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Characterizing Wood-Plastic Composites via Data-Driven Methodologies

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Abstract

The recent increase of wood-plastic composite materials in various application areas has underlined the need for an efficient and robust methodology to characterize their nonlinear anisotropic constitutive behavior. In addition, the multiplicity of various loading conditions in structures utilizing these materials further increases the need for a characterization methodology that accounts for this complexity.

In responding to these needs, this paper presents a data-driven methodology that utilizes multi-degree of freedom mechatronic loading systems to systematically collect behavioral data of specimens constructed from these materials. These data represent force, stiffness, and dissipated energy versus displacement data for each specimen tested. The highly nonlinear behavior of these specimens was confirmed and is discussed in the context of the associated damage strain-induced micro-cracking.

This methodology further utilizes the acquired data to construct an analytically defined model of the observed behavior in terms of identifying the total (recoverable and irrecoverable) energy density spent for deforming and damaging these materials. A constrained optimization formulation leads to the determination of the unknown parameters defining this methodology.

Subsequently, the identified constitutive behavior in terms of the dissipated energy density is utilized to predict load-displacement behavior of specimens tested outside the context of the automated loading frames utilized for the characterization. Validation discussion between the predicted behavior and the experimentally established behavior conclude this work.

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Introduction

The markets for wood-fiber thermoplastic composite (WPC) products used in housing and other building applications are growing rapidly. Though current use is dominated by the replacement of deck boards and railing systems in outdoor wood decks (Smith 2001), many other WPC building products are in use or under development, including window framing, simulated wood shake roofing, and house siding (Bender et al. 2003, Lundin et al. 2001). While the latter mentioned products are considered “non- or semi-structural” and generally do not bear life safety concerns, the use of these new composites in decking, railing, and other “structural” components does raise safety concerns. With foreseen advances in product development, it is certain that the WPC industry will expand into the large structural wood products market, replacing the structural framework (joists, posts, and beams) of decks and potentially other structural elements used in housing. Because this technology is recent (Clemons 2000), little technical information is available to predict the structural response of these products and the impact of their use on public safety. The multiplicity of various loading conditions in structures utilizing these materials further increase the need for a characterization methodology that accounts for this complexity.

This paper illustrates how data-driven material characterization combined with automated multi-degree of freedom mechatronic loading systems can be used to quantify the non-linear anisotropic response of WPCs subjected to the multiplicity of loading conditions that they would encounter in structural applications. The data-driven material characterization approach utilizes the data obtained via experimentation as the input for prediction of system behavior. As an example that will be discussed later in the paper, flexure is a combination of tension, compression, and shear. Thus, the data obtained by tensile, compressive, and shear testing is used to predict flexure behavior without relying on a priori assumptions of component behavior. In fact, making assumptions on WPC behavior will lead to erroneous results.

An important characteristic of WPCs is that tension and compression behaviors are vastly different. For most common construction materials, such as steel or solid wood, it can be assumed that the material strain behavior is the same in tension and compression and that shear effects can be ignored. This greatly simplifies the mechanics of materials equations used to calculate fundamental engineering properties, such as modulus of rupture (MOR, a measure of bending strength) and modulus of elasticity (MOE, a basic measure of material stiffness). Currently, manufacturers, and many researchers, assume that these simplified equations hold true for WPCs. This leads to inaccurate measurements of properties and to significant error in scaling up measured properties from small coupon tests to full-size structural members.

Therefore, the goal of this paper is to demonstrate the data-driven approach and provide a description of multi-degree of freedom mechatronic systems developed for polymer matrix composites (PMC) that have systematically obtained data on WPCs. This data subsequently can be used to determine the response of WPCs to the multiplicity of loadings seen in structural applications.

Multi-Dimensional Loaders for Data-Driven Characterization

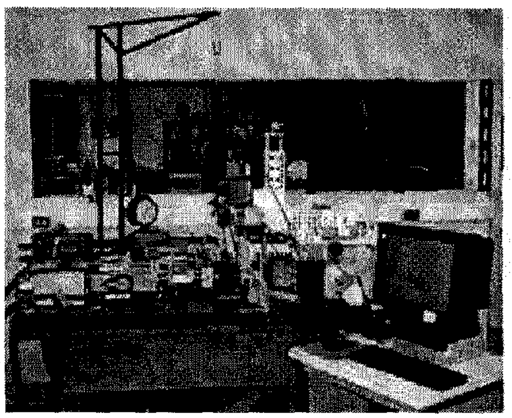
Multi-Dimensional Characterization of PMCs

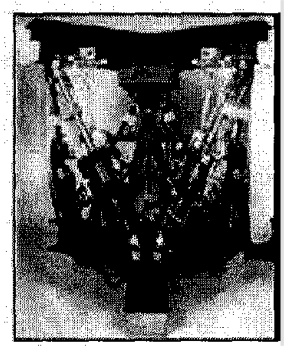
In order to characterize the constitutive response of a PMC system, the Naval Research Laboratory (NRL) has developed a system identification approach utilizing custom-made testing machines that expose material specimens to discrete loading paths spanning the loading space of the specimen structure. Two characteristic examples of such machines are the In Plane Loader System (IPLS) and the Six Degree of Freedom Loader System (NRL66) shown in **Figure 1.** Details about these machines and the associated automated processes are given in Mast et al. (1983), Mast et al. (1992), Mast et al. (1995a), Mast et al. (1995b), and Mast et al. (1995c).

Specimen Considerations

Composite materials associated with various applications range through a wide variety of constituent materials. Each different combination of matrix, fiber or particulate, fiber or particulate coating, layup angle, stacking sequence, etc. corresponds to a different material. Although the approach discussed in this paper is applicable to both fiber and particulate PMCs, it has been historically applied to fiber PMCs. Approximately 100 material systems with fibers ranging from Kevlar to IM7 graphite and several thermoset resins

Figure 1. ~ *Views of the IPLS (left) and the NRL66 (right).*





and thermoplastic organic polymers have been tested and characterized with the approach discussed.

Specimen geometry was designed to satisfy the following requirements:

- The characteristic dimensions should be large enough relative to fiber or average particulate diameter and lamina thickness (when applicable) to ensure that the material could be analyzed as either a single mechanically equivalent homogeneous anisotropic monolithic material or a collection of layers of varying orientations of such materials.
- The overall specimen size should be small enough to keep material costs at a manageable level.
- Strain riser(s) (such as notches, holes, etc.) should be present to guarantee that high strain regions occur well away from all specimen boundaries.

Experimental Procedure

The objective of the IPLS is to control the rigid body motion of the boundary of the specimen that is held by the movable grip and at the same time measure the boundary displacements and tractions. Because the actuators of the IPLS are constrained to move in a plane parallel to the specimen, the resulting motion involves only three degrees of freedom relative to any frame of reference on that plane. As can be seen in Figure 2, the grip motion can be resolved into three basic components:

- sliding (shearing) u_0,
- opening/closing u_1, and
- in-plane rotation u_2.

Specified combinations of actuator displacements, therefore, map into particular combinations of these three basic motions.

In order to visualize the loading space, it is advantageous to think in terms of a three-dimensional displacement space with coordinates (u_0, u_1, u_2). The issue then is how to select a representative family of paths that cover the space and how to sample along each path. It was decided to cover the boundary displacement space with a set of 15 uniformly distributed radial loading paths as indicated in Figure 3. Note that because of geometry and material symmetry about the axis along the notch(es), only the half space corresponding to positive sliding displacement ($u_0 > 0$) need be considered. The required set of observation points is generated by sampling boundary displacement and force data along each path. A particular test in which the actuator motions are continuously varied corresponds to a specific path in this space. Only 15 specimens are required, and 50 observations per loading path are obtained from a single specimen. The locus of the end points of all loading paths for the same increment is a sphere as shown in Figure 3, where two arbitrary loading paths at three arbitrary increments are presented as an example along with the two basis case loading paths of pure shearing and opening. The traditional NRL methodology for PMC characterization uses the dissipated energy density function (DEDF) as a storage mechanism for their constitutive behavior.

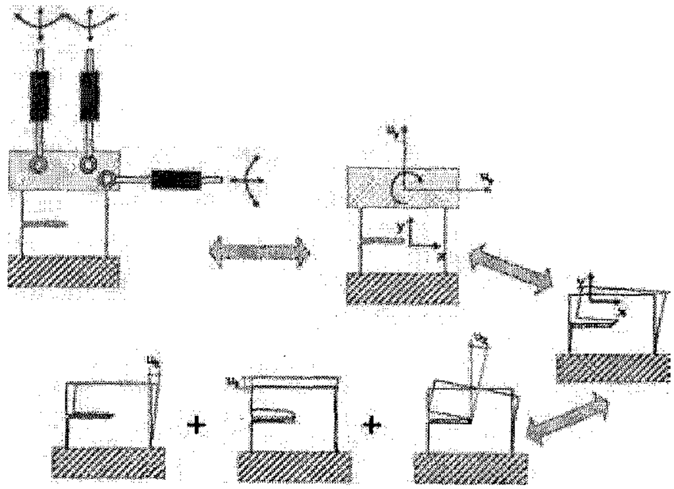


Figure 2. ~ Loading modes of the in-plane loader system.

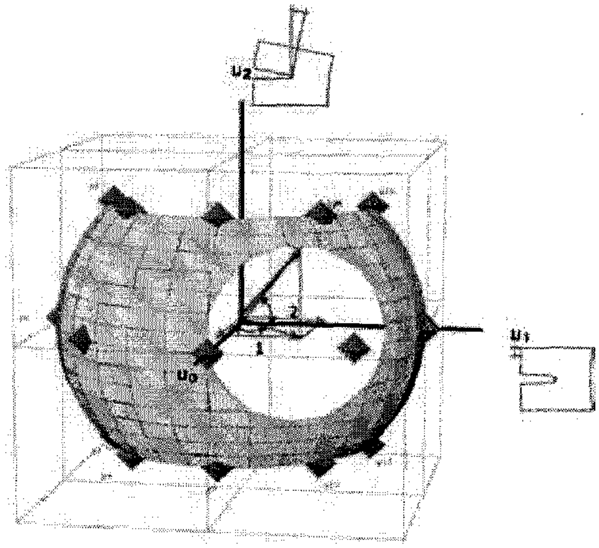


Figure 3. ~ *Loading paths shown in displacement space of the IPLS.*

The set of activities associated with the traditional methodology of determining the DEDF along with their interrelationship are shown in the Universal Modeling Language (UML) activity diagram of Figure 4. The process of computing the total dissipated en-

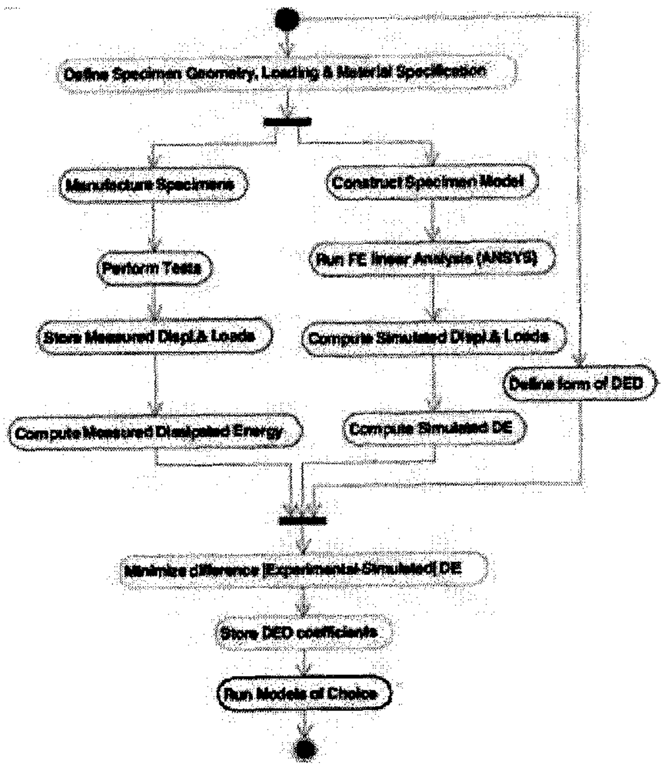


Figure 4. ~ *Universal Modeling Language ofthe activities for data-driven material characterization with dissipated energy density function as the storage mechanism for the constitutive behavior.*

ergy is based on boundary displacements and tractions that are measured at each increment imposed by the IPLS along each loading path. Additional details are presented elsewhere (Mast et al. 1992, Mast et al. 1995a, Mast et al. 1995b, Mast et al. 1995c). One specimen per loading path is used initially and the procedure is then repeated for two specimens per loading path.

The DEDF is constructed as a sum of basis functions c_i that depend only on the local strain state $\tilde{\varepsilon}$ of the material in the structure and are weighted by coefficients c_i that depend only on the material:

$$\phi(\tilde{\varepsilon}, \tilde{c}) = c_1(m)\chi_1(\tilde{\varepsilon}) + c_2(m)\chi_2(\tilde{\varepsilon}) + \ldots + c_n(m)\chi_n(\tilde{\varepsilon}) \qquad [1]$$

This particular form for ϕ accomplishes a full decomposition of the effects of the geometry from those of the material by forcing it to be only a function of the strain state. It also accomplishes scale independence within the domain of application of the continuum hypothesis. Determination of the dissipated energy density function can be accomplished by employing a desirable vector space defining the polynomials representing the basis functions, and subsequently determine the coefficients c_i. This is accomplished by considering the energy balance equation:

$$\int_0^{u_r} t_u dq^v - \frac{1}{2} t_s u_t u^v = \int_{\partial V} \phi(\varepsilon_i(x_j)) dx_j, \qquad [2]$$

where:

t and u = the components of the boundary tractions and displacements, respectively.

The left side of the Equation represents the dissipated energy lost in the structure as the difference between the total energy imparted by the testing machine to the specimen minus the recoverable energy. This side of the Equation is determined at the end of the left path through the red activities of **Figure 4.**

The right side of Equation **[2]** represents the dissipated energy list in the structure as the integral over the volume of the specimen of the dissipated energy density function. This side of the Equation is determined at the end of the right path through the red activities of **Figure 4.** In a finite element model, the total energy calculation of Equation **[2]** can be calculated by summing the energies over each element which will yield an over determined system of linear equations, with c_i as unknowns. Since this system is over determined, and since we have to consider the monotonicity and positive definitiveness of ϕ, the problem can be considered a global optimization problem with inequality constrains. Various algorithms are available to use for solving this problem. We have been using random hill climb with reversal algorithm as it has been captured in the ACM TOMS library algorithm 587. When the unknown c_is are determined, they are saved in a database for further use in simulating the behavior of the material in user defined geometries.

The DEDF concept has been applied to many applications that require factual determination of PMC behavior characterization including applications for establishing a metric for distributed health assessment in smart structures.

Constitutive Behavior Identifications/Characterization

WPCs have nonlinear behavior that is dependent upon the mode (tension, compression, and torsion, **Fig. 5)** and direction (anisotropy) of loading. The nonlinear behavior is thought to be due to the strain induced-damage developing in the composite. No material constitutive theory exists that adequately captures the complexity of the observed resultant load-deformation behavior in WPCs. Thus, a data-driven methodology is well suited to represent WPCs. Kobbe (2005) noted that an inverse hyperbolic sine function models the nonlinear stress-strain behavior very well for the case of the homogeneous state of strain associated with one-dimensional tension-compression specimens. We have added a linear term to encapsulate zero slope of the stress-strain behavior at the maximum load. Equation **[3]** shows the general form of the, inverse hyperbolic sine function used.

$$\varphi(\varepsilon) = a\sinh^{-1}(b\,\varepsilon) + c\,\varepsilon \qquad \textbf{[3]}$$

where:

σ = thestress,

ε = thestrain, and

a, *b*, and *c* = parameters to be determined to represent the data.

Given the functional form of the stress-strain relationship in Equation **[3],** the dissipated energy density function can be constructed to have the analytic form as given in Equation **[4].**

$$\varphi(\varepsilon) = \frac{a}{2b}\left(1 - \sqrt{1 + b^2\varepsilon^2} + b\,\varepsilon\sinh^{-1}(b\,\varepsilon)\right) \qquad \textbf{[4]}$$

From a data-driven perspective, the objective of the present effort requires that the free parameters associated with model (i.e., *a*, *b*, and *c*) are to be determined by the available experimental data. Prior to utilizing the data from appropriate IPLS tests, the low dimensionality of the parameter space suggests that we examine the usage of simpler experiments to determine the unknown material parameters. Therefore, a set of tests were performed and the appropriate parameter identification was established.

A functional model like the one expressed by Equation [4] for representing the constitutive behavior of a given WPC material system can be easily incorporated into a finite element analysis. ADINA (Automatic Dynamic Incremental Nonlinear Analysis) (2007) was used for the purposes of this paper. ADINA allows the incorporation of a user-defined algorithm that is implemented in the form of dynamically linked FORTRAN object file. The results of this analysis are presented in the next section for various simple loading cases.

Validation Testing Case Studies

Small coupon tension and compression tests were run on six diverse formulations of WPCs to generate data to develop a data-driven model. Four of the formulations used were produced commercially for use as deckboards. Two of the formulations are produced for research and development by noncommercial research organizations. Four of the profiles are solid 1- by 6-inch sections (formulations C, D, F, and L) with the other two sections (formulations A and Z) being hollow profiles. fill-size (typical for use as structural materials) specimens were tested in flexure to verify the data-driven modeling.

Tension

The tension data was obtained by following the procedures of ASTM D638 (ASTM 2002b) Tension Test Method Type I (for thickness <0.28 in.). The specimens were manufactured from sections of the stock material used for the full-size specimens to be tested in flexure. The gage length deformation was measured using an extensometer. The crosshead displacement rate was set to target a strain rate of 1 percent per minute (1% ε/min.). A typical stress versus strain curve along with the best fit of the inverse hyperbolic sine, Equation **[3],** is shown in **Figure 6.** The nonlinear fitting algorithm in GNUPLOT (2007) was used. The best-fit parameters are a = 628, b = 754, and c = –59800.

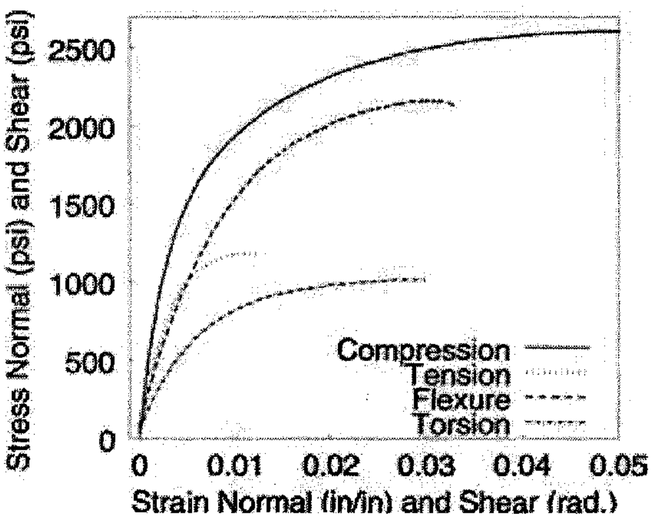


Figure 5. ~ *Typical stress us. strain curves for compression, tension, flexure, and torsion of a high-density polyethylene WPC. Note the large disparity in behavior.*

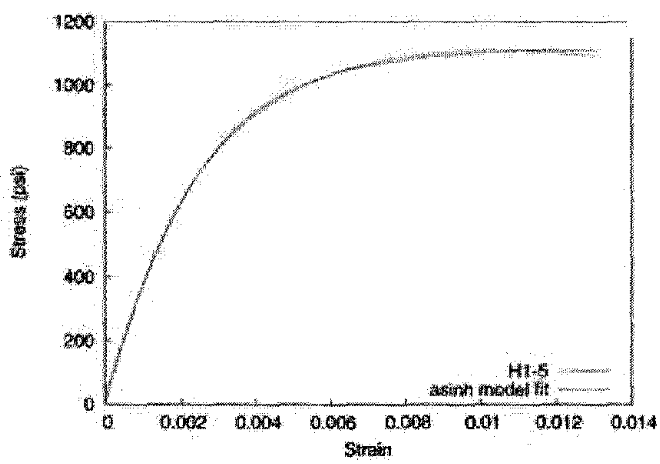


Figure 6. ~ *A typical stress vs. strain of a WPC in tension with the corresponding inverse hyperbolic sine representation of the data.*

Compression

The compression tests followed ASTM D695 (ASTM 2002a) with a strain rate of 1 percent per minute (1% ε/min.). The specimens were manufactured from sections of the stock material used for the full-size specimens to be tested in flexure (Fig. 7). The gage length deformation was measured with an extensometer. The nonlinear fitting algorithm in GNUPLOT was used. The best-fit parameters are a = 1496, b = 353.9, and c = –60210.

Beam Flexure

Flexure tests were conducted on the full-size profiles. The specimens were placed on edge rather than flat. A four-point loading system was utilized. The span was 84 inches, and the loading head span was 24 inches. The beams were laterally supported to prevent buckling. The crosshead speed was set to achieve a 1 percent strain rate per minute (1% ε/min.) at the extreme fiber. Because of the disparity in the tension and compression stress-strain curves, which affects the location of the neutral axis, and thus the extreme fiber strain, a finite element analysis was run to determine the loading rate to achieve a 1 percent stain rate on the tension face. The load and mid-span deflection were recorded. The recorded load versus displacement from a representative sample for each formulation is graphed in Figure 8 along with the results of the finite element analysis using the data-driven model developed in the tension and compression tests.

The finite element model was set up to represent the average geometric configuration of the flexure tests, not specimen actual dimensions. The user-defined material model passed the best-fit parameters determined from the tension and compression tests above. As can be seen from the graphs of **Figure 8,** the modeling capabilities using a data-driven methodology capture the behavioral form of the load-displacement behavior for each formulation. The differences (approximately ± 10%) in the graphs are within the coefficient of variation of the materials and actual dimensions of the specimen chosen to graph.

Conclusions and Plans

WPCs have nonlinear behavior that is dependent upon the mode (tension, compression, and shear) and direction (anisotropy) of loading. The nonlinear behavior is due to the strain induced-damage developing in the composite. No material constitutive theory exists that adequately captures the complexity of the observed resultant load-deformation behavior in WPCs. A data driven approach, however, can be employed to predict system behavior within the product variations using numerical analysis. This greatly simplifies the process of evaluating WPCs for use in structural systems. The caveat is to obtain the data for use in a numerical analysis. The mechatronic systems outlined in this paper accomplish obtaining behavioral data in the multiplicity of loading modes seen by end use structural applications. This behavioral data is then represented by an analytic function or represented as a sum of basis functions. This load-deformation behavior of the material is used within the context of the numerical analysis to predict the global response of the WPC structural component. An important aspect of the present analysis can be derived from the observation that the identified material constants seem to vary in a manner that is dependent on each individual test and the associated data. But, a constitutive model in order to be a true representation of the material behavior

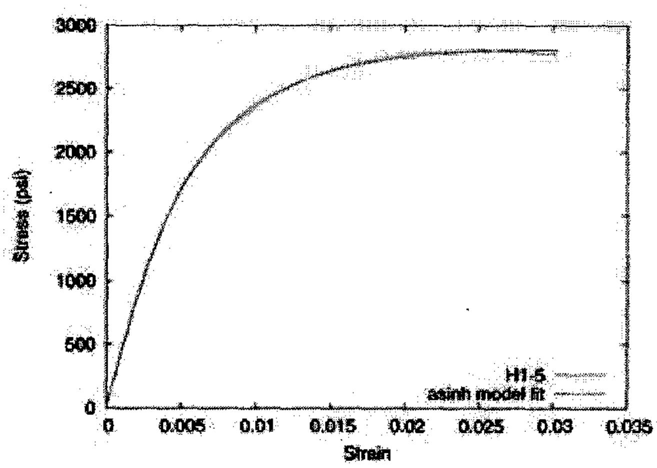


Figure 7. ~ *A typical stress vs. strain of a WPC in compression with the corresponding inverse hyperbolic sine representation of the data.*

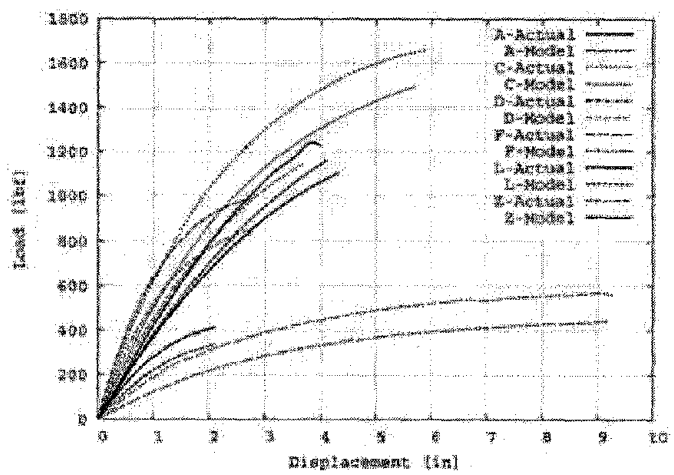


Figure 8. ~ *Load displacement behavior of six diverse WPCs formulations in flexure with their corresponding data-driven model fit using ALINA FEA.*

should not depend on specimen geometry and loading specification. In order to eliminate this discrepancy, we will use the IPLS data in the next phase of our research. Thus, in order to establish geometry and loading path independent representation of the constitutive behavior, we will be performing a global optimization that minimizes the error between the experimentally measured dissipated energy and the analytically predicted one, based on a generalization of Equation **[4]** that must contain the rest of the strain tensor components. This will be done in a manner consistent to **Figure 4.**

Literature Cited

ADINA. 2007. Automatic Dynamic Incremental Nonlinear Analysis Finite Element System. ADINA R&D, Inc. Watertown, MA.

American Society for Testing and Materials (ASTM). 2002a. ASTM D 695. Standard Test Method for Compressive Properties of Rigid Profiles. ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). 2002b. ASTM D 638. Standard Test Method for Tensile Properties of Plastics. ASTM, Philadelphia, PA.

Bender, D.A. and M.P. Wolcott. 2003. Experiences with development and commercialization of engineered wood-plastic composites. *In*: Proc. of the 7th International Conf. on Woodfiber-Plastic Composites. Forest Products Society, Madison, WI. pp. 15-19.

Clemons, C.M. 2000. Wood-fiber plastic composites in the United States - History and current and future markets. In: Proc. of the 3rd International Wood and Natural Fibre Composites Symp., Kassel, Germany. Sept. 19-20.

GNUPLOT. 2007. www.gnuplot.info

Kobbe, R.G. 2005. Creep Behavior of a Wood-Polypropylene Composite. Masters Thesis, Washington State Univ., Pullman, WA.

Lundin, T., R.H. Falk, and C. Felton. 2001. Accelerated weathering of natural fiber-thermoplastic composites: Effects of ultraviolet exposure on bending stiffness and strength. In: Proc. of the 6th International Woodfiber-Plastic Composites Conf. Forest Products Society, Madison, WI.

Mast, P.W., L.A. Beaubien, M. Clifford, D.R. Mulville, S.A. Sutton, R. Thomas, J. Tirosh, and I. Wolock. 1983. A semi-automated in-plane loader for material testing. Experimental Mechanics. 32: 236-241.

Mast, P.W., G.E. Nash, J.G. Michopoulos, R.W. Thomas, R. Badaliance, and I. Wolock. 1992. Experimental determination of dissipated energy density as a measure of strain-induced damage in composites. Technical Report NRL/FR/6383-92-9369. Naval Research Laboratory, Washington, DC.

Mast, P.W., J.G. Michopoulos, R.W. Thomas, R. Badaliance, and I. Wolock. 1995a. Characterization of strain-induced damage in composites based on the dissipated energy density: Part I - Basic scheme and formulation. International J. of Theory and Applied Fracture Mechanics. 22: 71-96.

Mast, P.W., J.G. Michopoulos, R.W. Thomas, R. Badaliance, and I. Wolock. 1995b. Characterization of strain-induced damage in composites based on the dissipated energy density: Part II - Composite specimens and naval structures. International J. of Theory and Applied Fracture Mechanics. 22: 97-114.

Mast, P.W., J.G. Michopoulos, R.W. Thomas, R. Badaliance, and I. Wolock. 1995c. Characterization of strain-induced damage in composites based on the dissipated energy density: Part III - General material constitutive relation. International J. of Theory and Applied Fracture Mechanics. 22:115-125.

Smith, P.M. 2001. U.S. wood-fiber-plastic composite decking market. In: Proc. of the 6th International Conf. on Woodfiber-Plastic Composites. Forest Products Society, Madison, WI. pp. 13-17.

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