ASSESSING THE STIFFNESS OF GAS-ASSISTED THERMOPLASTIC PARTS

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ABSTRACT

The hollow sections or channels created using gas assisted injection molding are sometimes used to stiffen parts and reduce part weight. The increase in stiffness or reduction of weight provided by this process is an important characteristic that the design engineer needs to consider before designing a part for this process. A method for calculating and comparing these properties must be established. In this paper, plaques having different gas-assist rib designs are compared to non-ribbed and conventionally ribbed plaques for both simply supported and end-clamped boundary conditions. It was observed that the gas-assist designs possess stiffness-to-weight ratios that are approximately five percent higher than those of identical solid rib designs. Significantly highter stiffness-to-weight ratios are possible when compareing tube-like geometries.

INTRODUCTION

The gas assisted molding process may be used to create injection molded parts with large hollow sections. The stiffness benefits obtained by adding a hollow rib to a flat plaque are evaluated. This geometry is typical of thin structural-bearing parts such as computer housings, automotive fenders and bumpers, and other instrument panels.

To perform an accurate structural analysis of a gas-assisted part, the size of the core formed by the penetrating gas during processing must be known. Because the temperature distribution in the molten core prior to gas penetration is approximately uniform, these dimensions can be estimated by performing isothermal, gas penetration experiments through viscous liquids in confining geometries. Such experiments [3] suggest that a significant portion of the final part thickness results from molten plastic that is deposited by the gas on top of the solidified skin. Because molten plastics are characterized by a high viscosity, the ratio of molten thickness to the effective radius of the cross-sectional flow area has been shown to approach a fixed percentage of approximately 1/3. Although further work is necessary to quantify the effects of shear-thinning on the thickness formation process, this 33% rule can be used as a first approximation to determine the total thickness of gas-assist parts. These assumptions are used to provide estimates of gas penetration in the analysis below.

ANALYSIS OF RIB GEOMETRIES

In this section, simple ribed plaques produced using gas-assisted injection molding are analyzed. The plaques evaluated are stiffened with structural ribs containing hollow gas channels (see Table 1). The structural performance of these plaques and of plaques produced by conventional injection molding is compared. The key objectives of this analysis are as follows:

- Evaluate the effect of structural ribs on part rigidity.
- Compare stiffness to weight ratios of plaques with conventional and gas-assist ribs.
- Predict load-displacement response of several cross sections by finite element analysis.
- Compare the load-deflection response to that of base plaques of equal volumes.

Analysis Method

The rib geometries shown in Table 1 were first analyzed for stiffness using Bernoulli-Euler beam bending theory. The following assumptions are made:

1. Beam is initially straight, unstressed and symmetric.
2. Material behaves elastically, i.e. no yielding occurs.
3. Beam material is homogenous and isotropic.
4. Young's modulus for the material is the same in tension and in compression.
5. Deflections are small, so that plane cross sections remain plane after bending.

Stiffness benefits of the semicircular and wide T-rib were investigated in detail using three-dimensional finite element modeling (FEM). Models of a long plaque were created for two rib geometries. The structural performance of each model was compared to that of an equal volume base model, loaded under identical conditions.

Load-displacement responses of the plaque models under simply supported and end-clamped boundary conditions were determined using the large-displacement non-linear analysis option of the ABAQUS finite element analysis code [5]. The plaque material was assumed to be elastic perfectly-plastic with an elastic modulus, E = 2000 MPa, and yield stress, σ_y = 60 MPa. The models were displaced at mid-span under the action of a concentrated load acting in a vertical direction as shown in Figure 1.

The 1/4 symmetry models were built using ABAQUS 3D-parabolic, type C3D20R, elements. The FEM models are shown in Figures 2 and 3. The model cross sections and dimensions are tabulated below in Table 2.

RESULTS

Effect of Structural Ribs on Part Rigidity

A structural rib makes a part resistant to bending by increasing its moment of inertia. Four simply supported plaques with different rib geometries were analyzed for bending using Bernoulli-Euler beam theory. The deflection y_{max} of the plaques under a concentrated load was compared to that of the base plaque. Adding a small semicircular rib to the base geometry under an identical load reduces its deflection by approximately 65%. The wide T-rib substantially stiffens the base plaque: the deflection of the stiffened plaque is only 2% of the base plaque deflection. The stiffening effect of the rib geometries is shown in Table 3.

Comparison of Gas-Assisted Ribs with Solid Ribs

Structural ribs with gas channels provide a higher stiffness to weight ratio. In Table 4, the bending stiffness to area (weight) ratios of plaque sections are compared with conventional (solid) and gas-assisted wide T-rib. In addition, the effect of gas channel shape on the plaque stiffness to weight ratio is evaluated by considering two gas channel shapes. In both cases, coring out material at the base of the structural rib improves the stiffness to weight ratio of the plaque; however, the percentage improvements are small and strongly depend on the cored-out area. For example, a 7% higher stiffness to weight ratio is predicted for the ribbed section assuming a triangular gas channel, but only a 3% stiffness to weight improvement is expected when a smaller circular gas channel is assumed.

Load-displacement Response of Plaque with Gas-assisted Semicircular Rib

The semicircular rib with hollow gas channel is effective in curtailing bending at deformations equal to its plaque thickness. The finite element analysis predicts that the semicircular ribbed-plaque, in simply supported configuration, is 35% stiffer than the base plaque of equal volume at a deflection of 4.8 mm (deflection/thickness = 1). The percent difference in stiffness corresponds to the ratio of the moments of inertia of the ribbed and base plaques which is about 1.33:1. With both ends restrained, the ribbed-plaque is very stiff as compared to the simply supported ribbed-plaque and shows a non-linear load-displacement response (Figure 4).

Load-displacement Response of Plaque Model with Gas-assisted Wide T-Rib

As expected, the wide T-rib with hollow gas-channel stiffens the base geometry significantly (Figure 5). In simply supported, center-loaded configuration, the FEM model of the plaque with gas-assisted wide T-rib is predicted to be 20 times stiffer than the base at a deflection/thickness ratio of 1. Also, at deflection/thickness ratio of 1, this ribbed-plaque model is 8 times stiffer than the plaque model with semicircular rib. It should be noted that the volume of the plaque model with the wide T-rib is 8% greater than the volume of the plaque model with the semicircular rib.

In end-clamped configuration, the plaque model with gas-assisted wide T-rib is about 4 times stiffer than the simply supported model at a displacement/thickness ratio of 1. The load-displacement response of the ribbed-plaque and the corresponding base is slightly non-linear in end-clamped configuration (Figure 5). However, for the plaque model with wide T-rib, the deviation from a linear response is small when compared to that of the plaque with semicircular rib in the displacement range considered.

DISCUSSION OF RESULTS

The stiffness of a part is a function of its geometry and material. A part is made stiffer by enhancing its section properties or by using a material with a higher elastic modulus. The moment of inertia (a section property) is increased by adding material to the part, for example, by increasing its wall thickness. The increase in moment of inertia is larger if material is added away from the neutral axis, for example, in the form of a structural rib. The analysis shows that adding a wide T-rib to the base beam reduces its deflection by approximately 98% while increasing its weight by only 26%. However, the weight of the base would have to be increased by more than 350% if part walls were thickened in order to equal the stiffness of the wide T-rib.

The analysis also shows that gas-assisted ribbed parts have a higher stiffness to weight ratio over conventionally ribbed parts. Table 4 shows that a hollow wide T-rib with gas channel increases the bending resistance (moment of inertia) of the base plaque by a factor of 40 while increasing its weight by 17%. The solid rib, on other hand, adds 26% to the weight of the base for a slightly higher moment of inertia. The difference in stiffness to weight ratios is expected to be less 10% with gas-assisted ribbed parts having the advantage; however, this assumes that a given part can be stiffened by conventional as well as gas-assisted structural ribs of equal size. In some situations, addition of large conventional ribs may not be desirable because of the resulting sink marks or higher cooling times required. In these situations, the gas-assist process provides a method for producing sink-free, short cycle time, ribbed parts with much larger stiffer ribs than could be produced by conventional injection molding. Also, closed-gas channel parts, although not a focus of this study, promise a significant stiffness to weight advantage over conventionally processed parts. For example, coring out the center of a long tubular part can result into a stiffness to weight ratio improvement of more than 40%.

For small deflections, the finite element load-deflection solutions for the ribbed-plaques agree with Bernoulli-Euler beam theory (linear-elastic) solutions. To illustrate this, the linear-elastic load-deflection curve of a plaque with a gas-assisted semicircular rib is compared to the one obtained by a non-linear large-displacement finite element analysis (Figure 6). For deflections up to the thickness of the plaque, the linear elastic bending loads agree with those predicted by the finite element analysis for the simply supported case, however, for the end-clamped case, the linear elastic bending loads diverge from the nonlinear finite element prediction for deflections beyond 1/10 of the plaque thickness.

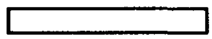
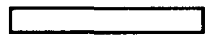
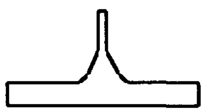
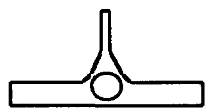
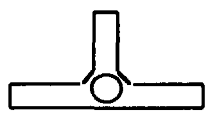
The three-dimensional finite element analysis of the plaques investigated shows that structural ribs are beneficial in the linear load-displacement range. Beyond the linear response range, the effect of added bending resistance diminishes. For example, the end-clamped plaque with a gas-assisted semicircular rib rapidly looses its stiffness advantage over the base as deflections increase, but the same plaque model in simply supported configuration is 30% more resistant to bending than the base for deflections of up to 2 times its thickness. This is shown in Figure 7 where the ratio of the stiffness of the ribbed-plaque to the stiffness of the non-ribbed base plaque is plotted as a function of displacement for the two boundary conditions. The stiffness ratio is calculated by dividing the stiffness of the ribbed plaque by the stiffness of the non-ribbed base plaque at set deflection intervals.

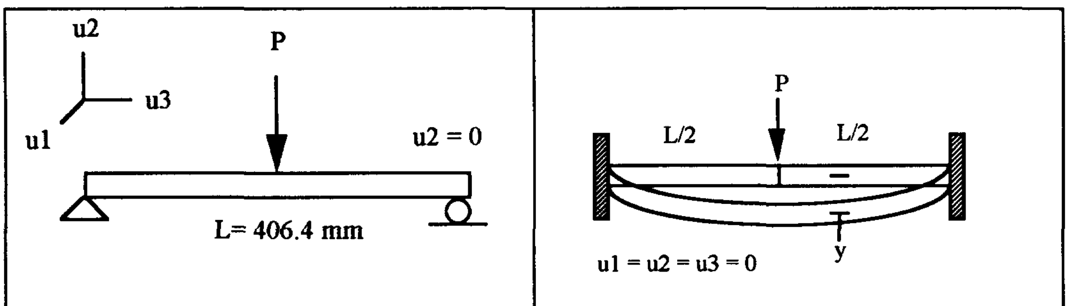
For deflections within the linear load-displacement range, geometric stiffness is determined by the sections moment of inertia. Whereas, at large deflections in-plane stretching becomes increasingly prevalent resulting in membrane stiffening. At this stage, the cross sectional area becomes increasingly important in determining the stiffness of a part. Because of the very restrictive constraints imposed in the end-clamped configuration, membrane stiffening occurs at smaller deformations. In the analyses reported here the ribbed and base geometries have the same cross sectional area and exhibit comparable stiffness at large deformation. However, the deformations and end-clamped boundary conditions imposed in these analyses are probably more severe than those experienced in most applications. It should be noted that membrane stiffening is a function of the boundary conditions, loading and stiffness of the part and will occur for conventionally rib stiffened as well as for gas-assist rib stiffened parts.

Although structural ribs increase part rigidity, they may reduce part strength by adding stress concentrators to a part. Stress concentration is an important design consideration for plastic materials in their brittle failure regime. Depending upon loading and boundary conditions, stress concentrations can substantially reduce the strength of a part. In tests on ULTEM 1000® material, ribbed disks failed in a brittle mode at loads an order of magnitude lower than those for flat disks [6]. Currently, little is known about the failure behavior of gas-assisted parts.

The analyses performed assumes a homogenous material and does not apply to fiber reinforced polymers. The effect of fiber orientation near the gas channel on the mechanical properties of filled materials is not known and needs to be investigated further.

Table 1. Rib geometries

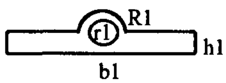
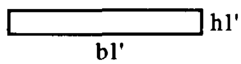
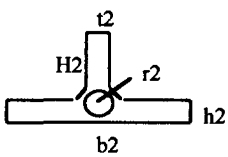
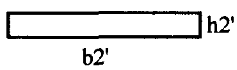
Rib Type	Solid	Hollow
Base		
Semicircular		
Oval		
Narrow T		
Wide T		



Simply Supported	End-clamped

Figure 1. Plaque model boundary conditions

Table 2: Cross sections of finite element models

Model	Section (mm)		Area (mm^2)
	Rib	**Base**	
1	 b1 = 76 2, h1 = 4 78 r1 = 2.63, R1 = 3 98 I = 963.7 mm4	 b1'= b1, h1' = 4 82 I = 711 07 mm4	367.00
2	 b2 = 101 6, h2 = 3 18 r2 = 1.92, t2 = 3.18 H2 = 22 22 I = 12516 mm4	 b2' = b2, h2' = 3.90 I = 460 92 mm4	396 00

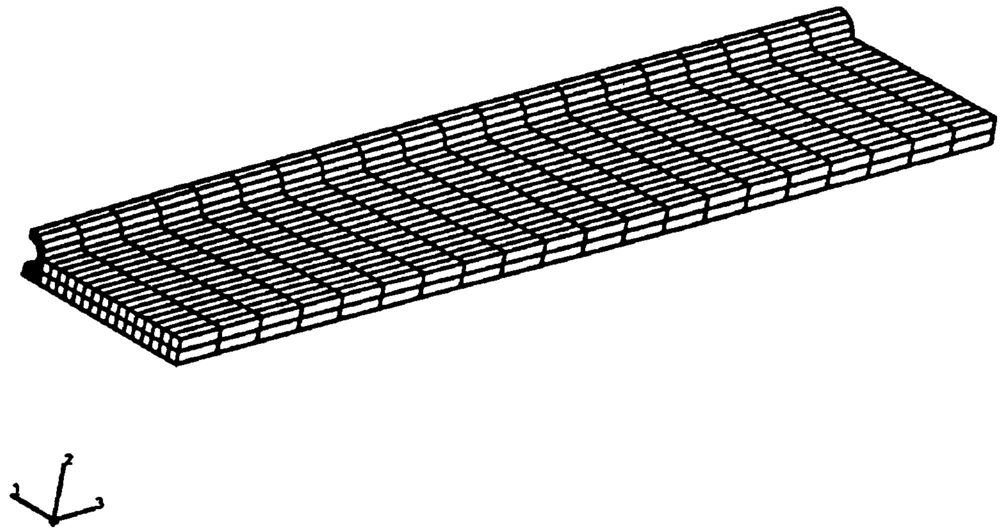


Figure 2. FEM mesh of plaque with semicircular rib (1/4 symmetry model)

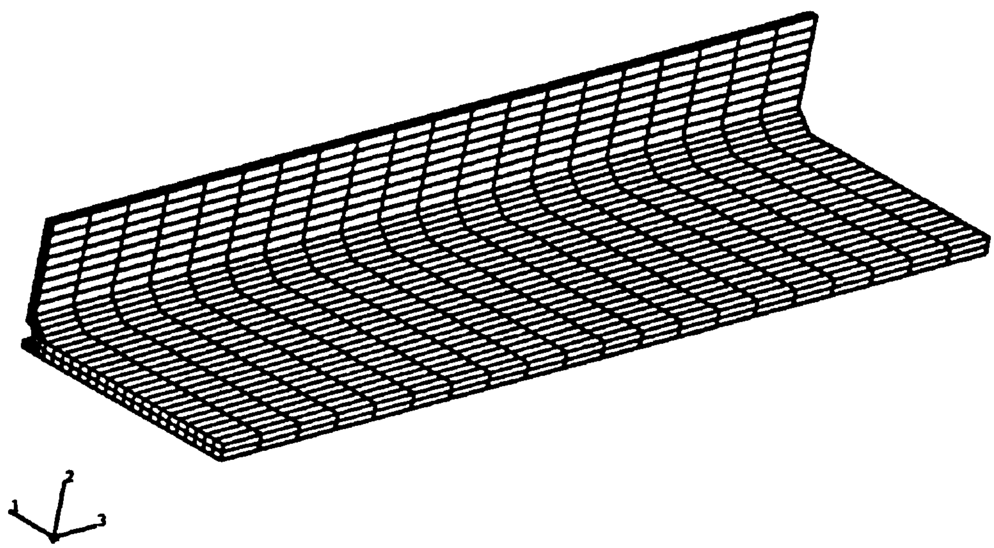


Figure 3. FEM mesh of plaque with wide T-rib (1/4 symmetry model)

Table 3: Effect of adding different structural ribs to a base plaque

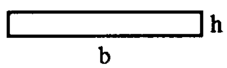
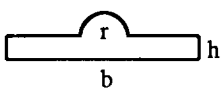
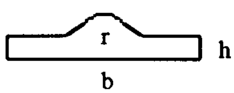
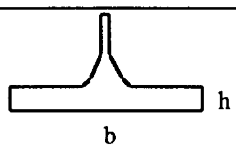
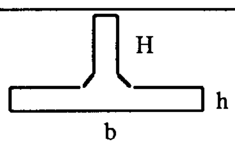
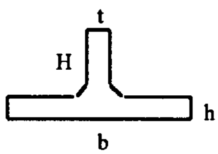
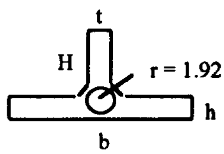
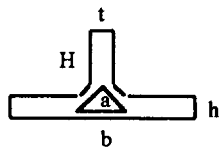
Cross-Section mm	**Moment of Inertia** I mm^4	**Deflection** (simply supported) y mm	**Deflection Ratio** $\left(\frac{y}{y_{base}}\right) * 100$ %
 b = 101.6, h = 3.18	272.27	3.21	100.00
 r = 4.76	745.05	1.17	36.54
	765.87	1.14	35.55
	7367.30	0.12	3.70
 H = 22 22	12530.50	0.07	2.17

Table 4: Stiffness-to-weight comparison of a solid-ribbed section to a ribbed section with gas channel.

Section mm	 b = 101 6, h = 3 18 t = 3.18 , H = 22 22		 a = 5.5
Area mm^2	408.00	396.00	377.00
I mm^4	12530.50	12514.00	12460.00
I/A	30.74	31.60	33.00
Normalized **I/A**	1.00	1.03	1.07

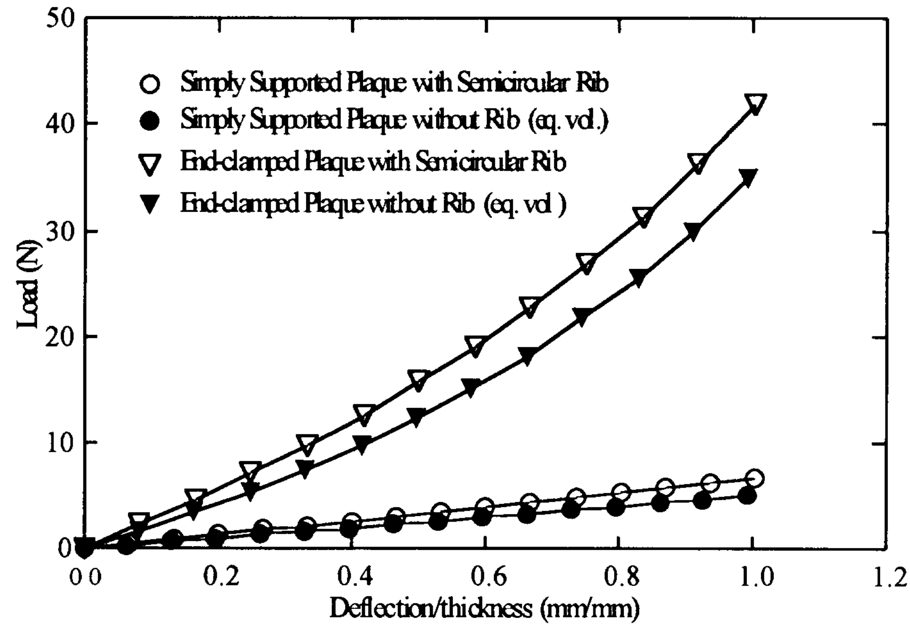


Figure 4. Predicted load-displacement for a plaque with gas-assisted semicircular rib, simply supported and end-clamped boundary conditions.

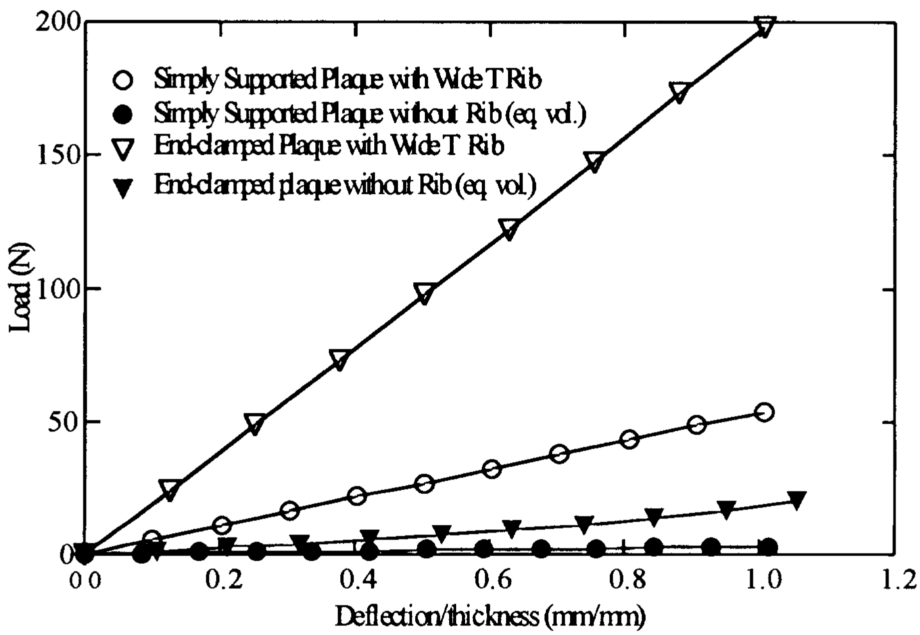


Figure 5. Predicted load-displacement for a plaque with gas-assisted wide T-rib, simply supported and end-clamped boundary conditions.

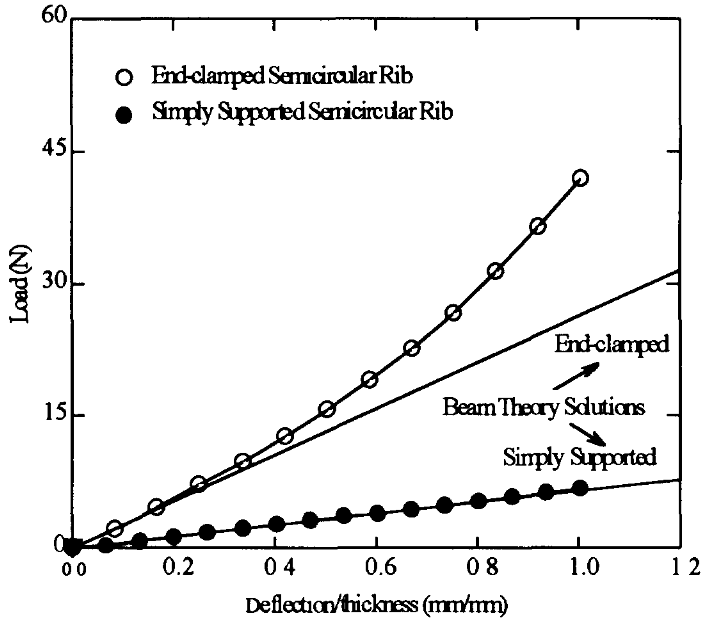


Figure 6. Comparison of beam theory and FEM load-displacement curves of a plaque with a gas-assisted semicircular rib.

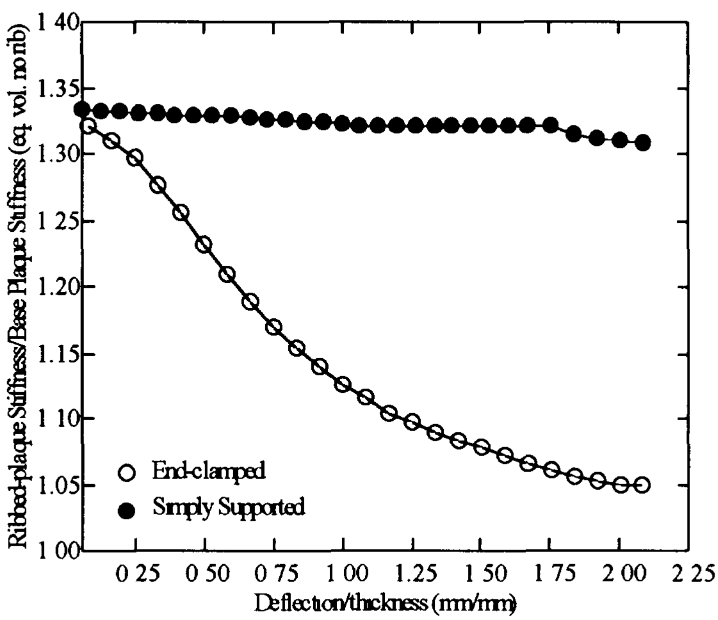


Figure 7. Ratio of the semicircular ribbed plaque stiffness to the non-ribbed base plaque stiffness as a function of displacement.

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BIOGRAPHY

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Anthony A. Gennari is a Process Simulation Development Engineer at GE Plastics in Pittsfield, Massachusetts, a position he has held for 2 years. Prior to that, he was a CAE engineer for Polymer Solutions, a joint venture between GE Plastics and Fitch RichardsonSmith of Columbus, Ohio. While a student, he also co-oped with both GE Aerospace and GE Plastics.

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