COMPUTER-AIDED DESIGN AND ANALYSIS PROCEDURES FOR STRUCTURAL FOAM COMPONENTS

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INTRODUCTION

The nonhomogeneous morphology which occurs naturally in the foam molding process poses problems of accuracy with respect to material characterization, engineering analysis, and ultimately in predicting part performance.

As a result, design engineers do not have the data, nor the comprehensive analytical tools to maximize the use of material properties, and thereby make the most efficient use of structural foam in the parts they are designing. Put simply, designers do not have the ability to design to the limit of the structural foam materials.

The major reason for this is the inability to account for discontinuities that occur in the cross-section of a foamed wall section. The problem is further compounded by traditional ASTM test procedures for tensile and flexural properties which do not adequately compensate for this unique morphology. Instead these values are truly an average range of performance for a cross-section, and generally do not allow for performance variations related to geometry and load.

Up to now, it has been the critical challenge of design engineers to combine knowledge gained from experience and published values in order to make performance assumptions for the parts they are designing. As foam parts see increased application in areas requiring higher load carrying capabilities, the challenge becomes even greater.

Yet it is specifically in these application areas where the inherent advantages of structural foam are most beneficial. Flatness, low-stress, high rigidity, enhanced chemical resistance and the economies of low-pressure molding offer the most attractive, cost/performance profile for numerous structural thermoplastic parts.

The work presented here describes new advanced design capabilities utilizing proprietary software developed in-house by General Electric Plastics, making accurate computer-aided design and engineering of structural foam a reality. This software, titled GEFOAMS (General Electric Foams Optimized through Analysis and Material Selection) embodies these capabilities in a single package.

The basis for GEFOAMS began over two years ago and culminated in the development of a mechanical model which accounts for the nonhomogeneous morphology of structural foam (1, 2). This layered, three-parameter model more closely simulates actual part performance by automatically and consistently accounting for the differences in average stiffness between tension and in-plane flexure.

The advent of this technology means design engineers, for the first time, have the tools to realistically maximize material performance and design in complex structural foam parts.

THE NEED FOR GEFOAMS

Thermoplastic structural foam materials are increasingly being used in applications requiring load carrying capability. In many of these applications, stiffness will be a critical engineering requirement. Although one might attempt to use "flexural moduli" for designs carrying load predominantly in bending and "tensile moduli" for uniform, in-plane loads, the ability to predetermine the mode of deformation in a complex body undergoing nonlinear deformation is extremely difficult. Thus, a more sophisticated methodology for predicting part performance is required.

In the past there has been much work done on the engineering properties of the nonhomogeneous foam structure. The bulk of these investigations (3–6) have focused upon the issue of predicting local as well as "average-apparent" flexural moduli for a foamed cross-section as shown in Fig. 1a. If an expression for the local modulus of a foam can be written as a function of unfoamed resin modulus, the reduced density (foam density/resin density), and the thickness coordinate of the part, then the "average-apparent" flexural modulus at a cross section can be calculated by integrating through the thickness.

However, local density and modulus variations throughout a single foam part are difficult to obtain (4). As a result, researchers have been forced to speculate about the mathematical form of this variation and carry out parameter studies based upon these speculations. Studies have also been carried out (7) to assess optimum values of resin rich skin thickness and modulus distribution.

Unfortunately, the ability to unify these variables and thereby use them to optimize design has been a difficult task. All of the previous research recognizes the fact that the variation in morphology of structural foam plays an important role in the stiffness of the section. However, faced with the complexity of variables and their interaction, the suggested design procedure is generally to use one modulus when tensile stress states prevail, and the other when flexural deformation is the rule. The philosophy of using different "apparent moduli" depending on perceived major stress state poses significant problems when designing complex parts subject to load.

First, the design engineer must make general assumptions as to which portions of the component will be subjected to flexural deformation, and which will experience tensile load. Secondly, the designer would have to consider reevaluating his assumptions when numerous load conditions must be factored into the design. Finally, large displacement deformation is a common occurrence in plastics which have a relatively low moduli; under these circumstances, both tensile and flexural loads are carried at the same geometric location. In these instances the design challenge is further compounded by the need then to choose what weighted averages of tensile and flexural moduli should be applied.

It is obvious that the trend towards large, load carrying parts in the structural foam industry has brought with it a complexity that is inadequately served by traditional design methodology. In fact, this complexity may actually be a barrier to new structural foam applications as it requires numerous design iterations, and long product development horizons to assure proper design and engineering.

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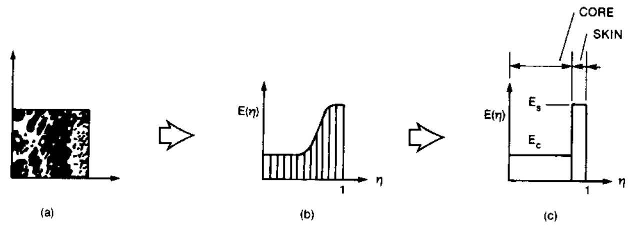

Figure 1. (a) Typical foam cross-section; (b) variation of Young's modulus with thickness dimension; local; (c) skin-core model

DEVELOPMENT OF GEFOAMS

The principal focus of GE Plastics work in this area was to provide a convenient alternative to complex structural foam design using finite element analysis. The goal was to establish a single, fundamental set of material data, accompanied by a convenient analysis procedure to predict the response of a general component to any load without forcing the design engineer to predetermine whether the response will be flexural or tensile at any particular point in the component.

The two overriding concerns in the development of this program were accuracy and simplicity. Therefore, the work began with the selection of a material model that when combined with non-standard test data would accurately predict actual material performance.

A typical foam cross-section consists of a porous, discontinuous core surrounded by two relatively solid "skins" – a distinctly different morphology in comparison to unfoamed polymers. The complexity of a material model accounting for these discontinuities exactly would make it impractical for large-scale analysis. Therefore, the mechanical model applied in GEFOAMS assumes that the material is approximately continuous, but *nonhomogeneous* with respect to the thickness direction.

In general, the properties of a structural foam could vary continuously through the thickness of a plate, as in Fig. 1b. A simpler approach to modeling the nonhomogeneous nature of a foam is to consider the cross-section to consist of three layers as in Fig. 1c a central core, and two face skins. The properties of the skin and core are distinct, but constant within a given layer. From the standpoint of deformation, such a model would require the definition of three "effective" properties, namely skin thickness, core modulus, and skin modulus.

Since most foam parts are by nature thin, the deformation can be assumed to be a combination of in-plane forces, flexural, and twisting moments. From the relationships defining the pertinent stress and deformation measures in both bending and in-plane extension; the cross-sectional stiffness constants are developed for the three-parameter model.

Using these stiffness relationships, along with the experimentally determined moduli from tensile and flexure tests, two of the three "effective" properties can be fixed. Then for a given skin thickness, t_s, the skin and core moduli can be calculated. That is, the expressions for E_s and E_c can be written in terms of E_t, the tensile modulus, and E_b the flexural modulus as:

$$E_s = \frac{E_b - E_t(1-\eta_0)^2}{\eta_0(2-\eta_0)} \tag{1}$$

$$E_c = \frac{(3-3\eta_0+\eta_0^2)E_t - E_b}{(1-\eta_0)(2-\eta_0)} \tag{2}$$

where E_s is the Young's modulus for the "skin" region, E_c that of the "core," and η_0 is the nondimensional skin thickness ($2t_s/h$) for the cross-section shown in Fig. 1c.

Development of Non-Standard Test Procedures

With the advent of the new material model which accounts for the inherent inhomogeneities, new test procedures had to be developed which accurately fit into the program framework. Standard ASTM tests were designed for homogeneous materials, and although they do lead to different "average" properties in tension than in flexure, these properties are inconsistent with experimental performance data from actual parts.

As discussed earlier, before GEFOAMS, a design engineer had to make assumptions and attempt to use flexural moduli for components carrying load in bending and tensile moduli for uniform tensile loads. This approach, however, makes it exceedingly difficult to predict the actual performance of a complex part under load, especially when it is undergoing nonlinear deformation.

At the center of the problem is the test bar itself. Because it is a molded specimen with skin surfaces on all four sides, the bar acts not as a plate "element" of a larger part, but as an individual molded part. Therefore, work was begun on designing proprietary test methodologies for giving a more accurate profile of material performance needed for computer analysis.

Through extensive parameter studies and experimentation, test procedures which more accurately predict actual material performance have been developed. These new procedures are currently being used to develop the material data base used in GEFOAMS.

Testing the Veracity of the Program

The combination of the new, more accurate mechanical material model, the nonstandard test data and finite element techniques is the key to GEFOAMS. However, numerous analytical experiments had to be conducted to test the veracity of the program.

The mechanical model used to predict structural foam performance within GEFOAMS was developed by V. K. Stokes at General Electric's Corporate Research and Development Center. Analytical predictions for the response of fundamental geometries and loadings were given based on the three-layer framework. Using these mathematical expressions, along with experimental results, the initial benchmarks were defined.

The next step was to move to more complex geometries, and again make analytical comparisons between the program results and actual experimental data.

Two simple form experiments, each demonstrating different fundamental modes of deformation were used to assess the veracity and applicability of the model. Comparison of analytical performance with experiment confirmed the ability of the GEFOAMS program to realistically predict material behavior.

The first test compared with analysis is a simple flexural component. The displacements imposed are moderate and the material behavior is linear-elastic. The geometric configuration for this test is shown in Fig. 2. The specimen shown is the same as the flexure coupon but rotated 90 degrees about its linear axis so that the structural foam layers are now perpen-

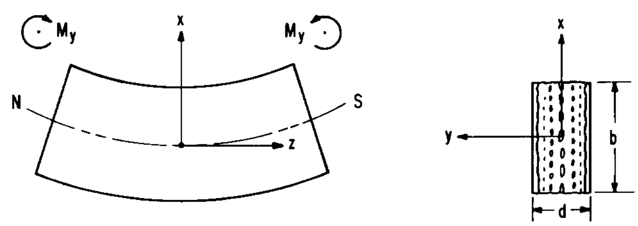

Figure 2. Deep-beam flexural configuration

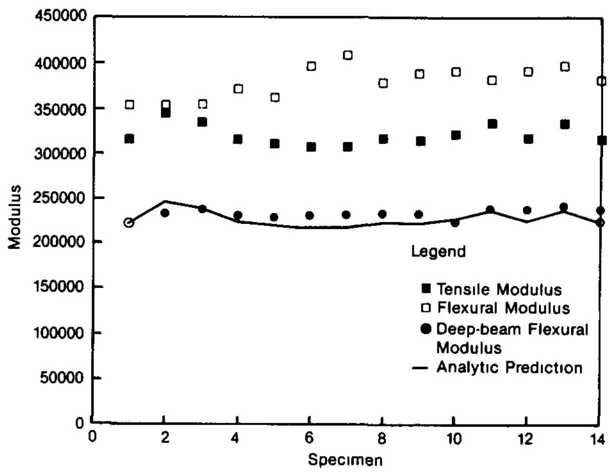

Figure 3. Measured and predicted average moduli for tensile, flexural, and deep beam configurations

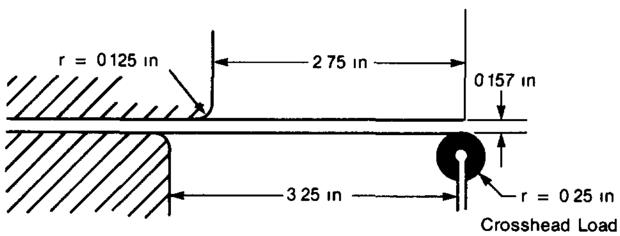

Figure 4. Clamped plate test geometry

dicular to the neutral axis. This configuration may be referred to as "in-plane" flexure, in contrast to the typical flexure, and modulus denoted as E_v.

It can be shown that based upon Euler-Bernoulli beam theory, the respective moduli $E_v = E_t$ not E_b as might be expected. The discrete points in Fig. 3 display the experimental results of several specimens in flexure, tension, and in-plane flexure. Respectively, three effective moduli, E_b, E_t and E_v were measured for each specimen. It is immediately obvious that based upon the experimental results, E_v is not equal to E_t. However, there are two significant effects active in the vertical bending test configuration left unconsidered with standard Euler-Bernoulli beam theory. These effects, active in the experiment, can be included when using a finite element analysis.

First, in a deep beam configuration where $L/H = 4$ as here, transverse shear deformation becomes significant (approximately 15% additional displacement) and must be considered. The second important effect contributing to the experimentally observed difference between E_v and E_t is the elastic indentation of the specimen under the crosshead. This was measured by using a dial gauge on the test specimens and considered analytically in finite element analyses. In the tests, the deflection due to indentation ranged from 5-7%. From the finite element models, a difference of approximately 7% is predicted.

By using the material properties from the individual tensile and flexure tests, the effective modulus in the deep beam configuration is predicted analytically and shown by the solid line in Fig. 3. Good correlation is seen for several comparisons by using the principles of GEFOAMS in an analysis where the effects of both shear and indentation are included.

The second test considered is a transversely loaded plate clamped at both its ends to prevent rotation and in-plane end shortening. This test allows consideration of several additional

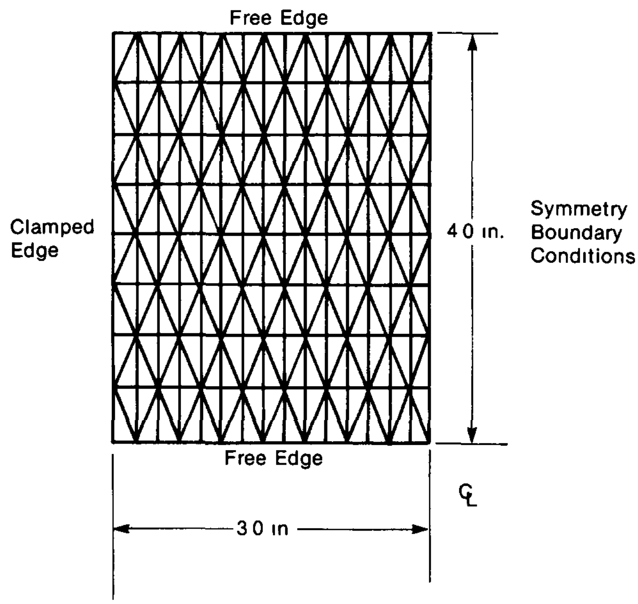

Figure 5. Finite element model applied in clamped plate test

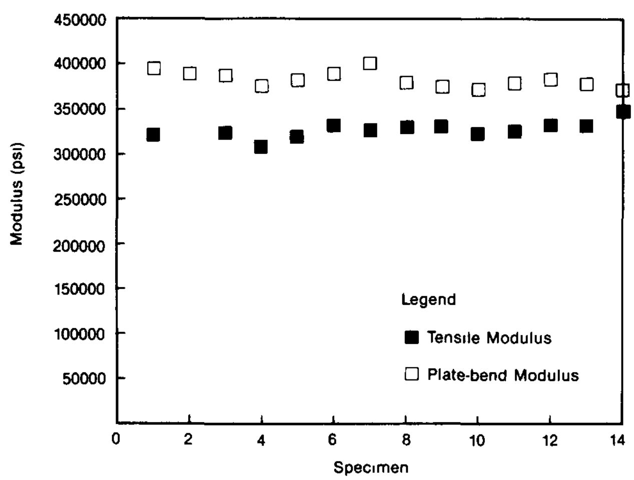

Figure 6. Tensile and flexural moduli for clamped plate test; material #1

aspects of modeling structural foam behavior. First, because of the fully restrained boundary conditions, the state of stress in the plate is a combination of flexure and in-plane tension. The behavior of the layered foam model in this combined stress situation is evaluated. Second, the displacements imposed in this test are much more severe, providing an opportunity to assess modeling techniques in a range approaching yield. As in the case of the deep beam, the material properties used in this analysis are obtained from the tensile and plate-like bending tests described earlier.

The geometry of the clamped plate test is shown in Fig. 4. The fixture used to clamp the plate actually contacts the top and bottom surfaces of the foam plates at slightly different locations as can be seen in the figure. Since boundary conditions are applied at midsurface nodal locations for shell elements, the finite element model considered here applies those conditions at the ends of a 6-in. unsupported span, as shown in Fig. 5. Over the range of displacements applied during this test, the load applied through the roller can be effectively modeled as a line load, as determined from a study using

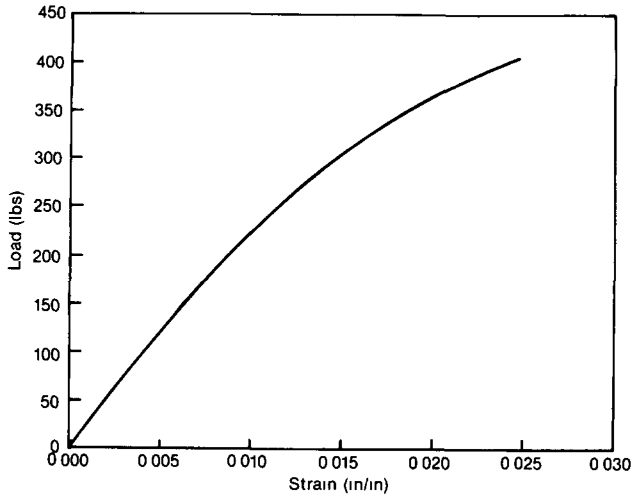

Figure 7. Load versus strain data for clamped plate test; material #1

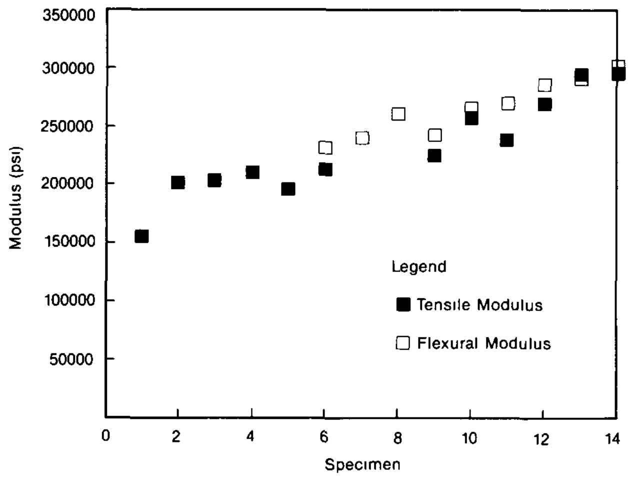

Figure 9. Tensile and flexural moduli for clamped plate test; material #2

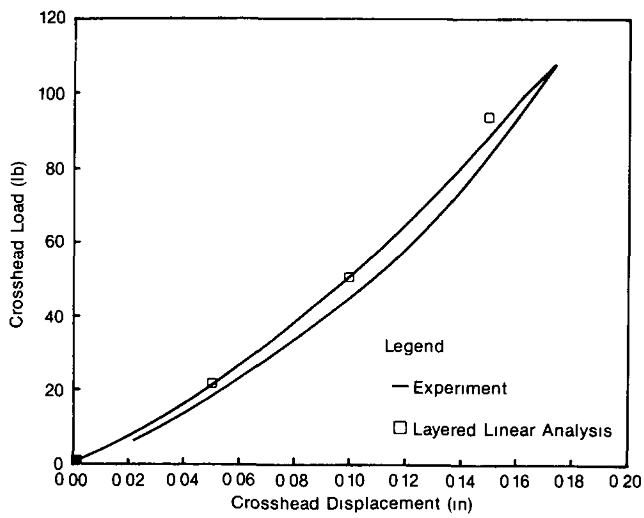

Figure 8. Comparison of experiment and prediction; load deflection

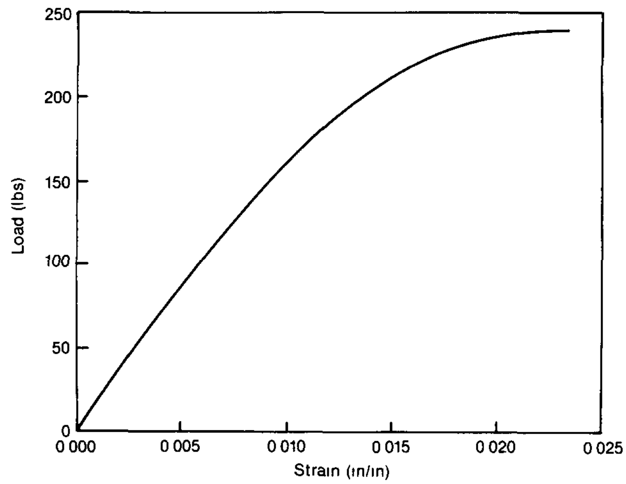

Figure 10. Load versus strain data for clamped plate test; material #2

a more detailed model of the roller-plate interface accounting for the changing contact area.

The first comparison is for a typical situation where linear elastic material behavior prevails and a layered morphology is most significant. The tensile and bending moduli measured on several coupons are plotted in Fig. 6. As can be seen, the tensile moduli measured in these tests are approximately 80% of the bending moduli. Figure 7 illustrates typical stress strain data measured during a tensile test. Observe that behavior is linear for stresses approaching 50% of the maximum value achieved in tests. The properties used in this analysis are the average values of specimens of the equivalent weight reduction and material. Using these values of E_b and E_t, the skin and core moduli for the laminated model can then be calculated from equations (1) and (2).

The load displacement behavior from the analysis is compared with test data in Fig. 8. Note the finite element analysis applied here is only applicable for stress levels in the linear elastic range. The analytic results shown are terminated at the load for which maximum outer surface strains reach yield strain levels as measured in tensile tests. The agreement between analysis and experiment over this range is quite good. In addition, the experimental results begin to show obvious hysteresis at loads above the analytically predicted yield load.

A second, somewhat different example of the complex mechanical response exhibited by structural foam, can be shown through the same test. In contrast to the material behavior in the first clamped plate example, the behavior in Figs. 9 and 10 illustrates two significant differences. First, there is little difference between the tensile and bending moduli for this material – indicating a less significant layering effect upon foam stiffness. Secondly, the stress-strain curves measured in the tensile tests are more nonlinear in nature than observed earlier.

Using the linear elastic, large displacement analysis, and constants E_s and E_c calculated from equations (1) and (2) results in a predicted load-displacement curve as shown in Fig. 11. As can be seen, the actual experimental results are more flexible.

Consideration of the stress-strain curve such as that in Fig. 10 suggested that the nonlinearity in the material's behavior may contribute to the flexibility of test results in comparison to linear elastic analyses. In order to assess the importance of this material behavior, a second analysis was carried out. In this case, the assumption of a layered morphology was dropped because of the small differences between bending and

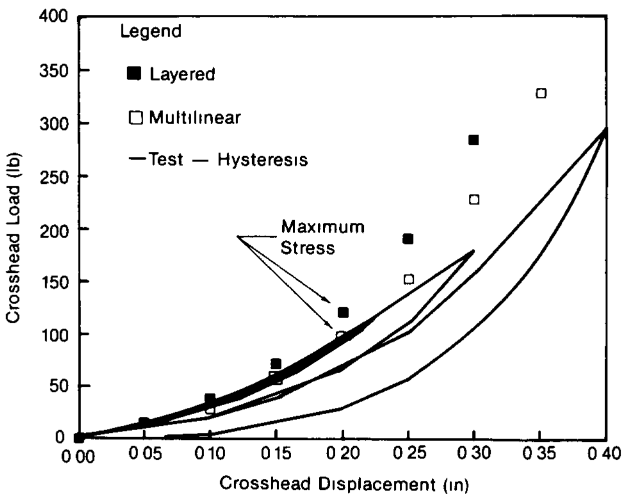

Figure 11. Comparison of experiment and prediction; load-deflection, maximum stress

tensile moduli visible in Fig. 9, and a nonlinear, elastic-plastic material model was applied.

The stress-strain relation used in the nonlinear material analysis was constructed from the tensile stress-strain data measured near the center of the plate. Using this curve in the analysis results in the predicted load displacement behavior shown in Fig. 11. Again, good correlation of load-displacement behavior is seen between finite element analysis and experiment. Furthermore, the analytic prediction of maximum stress in the clamped plate coincides with the appearance of significant hysteresis in the experiment.

Applying GEFOAMS

The significance of these tests notwithstanding, the application of the program to an actual complex part under development was the primary goal from the outset.

One of the first applications to apply the techniques which are the basis for GEFOAMS was the Equatorial Satellite Dish. Given that this one-piece 4 ft. by 6 ft. structure is to be used outside and unprotected, there were significant performance requirements placed upon the design. First, the structure had to survive load equivalent to 125 mile-per-hour winds, and function in 60 mile-per-hour winds; and functioning required no more than ±0.030-in. from the true parabolic.

The use of advanced design procedures not only accurately simulated the load performance, but allowed the design to move from the originally specified material into one with a lower data sheet performance range. Further, even using this new material, wall-thicknesses were able to be reduced, saving an additional 20% in material usage.

The second application is the materials handling pallet designed by GE Corporate Engineering and Manufacturing. A completely new application using a new foamable Xenoy resin, this pallet typifies the kind of design complexity and rigorous load-bearing performance that can be expected in the materials handling industry.

Each of the 9-ft. square, 24-lb. pallets must withstand a 3,500-lb. static load, a 3,000-lb. load when held on a forklift, and have the stability to be stacked eight high with each pallet loaded with 1,000 lb. in each of these tests. Deflection must be minimal with no permanent deformation.

The design features an intricate star pattern on the top surface to allow for automated robotic pick-up from either the center or any of the four quadrants. Therefore, flatness, dimensional stability and creep were essential design parameters. In addition, the design called for development of a modular wall system in increments of 6 and 12 in. to add further flexibility (and complexity), to the overall design.

As the pallet was designed to be used to carry jet engine parts in a variety of adverse environmental conditions, the choice was clearly metal or structural foam. Given the lack of application data in this market on foam, there was risk involved in the development of the part. Without computer-aided engineering, the process of building prototypes and testing would have made the project prohibitive from both a time and cost standpoint.

The computer analysis performed on this project provided significant economies. First, it nearly eliminated prototyping by accurately simulating variable load conditions which allowed optimization of design. Secondly, the time involved from receipt of the concept from the client to the molding of an actual functional part was less than one year.

CONCLUSION

The development of GEFOAMS offers new levels of accuracy and efficiency for the design of complex foam parts. There can be no doubt that the application of the program will give design engineers the ability to increasingly maximize design and thereby make in-roads into application areas heretofore considered too complex from both a geometric and a performance standpoint.

Already we have seen the use of these techniques in diverse market areas on parts whose parameters would have them exceedingly difficult to accurately design given traditional procedures. The advent of GEFOAMS offers, then, a realistic tool to augment the growth potential of the structural foam industry.

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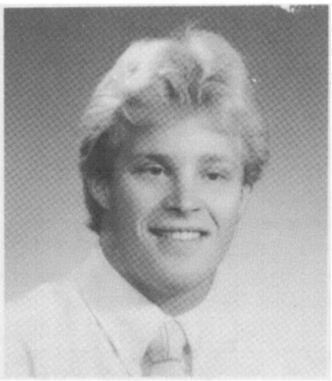
BIOGRAPHIES



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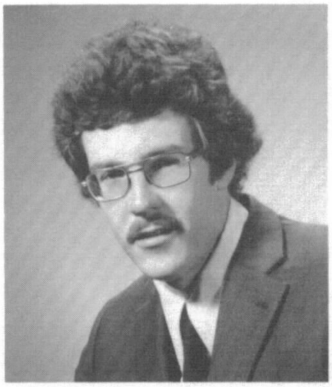
Since joining the General Electric Company in June of 1984, Mr. Ysseldyke has been involved in the development of design technology for thermoplastics. His work has focused on the application of Computer Aided Engineering techniques to plastics design in structural foam. Along with this, his studies include the characterization of the high temperature large-strain behavior of GE polymers relevant to the sheet forming process. In each of these areas he has coauthored a technical paper. He is an associate member of the American Society of Mechanical Engineers.

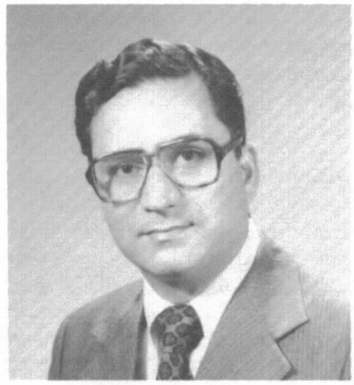


Dr. Ronald P. Nimmer is a Mechanical Engineer, Solid Mechanics Branch, Engineering Systems Laboratory, Corporate Research and Development, with General Electric Company. He received a B.S. in Engineering Mechanics from the University of Wisconsin, in Madison, in 1971. He also received an M.S. and Ph.D. in Aeronautics and Astronautics from Stanford University in 1972 and 1977, respectively.

Dr. Nimmer's doctoral research at Stanford focused upon large-displacement elastic-plastic collapse and energy absorption of thin cylindrical shells under axial compression and was supported in part by a National Science Scholarship. Since joining the General Electric Research and Development staff in November, 1976, his work has focused primarily upon nonlinear impact dynamics, composite materials, plastics, and computer-aided engineering. He is the author or coauthor of 16 technical papers as well as 22 additional company reports.

Since 1980, Dr. Nimmer has been primarily involved in a program to develop a comprehensive technology for engineering design and analysis with plastics. A number of specific topics have been addressed during that time including failure criteria for brittle, glass-filled phenolic materials, large strain plastic deformation of thermoplastics at room temperature, brittle fracture of thermoplastics at low temperatures, and design technology for structural foams. Dr. Nimmer has been significantly involved in developing analysis techniques and design criteria for thermoplastic automobile bumpers. During 1983, he was also heavily involved in a program to provide an integrated structure for the computing resources of the Solid Mechanics Branch.

In addition to his involvement in developing design and analysis technology for thermoplastics, Dr. Nimmer has also contributed to programs focused upon the design and development of high-energy density, composite flywheels for use in electric vehicles and development of analytical techniques for prediction of transient dynamic response of jet engine fan blades exposed to foreign object impacts.



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Prior to joining General Electric, Dr. Stokes was a Professor of Mechanical Engineering at the Indian Institute of Technology, Kanpur, India, where he served as the Chairman of the Mechanical Engineering Department from 1974 to 1977. During the academic year 1970–71, he was a Visiting Unidel Associate Professor in the Department of Chemical Engineering at the University of Delaware. From 1971 to 1972, he was a Senior Staff Engineer with Foster-Miller Associates, Inc., a firm of consulting engineers in Waltham, Massachusetts.

Dr. Stokes has written or coauthored twenty-six technical papers, twelve technical reports, and holds nine U.S. patents. They cover a range of mechanics problems in the areas of solid mechanics, fluid mechanics, heat transfer, and wave propagation in plastic materials. He is also the author of a book, "Theories of Fluids with Microstructure – An Introduction." He is a Fellow of the American Society of Mechanical Engineers, a Fellow of the Institution of Engineers (India), and a Member of the American Academy of Mechanics.