The Physics of Karate

A close examination of how the karate expert can break wood and concrete blocks with his bare hand reveals the remarkable capacity of the unaided human body for exerting physical force

by Michael S. Feld, Ronald E. McNair and Stephen R. Wilk

The picture of a karate expert breaking stout slabs of wood and concrete with his bare hand is a familiar one. The maneuver is so extravagant that it is often dismissed as some kind of deception or illusion, but the fact is that there is no trick to it. Even a newcomer to karate can quickly learn to break a substantial wood plank, and soon he would be able to break entire stacks of them. We have investigated in detail how the bare hand can break wood and concrete blocks (and by implication do similar damage to other targets) without being itself broken or injured. The key finding is that the hand of the karateka, or practitioner of karate, can develop a peak velocity of 10 to 14 meters per second and exert a force of more than 3,000 newtons, a wallop of 675 pounds. If the hand is positioned properly, it can easily withstand the resulting counterforce.

The maneuvers of the Japanese style of karate that is practiced today were developed on the island of Okinawa. When the Japanese conquered the island in the 17th century, they stripped it of all weapons and banned their making and importation; even the manufacture of swords for ceremonial purposes was forbidden. To defend themselves the Okinawans developed karate, a system of empty-hand combat based on the weaponless fighting methods of ancient Chinese monks, warriors and physicians. Karate is just one of a wide variety of martial arts that have evolved in the Orient, including tae kwon do, kempo and kung fu.

The techniques of karate differ markedly from those of Western methods of empty-hand combat. The karateka concentrates his blows on a small area of the target and seeks to terminate them about a centimeter inside it, without the long deliveries and follow-throughs of the punches in Western boxing. Whereas the Western boxer imparts a large amount of momentum to the entire mass of his opponent, pushing him back, the karateka imparts a large amount of momentum to a small area of his opponent's body, an amount that is capable of breaking tissue and bone. A well-executed karate strike delivers to its target several kilowatts of power over several milliseconds, quite enough to break blocks of wood and concrete.

Today karate is practiced as a sport and as a potential method of self-defense. The karateka studies many different maneuvers so that he can execute each one in a precisely prescribed manner. The precision demanded of him makes karate not only an excellent physical discipline but also a mental one. Although the breaking of objects is not the point of karate, we shall discuss it here because it is a good way of demonstrating how much energy a well-executed karate strike can deliver. Karate seems to develop to a maximum the capacity of the unaided human body for exerting physical force.

The wood blocks we used in our experiments were standard pieces of dry white pine that weighed .28 kilogram and were 28 centimeters long, 15 centimeters wide and 1.9 centimeters thick. They were cut so that the grain was parallel to the width. The concrete slabs were "patio blocks" that weighed 6.5 kilograms and were 40 centimeters long, 19 centimeters wide and four centimeters thick. The patio blocks were dried in an oven for several hours to remove excess water, thereby making them uniform in content. Under the ends of each block of wood or concrete a support was placed that reduced the effective length of the block by four centimeters.

In a block-breaking demonstration the karateka strikes the top of a block in a range of points near the center. In our experiments we assumed for the sake of simplicity that the force is evenly distributed in that range of points. We also assumed, and experiment subsequently confirmed, that the deflection, or bending, of the block when it is struck is quite small compared with its overall dimensions.

As a first step in understanding the physics of the breaking process, picture a fist moving toward a block supported at its ends. The impact will cause the block to bend in the direction in which the fist is moving. As the block is bent it is deformed: the upper half of the block is compressed and the lower half is stretched. The top surface is compressed the most and the bottom surface is stretched the most. Because wood and concrete are weaker under tension than they are under compression the block starts to crack at the bottom surface. The crack spreads rapidly upward as the fist continues to force the block downward.

The elongation of the bottom surface is caused by the force in the plane of the block that results from the impact of the fist. To put it another way, stress in this plane, or force per unit of cross-sectional area, gives rise to strain, or fractional elongation of the block. The relation between stress and strain is best understood by thinking of the bottom of the block as a horizontal coil spring. The block resists the stress pulling it apart just as the spring does. The spring pushes back with a force that is proportional to its extension. In other words, force equals extension multiplied by the spring constant, which for a given spring is a parameter that characterizes its stiffness. Since stress is analogous to force and strain is analogous to extension, an equivalent relation holds for the block: stress equals strain multiplied by the elastic modulus, which for a given material is a constant that corresponds to the stiffness of the material. When the stress reaches a critical value, called the modulus of rupture, the block breaks.

Since the stretching of a spring until it snaps is analogous to the breaking of a block, equations for the spring that yield formulas for the energy and force at the point of rupture also apply to the block. It turns out that the energy needed to break the block equals its volume (V) multiplied by the square of the modulus of rupture (σ) divided by twice the elastic modulus (E). This formula, $V\sigma^2/2E$, conforms to intuitions about the breaking process. It obviously takes more energy to break larger blocks and blocks that have to be subjected to greater stress. It is also not surprising that the

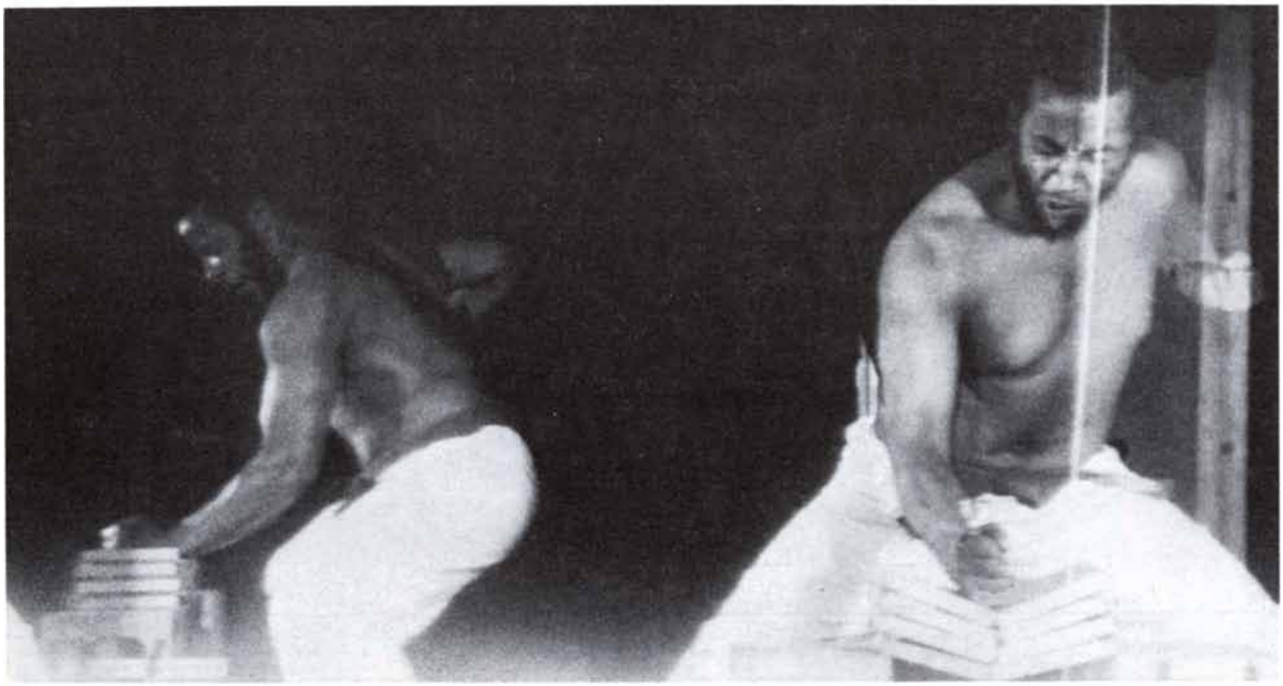
THREE CONCRETE SLABS are broken by one of the authors (McNair) with the heel of his right palm. Slabs were "patio blocks" that weighed 6.5 kilograms and were 40 centimeters long, 19 centimeters wide and four centimeters thick. The supports under the ends of the blocks reduced their effective length by four centimeters. Bone can resist 40 times more stress, or force per unit area, than concrete.

critical energy is inversely proportional to the elastic modulus. The elastic modulus is a measure of the stiffness of the block, and so stiff blocks have a lower critical energy because little energy is wasted in stretching them.

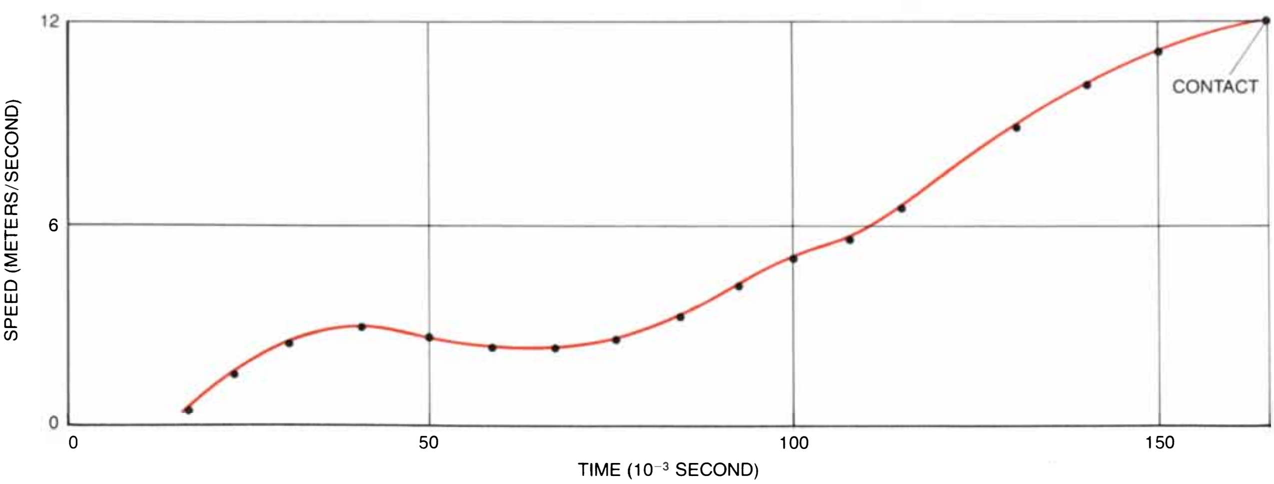
The formula provides only a rough estimate of the critical energy, because the physical properties of blocks are not as simple as those of springs. Nevertheless, it is useful because it indicates which parameters are important in the breaking process and how they are scaled with respect to one another. For example, the formula suggests that the critical energy is proportional to the square of the rupture modulus, and so if two materials have the same properties but rupture moduli that differ by a factor of 2, it takes four times more energy to break the material with the larger modulus.

Before critical energies can be computed from the formula it is necessary to know the modulus of rupture and the elastic modulus of both kinds of block. Because the appropriate values were not tabulated in the literature we measured these moduli ourselves by putting samples of wood and concrete in a hydraulic press and recording their deflection as a function of the applied force. Wood is a fairly elastic material, typically requiring about a centimeter of deflection before breaking. A force of 500 newtons will deflect it to that extent. (One newton is, appropriately, roughly equivalent to the force exerted by the weight of an apple.) A concrete block needs to be deflected by only one millimeter before breaking, but the deflection requires between 2,500 and 3,000 newtons. From these measurements we found the elastic modulus of wood is 1.4×10^8 newtons per meter squared and that of concrete is 2.8×10^9. The rupture modulus of wood is 3.6×10^6 newtons per meter squared and that of concrete is 4.5×10^6.

Putting these modulus values into the



ROTATING-DRUM CAMERA provided simultaneous side and front views of a hammer-fist strike, in which the fist is brought down from above the head in a circular arc. Here the fist is breaking four blocks of dry white pine, each .28 kilogram in weight and 28 centimeters long, 15 centimeters wide and 1.9 centimeters thick. The white-pine blocks were cut so that the grain ran parallel to the width.



SPEED OF THE FIST in the hammer-fist strike was determined by analyzing a sequence of drum-camera photographs, one of which is the photograph at the top. The fist reached a peak speed of 10 meters per second at the point of impact. Other sequences with the same subject yielded peak speeds as high as 14 meters per second. This strike is one of the most powerful karate maneuvers that involve the hand.

energy formula yields a critical energy of 32 joules for wood and 10 joules for concrete. (One joule is the energy needed to lift one kilogram 10 centimeters.) Such rough estimates of the critical energies seem to be the right order of magnitude, because measurements we made indicate that about 100 joules are available in a karate strike. Although these values for the critical energy are unreliable when they are considered individually, when they are considered together, they should give an adequate indication of the ratio of the energy needed to break wood to the energy needed to break concrete. The values suggest that the fist must deposit three times more energy in a wood block.

We made more precise estimates of the critical energy by considering the acoustical properties of the wood and the concrete slabs. When any object is struck, it vibrates, propagating waves through the material and sending sound waves into the air. The same phenomenon happens when the karateka strikes a block: vibrations are generated that sometimes deform the block to the breaking point. The properties of such vibrations can be predicted from a complex equation that describes the sound waves. The equation is a function of both time and the position along the length of the block, so that the vibration of the block depends on the shape it has immediately after the hand of the karateka strikes it.

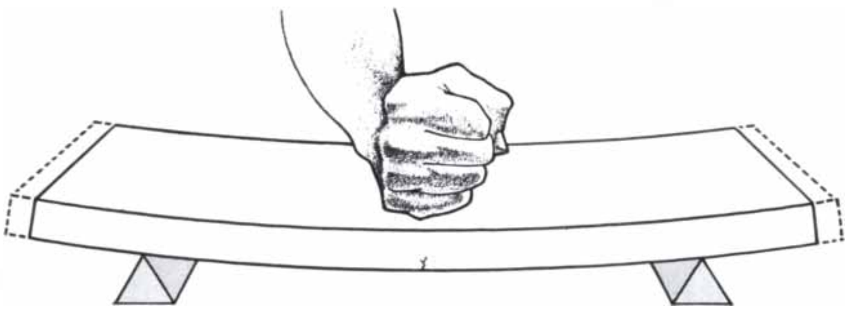
In this respect the block is similar to a violin string. When the string is plucked gently, only the fundamental tone is excited and the resulting motion is simple, but when it is plucked more vigorously, overtones are excited and the resulting motion is more complex. In a karate strike only the fundamental vibration is excited, because the hand and the target interact for several milliseconds. This interaction time is comparable to the period of the fundamental vibration but is much longer than the periods of the overtones. As a result the overtones are not sounded; there is simply not enough harmonic content to excite them.

Since only the fundamental tone is sounded, the equation that governs the motion of the block is simplified considerably. The block acts as if it were a mass, weighing half as much as the block actually weighs, sitting on top of a coil spring. The acoustical model yields a formula for the critical energy of the block. The formula indicates that the earlier rough estimates were six times too high. In other words, it takes only 5.3 joules to break wood and 1.6 joules to break concrete.

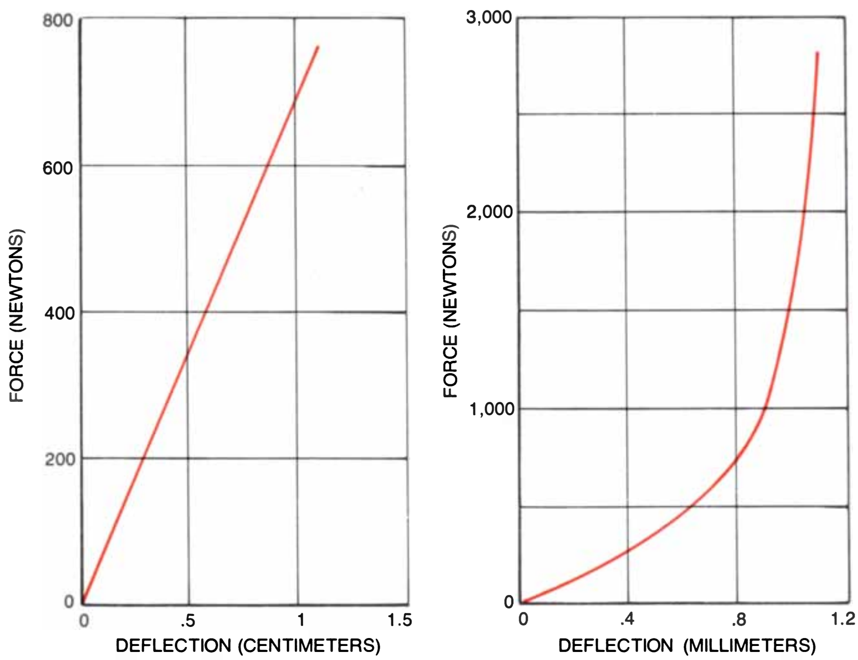
The acoustical model also yields formulas for the critical force needed to break the block and for the periods of the sound waves generated by the karate strike. We verified the predicted periods by lightly tapping blocks with a pen-

MANEUVER	PEAK SPEED (METERS/SECOND)
FRONT FORWARD PUNCH	5.7 – 9.8
DOWNWARD HAMMER-FIST STRIKE	10 – 14
DOWNWARD KNIFE-HAND STRIKE	10 – 14
ROUNDHOUSE KICK	9.5 – 11
WHEEL KICK	7.3 – 10
FRONT KICK	9.9 – 14.4
SIDE KICK	9.9 – 14.4

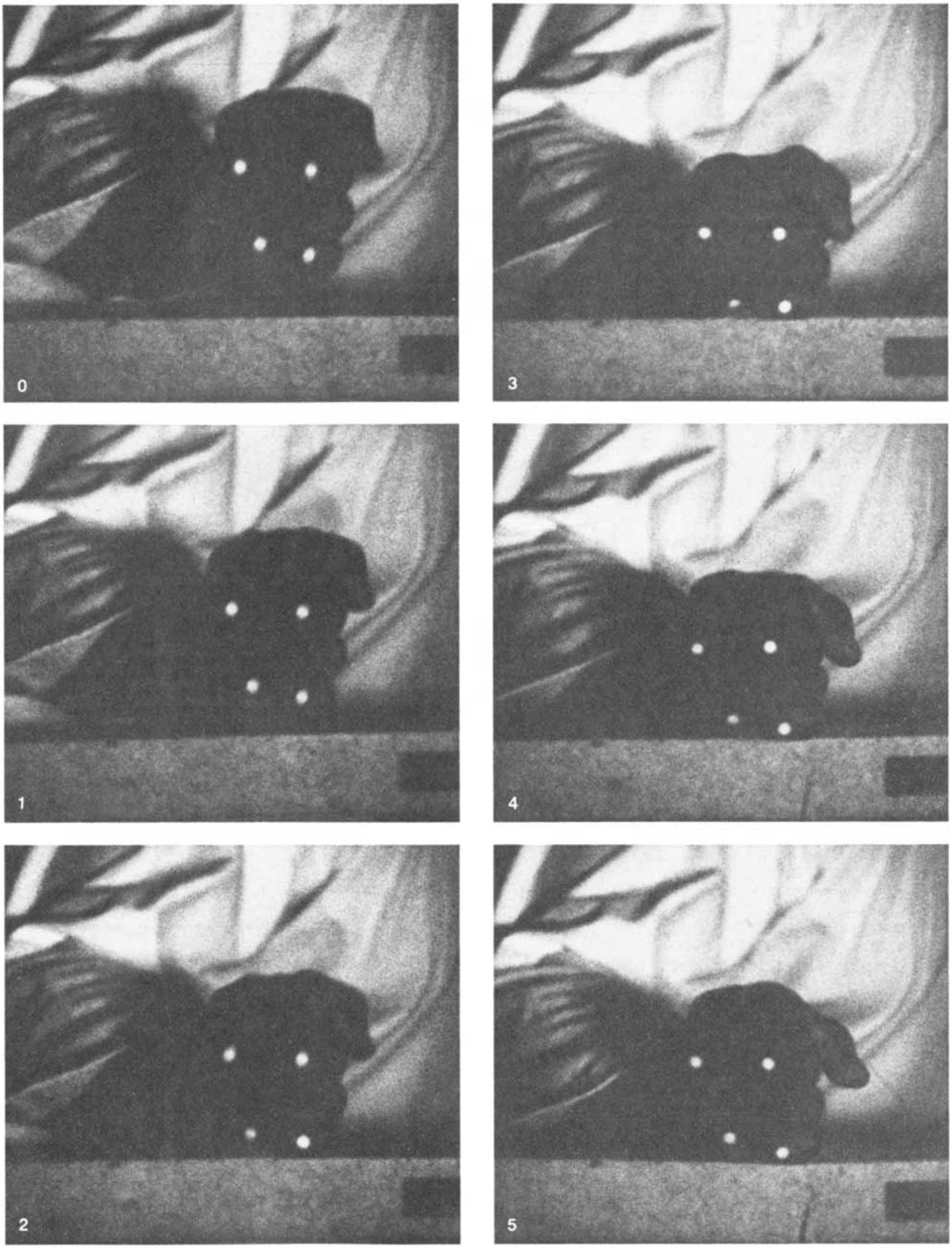
PEAK SPEEDS of karate maneuvers are listed first for empty-hand blows and then for kicks. The knife-hand strike is the "karate chop." In the roundhouse kick the foot moves in a clockwise circle as the opposite hand moves counterclockwise in order to keep the body balanced by minimizing net angular momentum. In the wheel kick the body rotates with the leg extended.



HAMMER-FIST STRIKE breaking a wood block is shown in a highly schematic diagram. In a well-executed strike the fist hits the block along a range of points near the center. The block acts like a coil spring: it pushes back on the hand with a force proportional to its deflection. The top of the block is compressed; the bottom is stretched. Because wood is weaker under tension than it is under compression the block cracks first on the bottom surface (near the center). The crack propagates rapidly upward as the block continues to be pushed downward.



HYDRAULIC-PRESS MEASUREMENTS were made of the deflection of a wood block (*left*) and a concrete block (*right*) as a function of the applied force. Each of these plots yielded values for the elastic modulus, which for a given material is a constant that indicates its springiness, and for the modulus of rupture, which is the minimum stress that causes a block to snap. It is useful to know these moduli in order to find the energy needed to break each kind of block.



FOUR MARKER DOTS were put on the side of a fist so that the displacement, velocity and acceleration of different parts of the fist during the impact could be determined from these photographs, which were spaced a millisecond apart. Although the fist makes contact with the block at *0*, the crack does not develop until *4*. The fist and the block are in contact for five milliseconds. As the fist strikes the block it decelerates rapidly. The change in the positions of the dots with respect to one another indicates that the fist is compressed and distorted to such an extent that it scarcely acts like a solid object. Hence models of the impact process cannot consider the fist as being solid.

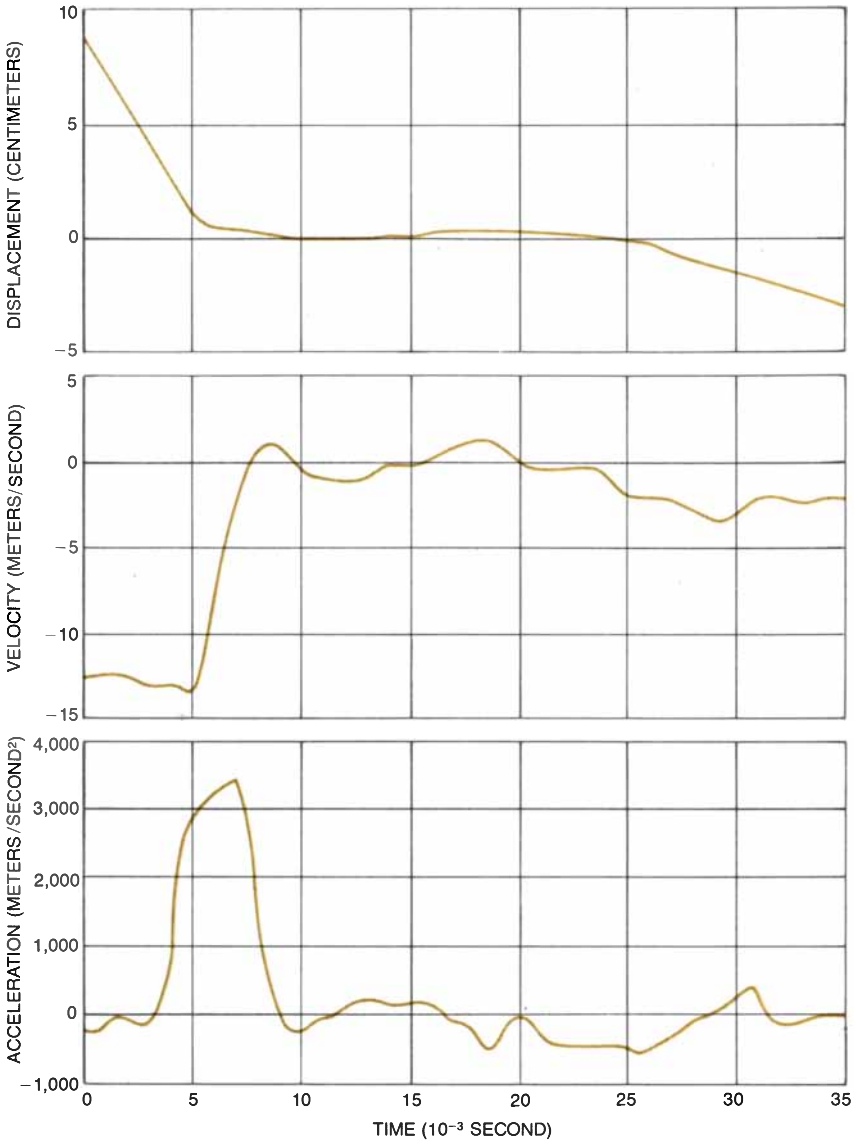
cil eraser and monitoring the resulting sound waves with a microphone hooked up to an oscilloscope. Oscilloscope pictures of the sound waves showed periods that were in reasonable agreement with the predicted values. That confirmed the validity of the acoustical model.

The formula for the critical force yields 670 newtons for wood and 3,100 newtons for concrete. Hence it takes almost five times more force to break concrete than to break wood but only a third as much energy. Energy is the product of force and deflection, and so the fact that wood is deflected 16 times farther than concrete is responsible for wood's having the larger critical energy.

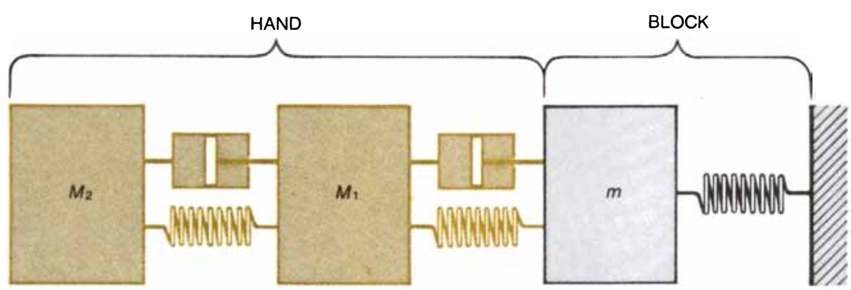
At first glance this result seems puzzling, because the larger critical energy of wood suggests that concrete is easier to break. Experience, of course, indicates the opposite. The puzzle is solved by the fact that not all the energy in the karate strike can be deposited in the target. Each critical energy we had computed represents not the energy of the karateka's hand but the energy that must be transferred to the target in order for it to break. The energy the hand needs depends on how easily energy can be transmitted from the hand to the target, which in turn depends on the relative masses of the hand and the target. When the target is less massive than the hand, as is the case with wood, it accepts most of the energy. When the target is more massive, as is the case with concrete, it accepts only a small fraction of the energy. That explains why wood is easier to break.

The role of mass in energy transfer can be made clearer by considering rubber balls. Think of a rubber ball thrown through the air. If the ball hits an identical ball that is at rest, the first ball stops and the second ball absorbs its energy and continues along the trajectory of the first ball. If, on the other hand, the ball hits a much heavier ball, the first ball rebounds at nearly the same speed and the heavier ball hardly moves. These two instances are examples of an elastic collision; in such a collision kinetic energy, or energy of motion, is conserved. In other words, the kinetic energy the first ball has before the impact equals the kinetic energy it has after the impact plus the kinetic energy the second ball has after the impact.

A karate strike is not an elastic collision. We made high-speed motion pictures showing that the hand and the target are in contact during the entire breaking process. On impact the hand and the block move together. In such an inelastic collision not all the kinetic energy in the hand becomes kinetic energy in the combined system. Some of the energy unavoidably is expended in deformation: the flattening of the hand and the target against each other. The heavier the target is, the less the kinetic



VERTICAL DISPLACEMENT, velocity and acceleration are plotted for the dot at the lower right on the fist in the photographs on the opposite page. The peak deceleration of the dot was 3,500 meters per second squared; that of the other dots was 4,000 meters per second squared.



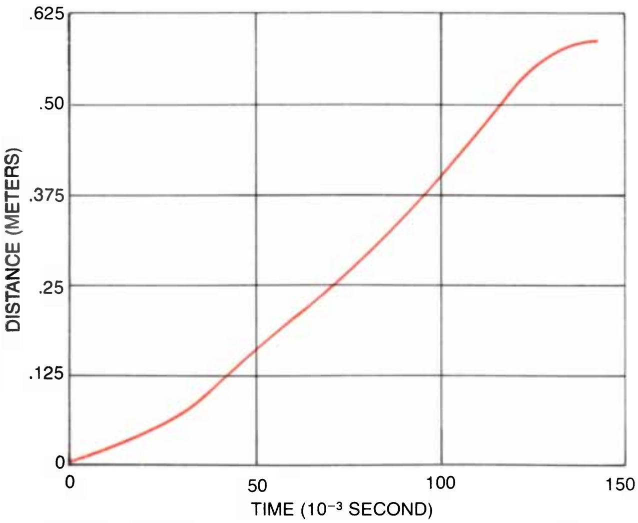
IMPACT PROCESS is represented by a dynamic model that regards the hand and the lower forearm as consisting of two masses, the first (M_1) corresponding to the surface hand tissue and the second (M_2) to the rest of the hand and the lower forearm. The masses are linked by springs and dampers. In modeling the karate strike the hand, represented by the coupled masses, hits the block, represented by a mass (m) on a spring. When the coupled equations governing the interaction were solved, it was found that the hand needs 12.3 joules of energy to break wood and 37.1 joules to break concrete. The dynamic model is a slight modification of one that John W. Mishoe and Charles W. Suggs of North Carolina State University developed to study the response of the hand and forearm to vibrations generated by industrial machinery.

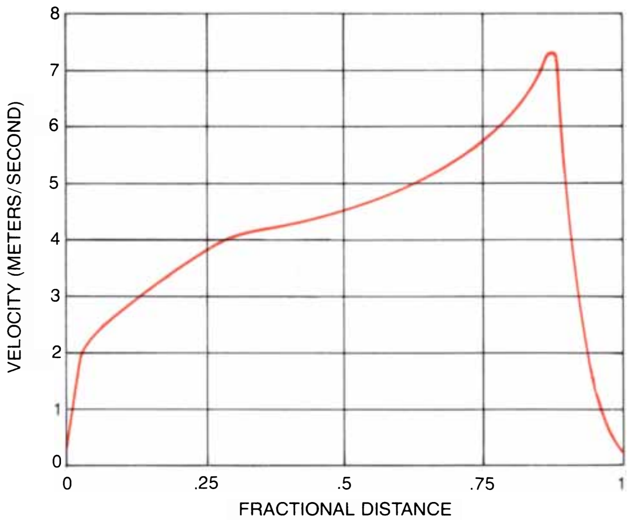
energy goes into motion and the more it goes into deformation. With wood most of the kinetic energy is conserved, but with concrete a substantial fraction goes into deforming the hand.

A simple estimate of the energy transferred in a karate strike can be made by assuming that the collision between the fist and the block is perfectly inelastic. From kinematic laws describing the motion of objects colliding inelastically and from the critical energies we have computed it is easy to determine the energies a hand would need in order to break the blocks: 6.4 joules for wood and 8.9 joules for concrete. The inelastic-collision model confirms the obvious: wood is easier to break.

It is time to put the theoretical model aside and see how much energy, velocity and acceleration are actually available in the karate strikes. We determined these quantities primarily from multiple-flash stroboscopic photographs,

STROBOSCOPIC PHOTOGRAPH of a forward karate punch, in which the karate expert was illuminated by 120 flashes per second, indicates that the fist reaches maximum speed shortly before the arm is fully extended. The karate expert focuses his punch just inside the target, so that his fist reaches maximum speed at the point of contact. As a result the punch imparts a large amount of momentum to target.





MAXIMUM SPEED of about 7.5 meters per second was achieved by the fist shown in the upper illustration on this page. From the distance between each position (*left*) the velocity of the fist was plotted as a function of the fraction of the total distance it traveled (*right*).

made with the shutter of the camera left open as the karateka executed a maneuver. The karateka was illuminated by 120 flashes per second, so that his position at the time of each flash was recorded in the photograph. From measurements of the distance between each position the velocity and acceleration of the hand of the karateka could be easily calculated. The stroboscopic photographs showed peak velocities of between 10 and 14 meters per second for the hammer-fist strike (in which the fist is brought down from above the head in a circular arc) and the knife-hand strike (the "karate chop"). In the forward punch of karate the hand reaches speeds of between 5.7 and 9.8 meters per second, and in various kicks the foot reaches speeds of between 7.3 and 14.4 meters per second. The peak speeds in the hammer-fist strike correspond to energies of between 50 and 100 joules, much more than the 6.4 joules the hand needs to break wood and the 8.9 joules it needs to break concrete as calculated from the inelastic-collision model.

In spite of this encouraging result the inelastic-collision model only roughly approximates the interaction of the hand and the block. The model erroneously assumes that the collision is completed before the block begins to break. Our high-speed motion pictures show that the hand and the block are still interacting while the block is fracturing. Another shortcoming of the model is that it yields no insight into the dynamics of the fracture process or into the forces acting on the hand and forearm during the strike.

The motion pictures were made at 1,000 frames per second. That made it possible to observe the impact process in slow motion and to study the frames individually to see what happens from one millisecond to the next. One sequence of frames recorded a hammer-fist strike impinging on a concrete block. We put four marker dots on the side of the fist so that we could study the velocity and acceleration of different parts of the fist during the collision. As the fist strikes the block it decelerates rapidly, reaching a maximum deceleration of 3,500 meters per second squared for the lower right-hand part of the fist (when the blow was struck with the right fist) and 4,000 meters per second squared for the rest of the fist. The fist is compressed and distorted to such an extent that it scarcely behaves like a solid object. The impact lasts for five milliseconds, with the slab starting to break at the bottom after having been deflected only a millimeter.

The data gathered from the motion pictures can be utilized to estimate the peak force exerted on the fist during the impact. The peak force is the product of the mass of the fist and its deceleration. For a mass of .7 kilogram the force is between 2,400 and 2,800 newtons, which is about 400 times greater than the force of gravity. Similar motion pictures were made of a hammer-fist strike impinging on a wood block, but here the deceleration was much too small to measure accurately.

For a better description of the impact process we turned to a dynamic model that John W. Mishoe and Charles W. Suggs of North Carolina State University had developed to study the response of the hand and forearm to vibrations generated by industrial machinery. Unlike the inelastic-collision model, the dynamic model does not treat the hand as a solid object; it regards the hand and lower forearm as consisting of three masses (corresponding to the skin of the hand, the hand tissue immediately under the skin and the remaining 90 percent of the mass of the hand and lower forearm) linked by springs and dampers. For our purposes it is necessary to represent the hand by only two of the three coupled masses, because the mass corresponding to the skin is negligibly small.

In modeling the karate strike the hand, represented by the coupled masses, hits the block, represented by a mass on a spring, whose parameters were determined from the acoustical analysis described above. When the complex equations governing this interaction were solved with the aid of a computer, it was found that the hand needs 12.3 joules of energy to break wood and 37.1 joules to break concrete. These values are somewhat higher than those predicted by the inelastic-collision model.

Although it is not clear that the dynamic model precisely describes the karate strike, in which the forces are much larger than those encountered in the operation of vibrating machinery, the results are encouraging. The model indicates that the hand must reach a speed of 6.1 meters per second to break wood and 10.6 meters per second to break concrete. Such speeds agree with our observation that beginners can break wood but not concrete. A hand velocity of 6.1 meters per second is within range of the beginner, but a velocity of 10.6 meters per second calls for training and practice. The dynamic model also predicts correctly that a concrete block fractures in less than five milliseconds.

How is it that the hand of the karateka is not shattered by the force of the karate strike? Part of the answer lies in the fact that bone is much stronger than concrete. Consider how easy it would be to shatter a piece of concrete the size and shape of a bone. Indeed, the rupture modulus of bone is more than 40 times greater than that of concrete. If a cylinder of bone two centimeters in diameter and six centimeters long were simply supported at its ends, it could withstand a force exerted at its center in excess of 25,000 newtons. Such a force is eight times greater than the force concrete exerts on the hand in a karate strike. The hand can actually withstand forces much larger than 25,000 newtons because it is not a single piece of bone but a network of bones connected by viscoelastic tissues. Furthermore, the hand is not supported at the ends and struck in the middle, as a block of concrete or wood is.

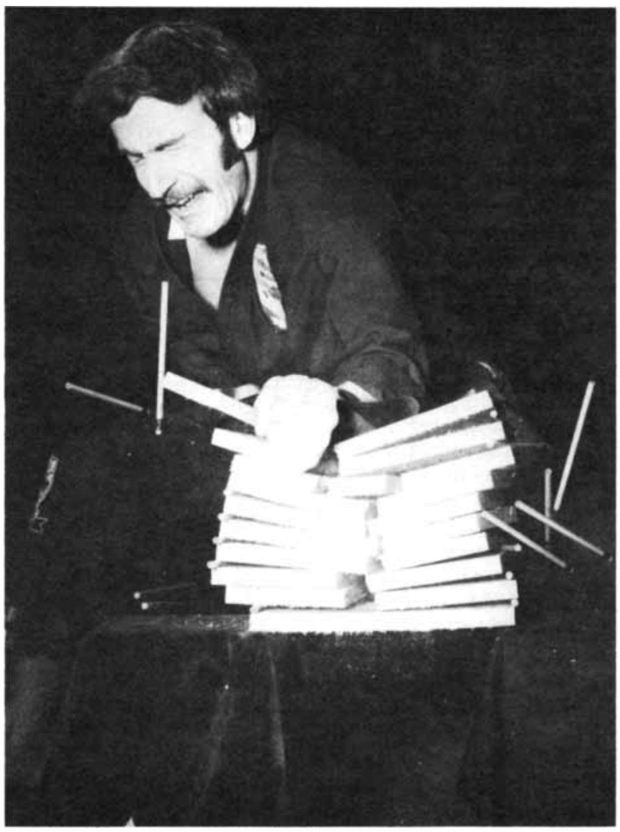
Under impact the bones move and transmit part of the stress to the adjoining muscle and other tissue. Some of the stress is absorbed by the skin and muscles that lie between the point of impact and the bones. Moreover, much of the force is rapidly transmitted to other parts of the body. Work remains to be done to determine what fraction of the stress is absorbed where.

In the hammer-fist strike the fifth metacarpal, the bone at the bottom of the fist and the one most vulnerable to the impact of the blow, is protected by the muscle called the abductor digiti minimi. As the fist is tensed the abductor muscle stiffens and thickens. The first line of defense against the blow is the skin. The next is the abductor, which acts as padding in absorbing some of the impact force. Then the tendons in the wrist absorb some of the blow as the fist bends back at the wrist. Finally the energy transmitted to the arm is absorbed by muscles and other tissues in the forearm and the upper arm.

In karate the proper positioning of the hand, and of the foot when it is used to deliver a blow, is critical. In many maneuvers, such as the open-hand strike and the side kick, contact is made with the edge of the hand or the foot. These techniques concentrate the force on a small area of the target, thereby reducing the likelihood of deflecting a bone to the point of fracture. In fact, if the striking part of the body is oriented properly, the force required to break it is much greater than the force required to break the target. For example, we have estimated that in a well-placed side kick the foot can withstand roughly 2,000 times more force than concrete can.

So far we have discussed only the breaking of a single block, and karatekas can also break stacks of wood and concrete blocks. With a well-executed strike or kick the karate expert can demolish several concrete blocks placed directly on top of one another. Even higher stacks of concrete blocks (and of wood blocks as well) can be broken if the blocks are not stacked flush on top of one another but are held slightly apart by dowels placed between them. The dowels ensure that the critical force is reduced by a favorable effect of angular momentum. When the first block breaks, it absorbs energy from the fist. As the two halves of the broken block move downward, they acquire angular momentum. The angular momentum and linear momentum of the broken pieces are often large enough to break the second block, which in turn breaks the third block, and so on. Hence the peak force needed to break, say, eight wood blocks is less than eight times the peak force needed to break only one block.

All the karateka has to do is properly hit the first block hard enough near the center. An off-center strike may fail to break the entire stack. Photographs show that in such a strike each successive block that breaks does so at a point that is closer to its center. Thus part of the energy of the hand is lost to the horizontal motion of the fracture wave. When too much energy is lost to such motion, there may not be enough left to break the bottom blocks.



EIGHT WOOD BLOCKS (*left*) are broken by the hammer-fist strike of one of the authors (Feld). Originally the blocks were not stacked flush on top of one another but were kept slightly separate by pencils placed between them. The pencils ensured that the critical force was reduced by a favorable effect of angular momentum. When the first block broke, it absorbed energy from the fist. As the two halves of the broken block moved downward, they acquired enough angular momentum to break the second block, which in turn broke the third block, and so on. Hence the force needed to break the eight blocks was much less than eight times the force needed to break one block. An off-center strike (*right*) failed to break the bottom block in a stack of 10. The fracture wave traveled toward the center, where the blocks are most easily broken. Much energy was lost to this horizontal motion, so that not enough was left to break the bottom block.

PONTIAC'S NEW SAFARIS

TWO OF OUR MOST LUXURIOUS PONTIACS HAPPEN TO BE WAGONS.

Mid-size luxury! Grand LeMans Safari's available 60/40 seats.

This richly appointed dash features simulated woodgrain applique.

Grand LeMans Safari's spacious cargo area holds 72.4* cu. ft.

Our luxurious full-size Bonneville Safari's available 60/40 seats, luxury cushion steering wheel, power windows and fold-down third seat.

Std. 3-way gate opens to 88.7*cu.ft. for cargo. Plus hidden storage!

THE 1979 PONTIACS OUR BEST GET BETTER

GM

*Load space with rear seats folded down.

Lockheed knows how.

"Biggest advance since the autopilot."

That's one widely held opinion of an exclusive fuel-saving system now being installed in many L-1011 TriStars.

Called the Lockheed Flight Management System, it senses altitude, speed, and other flight factors. Then it can act automatically to control the engine throttles for best fuel-use efficiency at all times during flight—takeoff to landing.

Flight management control panel.

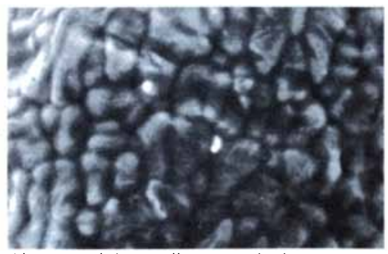
Though a new feature, the system isn't just for new planes; it can easily be added to existing L-1011s. And the savings, over the life of each plane, could total millions of dollars.

Making aircraft lighter.

Since the 1930s, most aircraft have been structured of strong, lightweight aluminum. Future generations of aircraft may also be made mostly of aluminum, but of a very different nature.

A new technology being explored by Lockheed uses powdered aluminum, alloyed with such elements as iron, lithium or cobalt, to create lighter, stronger and stiffer metals than can be achieved with conventional aluminum technology.

Results indicate this 'new aluminum' could reduce present-day jetliner weight by 10%. That in turn means savings of millions of gallons of fuel over each aircraft's life, a big benefit in energy-short years.



Aluminum lithium alloy magnified 1,000 times.

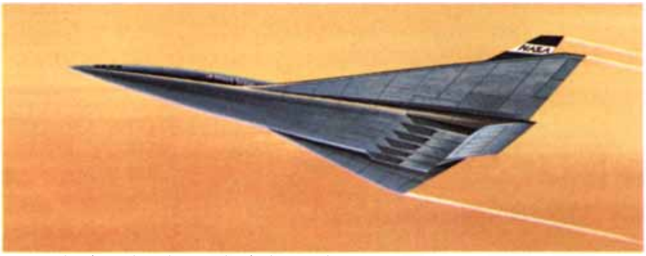
For this new-material process, Lockheed scientists even had to employ astonishing techniques for turning the powdered aluminum and alloys into superior metal. After heating and melting, for example, the mixture is rapidly cooled *a million times faster* than the cooling rate used with standard aluminum ingots.

Down the road: liquid hydrogen.

Lockheed scientists are deep into a NASA-sponsored study of a future aircraft, powered by a clean-burning liquid hydrogen, that could cruise at a flashing hypersonic speed of about 4,000 mph, or six times the speed of sound.

Because liquid hydrogen can be made from coal or even water, its future use in aircraft could eliminate the need for scarce, expensive petroleum.

The aircraft would cruise at altitudes as high as 120,000 feet and have ocean-spanning range. Its 200 passengers


Design for liquid hydrogen fueled aircraft

could be whisked from New York to London in under two hours, and could make the Los Angeles/Tokyo flight in a mere two hours, 18 minutes—takeoff to landing.

Fine-tuning the flight plan.

When a pilot calls Lockheed's JetPlan, he's in touch with a computerized encyclopedia of information affecting his proposed flight. And the benefit he gets is eye-opening economy—savings of both time and fuel.

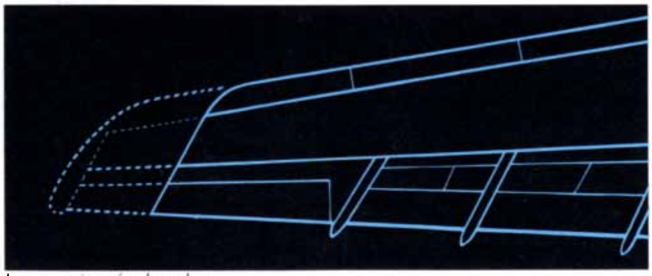
To tap a constantly updated reservoir of data, a pilot makes preflight contact via telephone and a small printer terminal. In minutes, he gets back his most efficient flight plan. Given origin, destination, and type of aircraft, JetPlan reckons its answer from such factors as route analysis, current weather, recommended fuel load, cruise altitude, speed and shortest route.

How well does it work? Over a recent 12-month test period, U.S. military and corporate aviation saved more than 30 million gallons of fuel, or better than $1.5 million. But that's just the beginning. The number of JetPlan users and the savings are both growing steadily.

Stretching wings.

Longer wings mean reduced drag and consequently a substantial cut in fuel use. But among big wide body jetliners, only the Lockheed L-1011 TriStar can add nine feet of wingspan without costly structural redesign.

That's because of the L-1011's advanced technology, in this instance an exclusive system of Active Control ailerons. Controlled by computers, these ailerons will act automatically to reduce the structural loads on the lengthened L-1011 wings.


Longer wings for less drag

The longer wings and Active Control ailerons will mean a healthy savings of fuel when they enter airline service in 1980. And they'll also help the L-1011 have the smoothest ride of any jetliner through gusts and turbulence.

When it comes to devising farseeing programs to meet the growing fuel crisis, Lockheed knows how.

Lockheed