A Novel Grabbing/Latching Mechanism Without Moving Parts

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Abstract

A preliminary design concept and prototype hardware have been developed for a grabbing/latching mechanism that uses no moving parts. The mechanism uses an innovative material named a Machine Augmented Composite (MAC), or MACterial, in a female configuration to accept a male bar or rod with almost imperceptible resistive force. However, when a reversing force is applied to disengage the bar/rod, it is virtually impossible to remove it due to the increasingly applied holding force. In other words, the higher the removal force applied, the higher the clamping force to resist it. The theory and physics behind this and other MACterial concepts are presented herein, as well as several potential applications that have been defined; surely there are many other applications only limited by one's imagination.

Introduction – or, How Does it Work?

A "machine" is defined in the Merriam-Webster dictionary as

> **Machine** *n*, An instrument (as a lever) designed to … modify the application of force, power, or energy.

The Aerospace Corporation's Dr. Gary Hawkins has developed a material dubbed a Machine Augmented Composite, or MACterial, which uses tiny machines, or flexures, embedded within a softer matrix material to give the composite unique properties. For example, when one applies a compressive force to a sample of MACterial, the sample deflects as if it is in shear. Conversely, if one applies a shear force, the material can either compress or elongate, depending on the direction of the shear force applied. Figure 1 illustrates a simple 4-bar linkage machine used in a typical MACterial and its resulting stress/strain response.

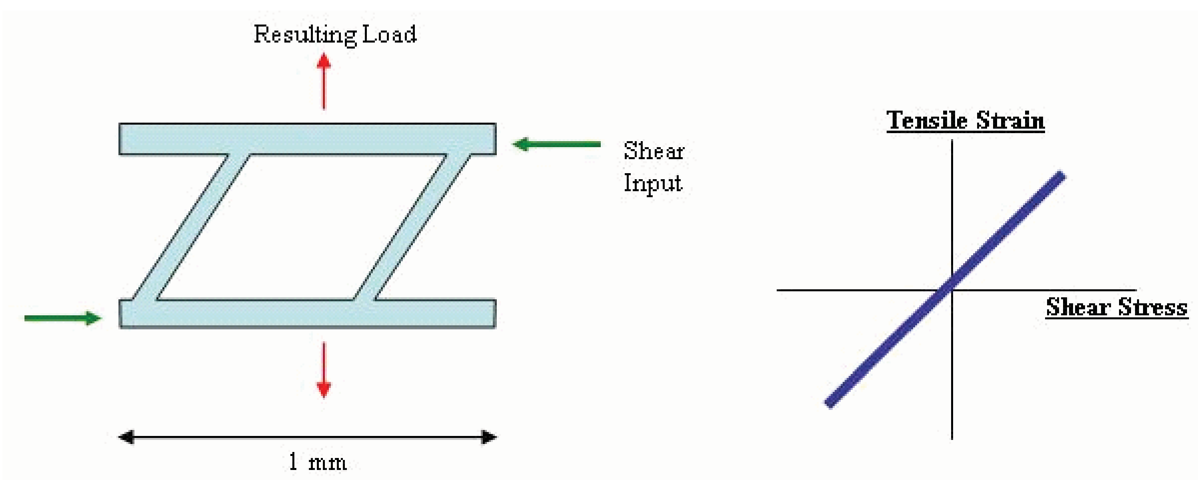

Figure 1. Example Of A Machine To Be Placed Into Composite Material

When a series of these machines, placed in a row or in a 2-dimensional array as in Figure 2, are embedded into a matrix material such as silicone, graphite epoxy, or any other suitable material (see Figure 3), the material takes on the properties of the machine when subjected to external loads.

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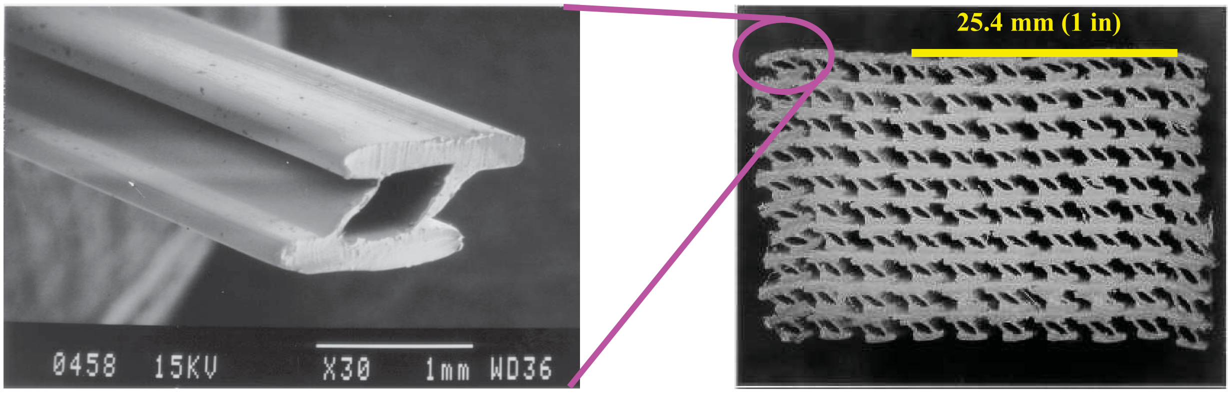


Figure 2. Extruded Nylon Simple Machine (Left); 100 Machines In 2-D Arrangement Before Matrix Infiltration

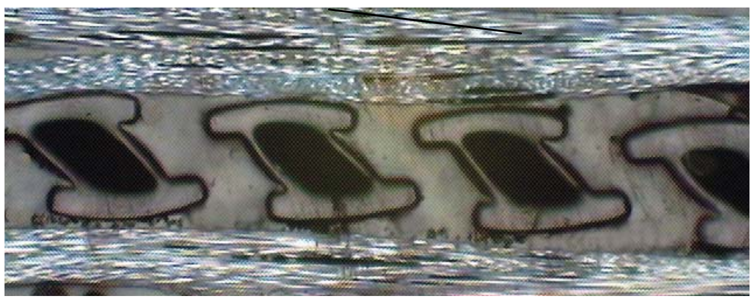


Figure 3. One Ply Of Machines Inside Matrix Material

With a bulk material made up of many little embedded machines, or even a material made up of a few number of larger ones, one can construct a combination of material and mechanism to accomplish interesting tasks. Figure 4 shows a simple example of a one-layer MAC and an engaged slider bar that can be measured for push-in or pull-out forces. In this example, pushing the slider bar to the left is considered the "easy" direction, and pulling it to the right is considered the "hard" direction, since that is the direction with the tendency of the MAC to grab or latch onto the slider bar, much like the common "Chinese finger puzzles" in which the harder one pulls, the more tightly the subject is constrained.

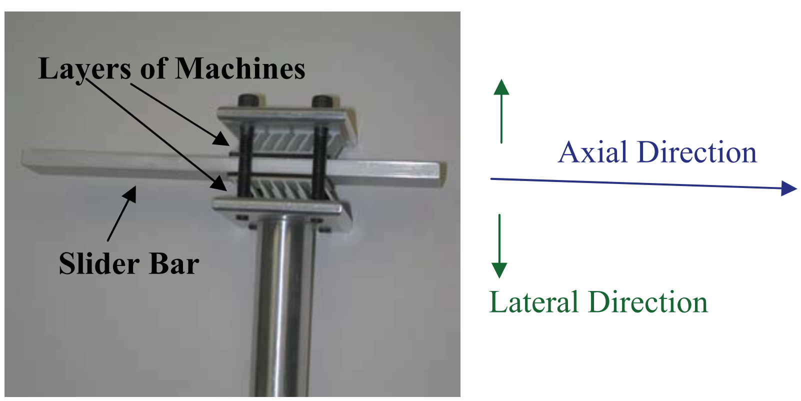


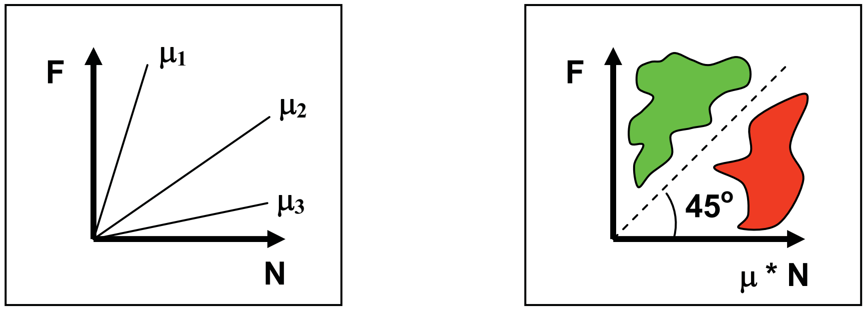
Figure 4. Grabbing Mechanism Prototype, With Slider Bar Engaged

Theory – or, Why Does It Work?

It is all about friction. The explanation starts with the classical friction equation,

$$f = \mu * N, \tag{1}$$

where f is the force required to break static friction and generate motion. A typical plot of this relationship is shown in Figure 5a, in which several values of μ are shown.



(a) (b)

Figure 5. Classical Friction Relationships

In Figure 5b, F is plotted against the quantity μ * N, so one can see that if F is above the dotted equality line (in the green zone), motion will occur, and vice-versa for the red zone below the equality line. Normally this relationship is true for the classical block-on-an-inclined-plane example, but this application, with the schematic shown in Figure 6, is a bit different.

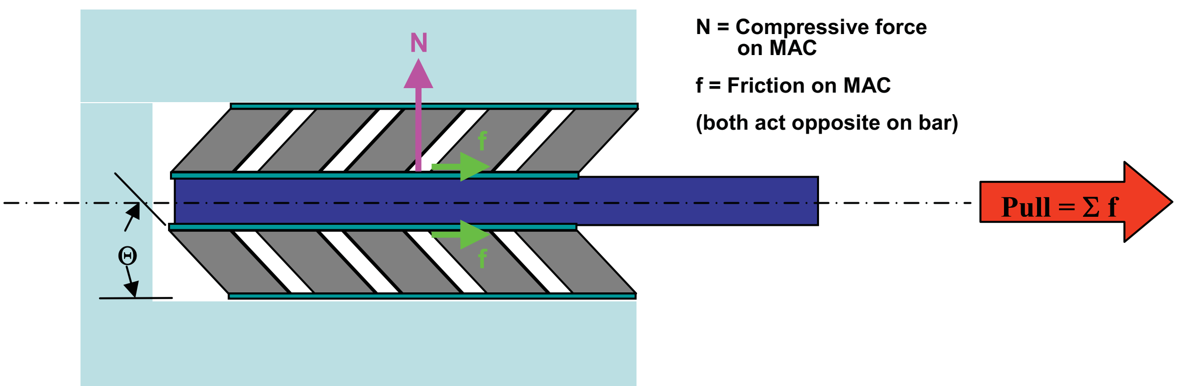


Figure 6. Schematic Of Grabbing Mechanism Prototype, With Slider Bar Engaged

We can also break down the schematic into a more simplified model of what is occurring, as illustrated in Figure 7.

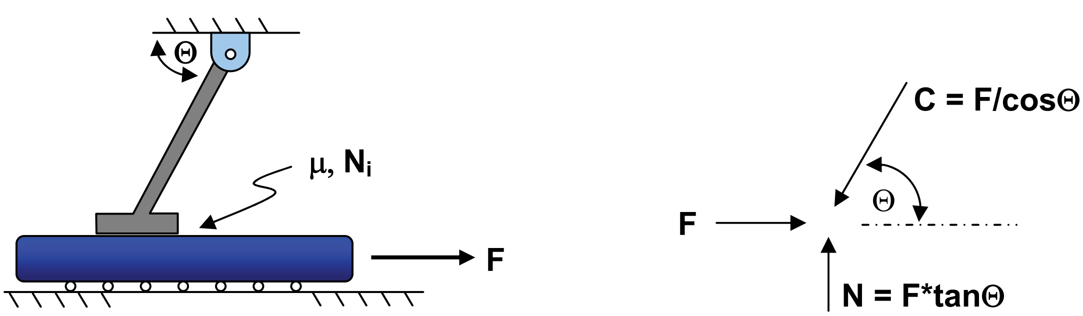


Figure 7. Force Model for Bar Retraction Case

Assuming there is a small compressive preload, N_i, between the gray MAC member(s) and the bar, and if one begins to pull the bar out of the device (to the right, as in Figure 6), friction between the bar and the MAC member creates a compressive force, C, in the MAC members which, in turn, increases the Normal force, N, between the MAC member and the bar. It is now clear that, unlike the classical example, N is a function of F such that

$$N = N_i + \{F * \tan(\Theta)\} \quad (2)$$

The next logical question is, under what conditions will the bar seize and not be able to be pulled out of the device as in Figure 6? By substituting Equation (2) into Equation (1) and rearranging terms, an expression for f, the required force to overcome friction in this system, can be determined.

$$f = \mu N_i / \{1 - \mu * \tan(\Theta)\} \quad (3)$$

One can see that for the classical example, or when $\Theta = 0^o$, the denominator goes to 1 and the familiar equation, $f = \mu N$, exists. This is because there is no component to cause compression in the MAC member. Also interestingly, when $\Theta = 90^o$, the denominator goes to $-\infty$, and thus f goes to zero. This is because the MAC members are at their bottom-dead-center position, and any movement of the bar will tend to bend, or raise, the MAC member up off of the bar with decreasing normal force. But for the seizing condition, the additional factor – compared to the classical equation – in Equation (3) plays a part. If this "Slide Factor," S, is defined as

$$S = 1 / \{1 - \mu * \tan(\Theta)\}, \quad (4)$$

then S can be plotted for various values of μ and Θ, as shown in Figure 8.

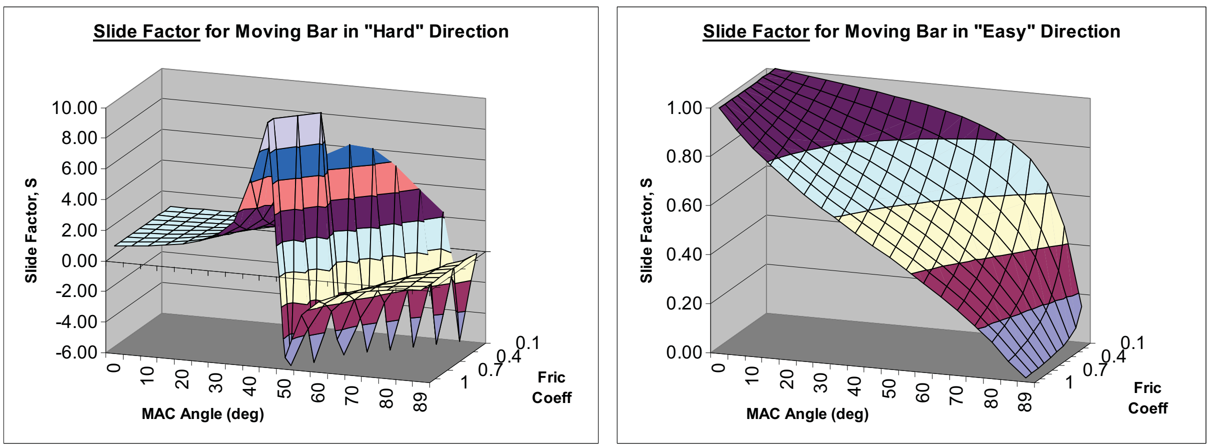


Figure 8. Threshold Values for Seizing for Various Friction and MAC Angle Values

This is a useful format to determine when the bar will be seized and when it will be free to slide. As long as S is positive, it means that a realistic value of f (force required to break free) DOES exist to give the bar the capability of breaking free from static friction; it does become more difficult as S approaches ∞. This describes the green region in Figure 5b. After the discontinuity, for higher values of μ and Θ, S values flip their sign and become negative. What this means is that the only way to break free is to apply a negative f, which means pushing it in the opposite direction.

For the opposite case of pushing the bar in the reverse, or "easy" direction, the same essential theory holds true, except Equation (2) contains a negative sign since the friction resulting from the applied force F tends to reduce the normal, or compressive, force between the MAC and the bar. That also flips the sign in Equation (3), and results in the S-values plotted on the right in Figure 8. By the same discussion above, since ALL of the S-values for reasonable MAC angles and friction coefficient are positive (and ≤ 1), it is proven that it is always easy (f is always $< \mu * N$) to push the bar into the device as in Figure 6.

Some Results – or, DOES it Work?

Several prototypes in various stages of this application were constructed in The Aerospace Corporation's Space Materials Laboratory (SML), and experiments were compared to theoretical analyses. The first study used laboratory instrumentation to compare the axial and transverse deflections of the small nylon machines with and without a matrix material surrounding them. Figure 9 illustrates that, much like traditional composites, the matrix material has very little effect on the behavior of the bulk material.

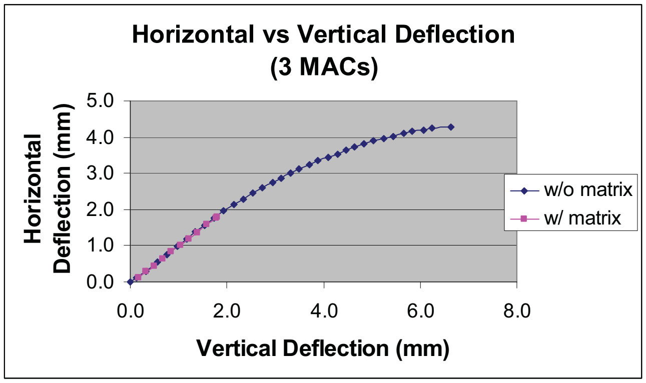


Figure 9. Matrix Material Has Little Effect On Bulk Behavior

The next investigative study compared similar results as above for different geometric configurations of the machines. Samples were constructed with 45-, 60-, and 75-degree machines in them, and the same horizontal-vs.-vertical deflection tests were run. It was shown, as in Figure 10, that the "grabbing" efficiency can easily be affected by the design of the machines. For both the 60- and 75-degree machines, there is more than a one-to-one effect between shear and axial displacement, indicating very desirable potential applications that can exploit this mechanical advantage.

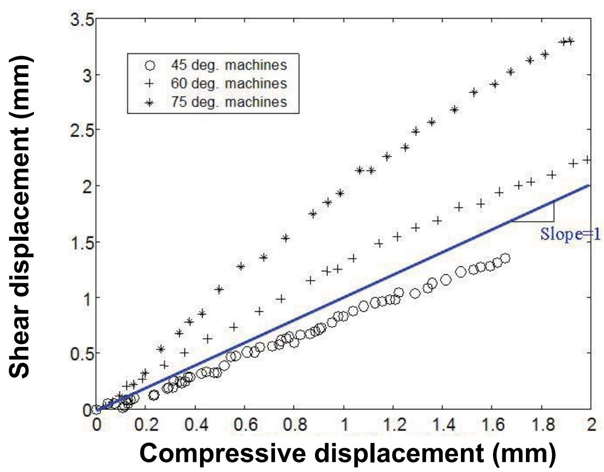


Figure 10. Geometric Effects Of Different Angled Machines

In addition, a similar laboratory experiment was constructed to measure the transfer of force from a compressive direction to a transverse direction, using MACterials. Figure 11 depicts the experimental setup, and Figure 12 displays the force relationship data. One can see that the force relationship in Figure 12 is very similar to the displacement relationship in Figure 10 for the same MAC design, with the 45-degree machines producing a relationship slope in both cases of slightly less than one.

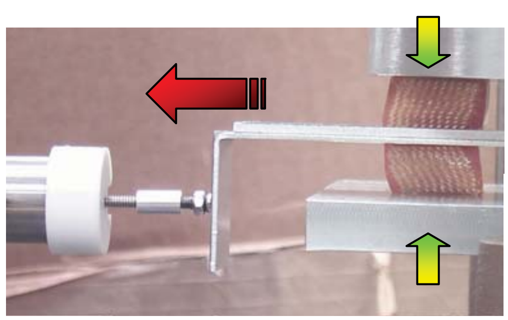


Figure 11. Measuring The Relationship Between Compressive And Shear Forces

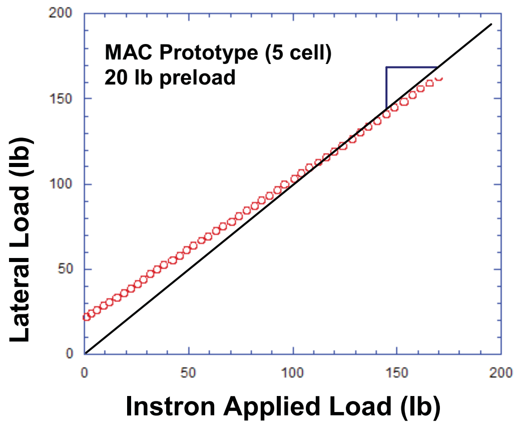


Figure 12. Effect Of Instron Applied Load On The Lateral Load Caused By MAC Movement

Next, getting back to the type of MAC device discussed in the theory section, Figure 13 shows axial and lateral force measurements that were made using this setup while sliding the bar in the “easy” and “hard” directions.

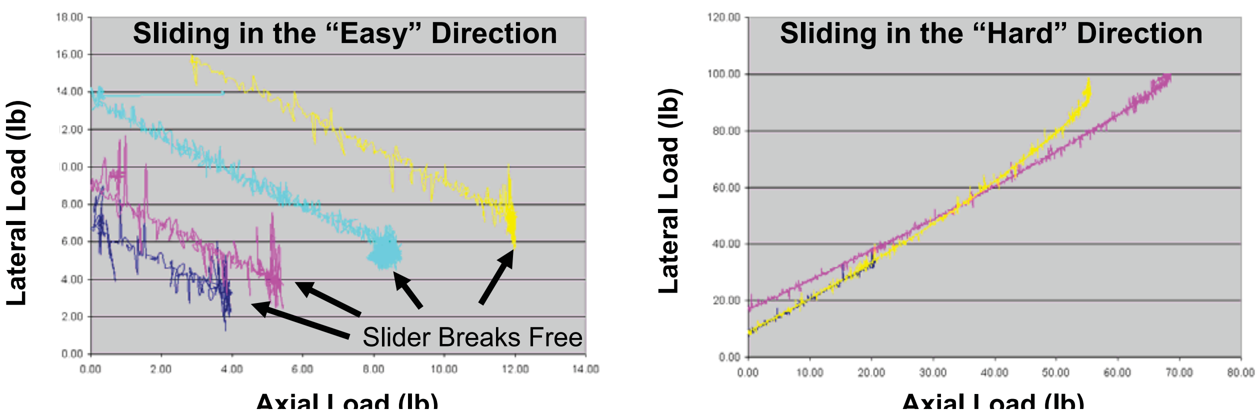


Figure 13. Experimental Data From Insertion/Retraction Test

When sliding in the easy direction, the data in the plots moves from the upper/left direction, where axial load applied to the bar is zero, and the finite values of lateral load are the initial compressive preload, N_i. As axial load is applied and increased, moving to the right, the lateral – or pinching – force gets reduced until the slider bar breaks free. Conversely, when sliding in the hard direction, the data starts out in the lower/left corner with no axial load applied, but with a finite lateral preload, N_i. As retraction force is increased the lateral, or pinching, load moves upward with an increasing slope as the resultant lateral load seizes it.

Data from these measurements can also be shown to be well correlated with ABAQUS finite element analyses, from which a sample finite element model (FEM) is shown in Figure 14.

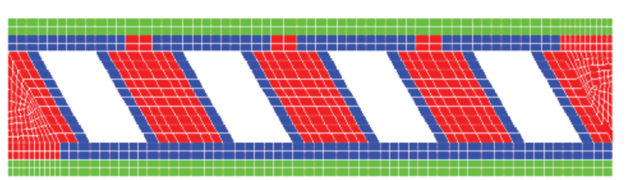


Figure 14. Sample Abaqus Finite Element Model

Using a FEM for a sample with a 60° MAC angle, Figure 15 shows one case of measured and experimental data, and how well they typically agree. Having a well-correlated FEM is very important and convenient so as to not have to make many different variations of hardware prototypes for testing.

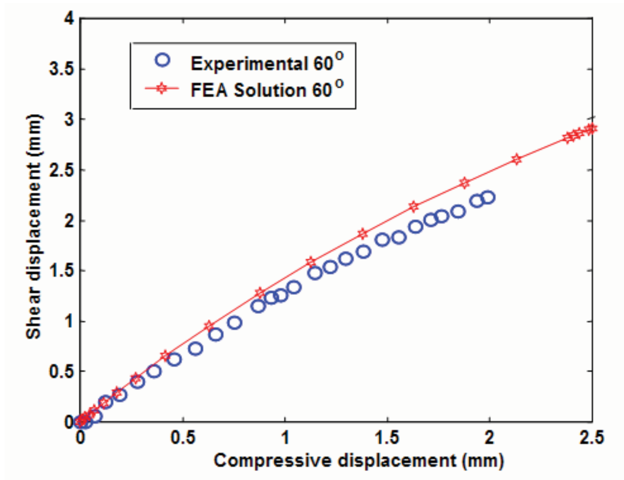


Figure 15. Correlation Between Analysis And Experiment For MAC Displacement

So far, this paper has discussed the static behavior of MACs, but there has also been a significant amount of effort expended to study the dynamic response of these MACterials. Specimens can be designed to drastically alter the behavior of impacting bodies, redirecting energy and stresses in ways that cannot be achieved with standard materials. For example, the use of a material that modifies forces may provide new methods for energy control in vehicles that can minimize impact damage to people or property. Also being explored is this material's potential use in ballistic applications, such as bulletproof vests and armor. For more information on the dynamic behavior of MACs, see Reference 2.

Conclusion – or, Can it Work FOR YOU?

Machine Augmented Composites have been developed in the Space Materials Laboratory (SML) at The Aerospace Corporation and have been shown to have the potential of achieving fascinating results. With the ability to change the direction of force, displacement, shock, or rotation, or act as a one-way retention mechanism without moving parts, MACs could provide unique and innovative solutions to a wide variety of problems. By presenting the work done by SML, perhaps it will resonate with one or more members of the space mechanisms community to solve a particular issue which has eluded a more conventional solution.

Alternatively, devices utilizing this concept, perhaps even in conjunction with current device technology could be newly developed and used by the industry. Being able to design from the start using MACs could lead to more efficient designs and better performance, with lower risk. An increased robustness as a result of a lack of moving parts, pyrotechnics, or other weaknesses in contemporary mechanical assemblies is a driving factor and a worthwhile goal.

There are varied space-related static applications that have been identified thus far for which this concept could be useful. Some examples include release devices, end-of-travel retention devices, electronic board clamps, or zero-insertion force electrical connector interfaces. Besides being useful for static applications, dynamic studies have also led to other investigations, both theoretical and practical, in widely varying areas such as hard-stop load re-distribution, shock attenuation, even sporting goods and body armor protection. Other space (or non-space) related applications are only limited to the engineer's imagination.

Acknowledgements – or, Who Did the Work?

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