These are in process and intended to investigate if the strain capacity of the modified specimens remains constant across both short duration and long duration compression tests, as is commonly assumed for typical creep behavior.

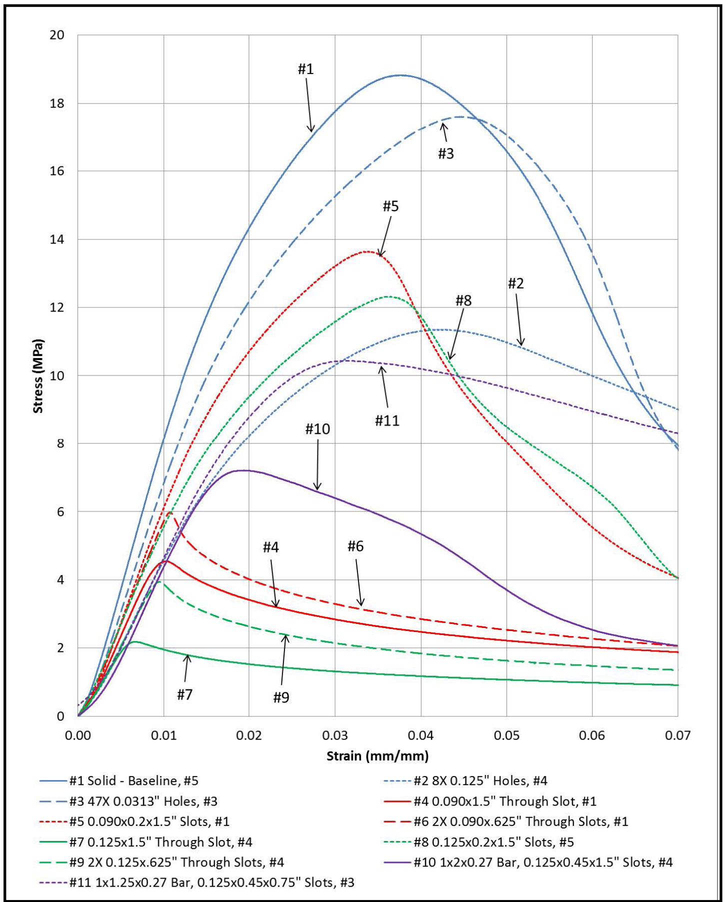

Fig 6. Stress-strain comparison.

Future work utilizing this modified ASTM D695 test setup aims to use the test configurations as validation tools for finite element analysis. By simulating the test configurations, the material model and structural configuration of the model can be adjusted to accurately capture the changes in buckling behavior.

This in turn will allow the evaluation of true, fully contained gas pockets, which cannot be directly machined but are the true representation of the real-world part. This also can be extended to allow for the analysis of specific-sized gas pockets located at critical locations in the arch by combining simplified analyses of the chamber (such as those per ASTM F2787 [5]) to predict the overall loading on a specific section of chamber wall, then implementing a sub model of the region of interest with the global loading conditions superimposed.

Application to Quality Assurance Process:

Because of the size of the stormwater chambers and the associated manufacturing costs, a number of nondestructive test methods are being evaluated to inspect the chambers. It is important to reliably identify critical voids, however the techniques that can be used, as well as their associated cost and time to complete, are directly influenced by the size of the void that is being pursued. For this reason, it is desirable to identify how large a void must be before posing a structural hazard, and limit the inspection for voids that meet or exceed that size. By utilizing the testing and analysis approach described here, it is possible to identify this critical size.

The results from this study indicate that it is likely that the small, difficult to detect gas pockets that are known to occur in the part are unlikely to significantly affect the collapse strength of the chamber. In addition, by utilizing these test results in conjunction with future testing and analysis of chamber wall profiles, critical locations on the chamber can be determined, and the maximum allowable void size at these locations calculated.

Possible nondestructive techniques that could be used in an ongoing Quality Assurance process include ultrasonic testing and laser flash diffusivity. These processes allow for varying degrees of void identification and measurement, but both become more cost effective and technically feasible as the size of the voids of interest increases.

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Key Words:

FOAMS, Structural Foam, Cellular Plastic, Closed Cell, Polypropylene, Failure Mechanisms, Chamber, Long-term, Compression, AASHTO, ASTM, Stormwater.

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