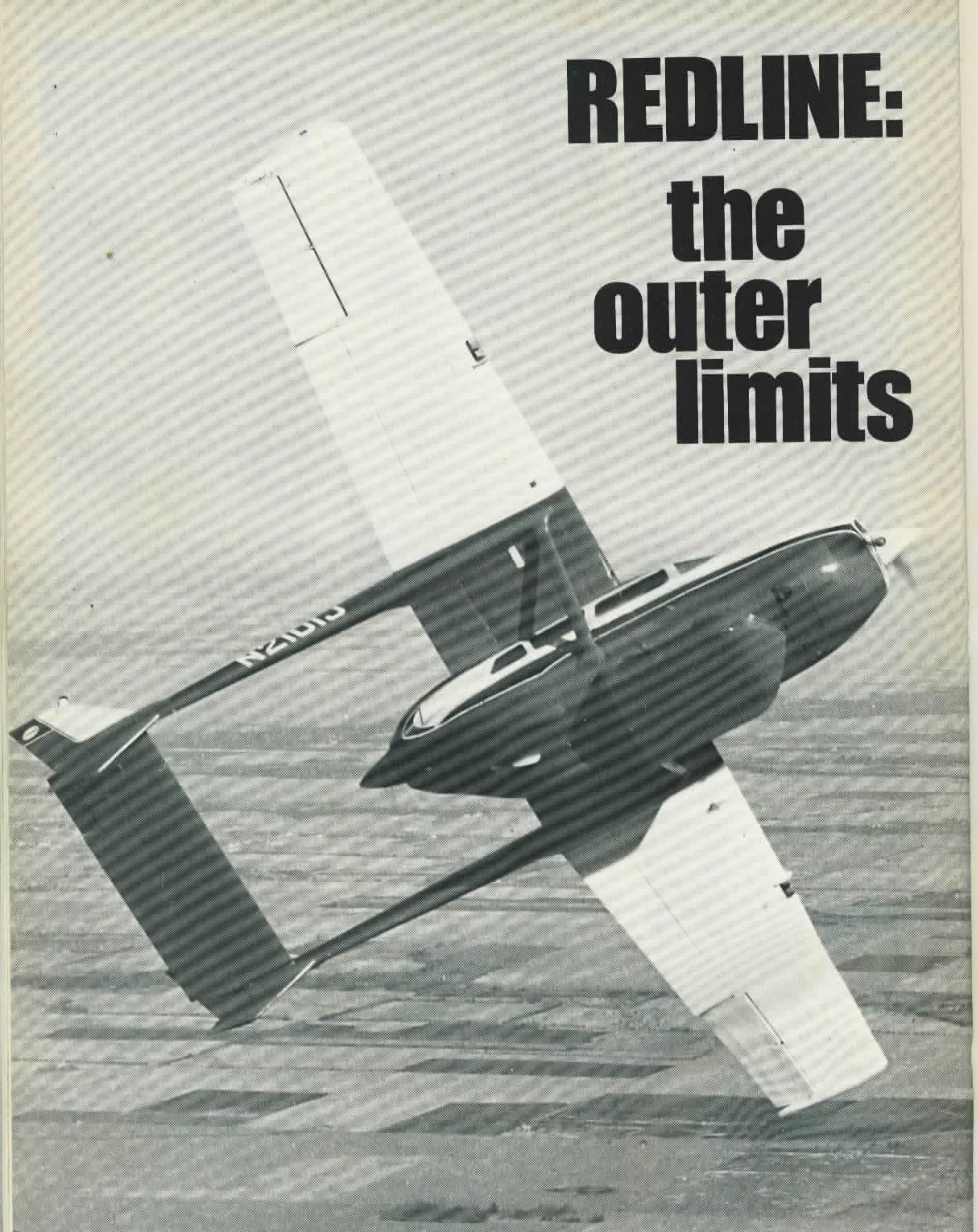
REDLINE: the outer limits



THE AIRPLANE YOU FLY CAN BE OVERSTRESSED.

DO YOU KNOW HOW MANY WAYS IT CAN HAPPEN?

By BARRY SCHIFF

WHEN A PILOT flies a new airplane, he generally does so caringly, caressingly, the way a driver handles his new car. But an aircraft manufacturer does not. When a new design is born it is subjected to a brutal beating: wings are bent to destruction, it is dropped mercilessly on its landing gear from heights of 20, 30 and 40 feet, the fuselage is twisted by unrelenting hydraulic forces and other components are manhandled to their breaking points.

These are moments of truth. It is in the testing of a prototype aircraft that the dreams of engineers and designers are either proven or shattered.

Manufacturers dare not rely on information from an electronic computer or the paper calculations of a stress analyst to determine the character and strength of a new aircraft. Before it can be certified, elaborate testing must prove that a new design is everything it is supposed to be.

After a new aircraft has taken its punishment, the manufacturer gets out the Crayolas and begins to draw colored lines and arcs – red ones, white ones, green ones and yellow ones. These are the operating limits of the aircraft – the operating envelope. As long as a pilot remains "within the envelope," he can rest assured that the airplane won't turn around and bite him. This is because the established limits are well below the actual limits determined by testing. It is indeed a tribute to airframe manufacturers that so very few accidents can be attributed to structural failure. And most of these occur only when a pilot pushes an airplane beyond its limits; he flies "outside the envelope."

Although superbly designed and elaborately tested, an airplane is, nevertheless, a piece of machinery. Like any other piece of machinery, it can be broken if a pilot tries hard enough – intentionally or otherwise. This is why manufacturers place all those pretty markings on the instruement panel. They are flags waving in a pilot's face, flags that indicate what he may and may not do. But despite the warnings, a pilot occasionally exceeds a limit. He does what a manufacturer has told him not to do. Usually he gets away with it, not because of his superior airmanship, but because of the safety margins built into the airplane. But sometimes he doesn't get away with it.

For example, how many pilots have overloaded their airplanes at one time or another? Probably most. They hear about other pilots flying overweight and figure they can do it too. They figure wrong, probably because they don't understand the significance of the weight limitations. Or, for that matter, any of the other limitations that determine the shape of the airplane's safe operating envelope.

Most pilots do know that an overloaded airplane doesn't climb very well and that it needs a longer runway for takeoff, but most are unaware of other serious problems that also can be created.

Gross weight (and many other limitations) usually is determined by structural strength, something the manufacturer determines by actual testing before the aircraft is certified.

Let's assume that a new aircraft, the Gilded Buzzard Mark IV, is ready for prototype testing. It has been designed to have a gross weight of 3,000 pounds. Its wing has an area of 200 square feet, which means that each square foot of wing is to support 15 pounds of aircraft weight in normal flight (3,000 pounds divided by 200 square feet equals 15 pounds per square foot). Also, the Buzzard has been designed to withstand a 4.0-g positive load (3.8-g's is the minimum required of normal category airplanes). This means the wings must be capable of carrying 4 times the normal weight of the aircraft, or 60 pounds per square foot of wing.

But to be super-safe, manufacturers must build wings that are at least 50% stronger than they need to be, offering pilots wide safety buffers. This means that the Buzzard's wing must be able to lift a minimum of 90 pounds per square foot (150% of 60 psf) or a total of 18,000 pounds. To make sure the manufacturer has done his homework properly, the Buzzard's new wing is installed in a test stand and subjected to gruelling hydraulic forces. Engineers watch with apprehension as the loads are increased, waiting for the wing to give under the strain. If the wing doesn't give until an ultimate load in excess of 18,000 pounds breaks the main spar, it has proven itself and everyone is satisfied that there's no way for a pilot to damage the wing if he observes the designed load limit of 4-g's at the maximum allowable gross weight of 3,000 pounds. After all, this is only a total load of 12,000 pounds, far below what the wing can really take.

Delighted with the new Buzzard, aircraft salesmen have a field day filling pipelines with the wonderful new machine from Wichihaven.

Finally, one is sold to Hiram Hotshot, a pilot who wouldn't recognize an operating limitations manual if it spoke to him in seven languages. Prior to his first flight, he stuffs 250 pounds in the baggage compartment, 100 pounds in excess of the placarded limit. "What the heck," he muses, "this compartment is cavernous. Everything fits with lotsa room left over for the fish we're gonna catch."

So off he goes. Enroute he encounters moderate turbulence and fights the controls like a madman to keep the Buzzard headed unerringly toward the distant fishing hole. At one point, his g-meter hits the 4.0 mark. No problem, right? Wrong. The floor of the Buzzard's baggage compartment is designed to carry 150 pounds at 4.0 g's or a total of 600 pounds of load. But Hotshot has 250 pounds in back. At 4-g's, this amounts to a total load on the floor of 1,000 pounds, 400 pounds above the designed limit. The wings are fine because the gross weight of the airplane hasn't necessarily been exceeded, but oh, those floorboards! They could give way. They weren't designed to take that kind of punishment.

It's another day, another flight. Hiram learned finally not to overload the baggage compartment. This time the Buzzard is loaded properly, but the gross weight is nudging the maximum allowable, 3,000 pounds. Enroute to a business appointment, he flies into that now-familiar patch of turbulence. At the Buzzard's high cruising speed, the ride gets fairly rough, but Hiram's in a hurry and doesn't even consider slowing down. What can he expect to happen as he horses on the controls to prevent altitude fluctuations? He can expect to overload the wings, especially if control variations become excessive. This is because load factors increase rapidly when maneuvering at progressively higher airspeeds; they increase in proportion to the square of the airspeed.

For example, assume the Buzzard has a stalling speed of 50 mph. At twice this speed, 100 mph, abrupt application of full-up elevator quadruples the load factor, the maximum allowable. At three times the stall speed, or 150 mph, similar use of the elevator causes a 9-g load and at 200 mph (four times the stalling speed), abrupt, full-up elevator creates a 16-g load. Well, no one in his right mind would haul the yoke back this hard at such a high speed. But just how much up elevator is tolerable when flying at four times the stall speed, especially when flight loads have already been increased by the gusts? In turbulence, it's difficult to gauge just how much elevator control input is being applied. A g-meter is helpful in observing structural limitations, but most aircraft don't have one. There is another method, a better method. When abrupt maneuvering is required and/or severe turbulence is encountered, reduce airspeed to where it would be impossible to exceed the allowable g-limit, no matter what is done with the controls and no matter how the elements of nature conspire against the pilot. Such a speed is called the maneuvering speed. Unfortunately, it is not shown on the airspeed indicator as are other airspeed limitations, but it can be found in the aircraft operating manual.

The Buzzard's maneuvering speed is 100 mph. At this speed it is impossible to exceed the load factor limit, because the airplane stalls before more than 4.0-g's can be attained. In all aircraft, the maneuvering airspeed is equal to the stall speed (gear and flaps up) multiplied by the square root of the limiting load factor. For example, the E33A Bonanza has a stall speed (clean) of 73 mph and a limiting load factor of 4.4-g's. The square root of 4.4 is 2.09 and multiplying this by the stall speed (73 mph) produces maneuvering speed, 152 mph.

What this means in reality is that no matter how hard you try, you cannot exceed the design load factor when flying at or below the maneuvering speed. Applying full and rapid "up" elevator or encountering a severe gust at such a time may cause the aircraft to stall, but a momentary stall at altitude is much preferable to exceeding structural limitations. This is why it is recommended to slow down to the maneuvering speed in turbulence or when practicing very steep turns. Remember, g loads also increase as the bank angle increases while maintaining a constant altitude. In a 30 degree banked turn, the normal g loading is only 1.15 g's, but double the angle of bank and the load factor increases to 2 g's. Add to this the effect of turbulence and/or pulling back on the yoke to prevent altitude loss and even larger load factors are created.

When abrupt maneuvering or heavy turbulence is anticipated, reduce airspeed to the maneuvering speed. If this performance figure is not immediately available, a rule of thumb can be used to determine it. In most light aircraft, the maneuvering speed is about double the clean stalling speed. Simply note the stall speed from the airspeed indicator (the bottom of the green arc) and multiply this by 2. An airplane with a clean stall speed of 60 mph, for example, could be assumed to have a maneuvering speed of 120 mph at maximum gross takeoff weight, a little less at lighter weights.

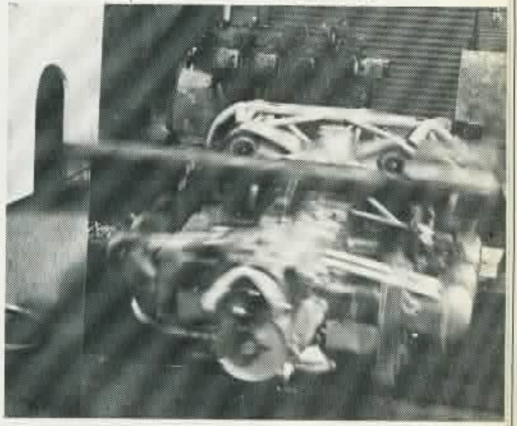
Since the effects of abrupt maneuvering and turbulence are cumulative, it is wise never to combine these loads. In other words, restrict all maneuvering to smooth air, and while in turbulence avoid making rapid control inputs. Ride the turbulence, don't fight it. If the airplane wants to climb in a strong, turbulent updraft or descend in a downdraft, let it (terrain permitting). In turbulence, it is not difficult to overcontrol and overstress the aircraft. A pilot is apt to apply control pressures that he would never do otherwise. But remember, if the airspeed is reduced sufficiently, airframe limits cannot be exceeded. This is a comforting thought but doesn't mean much to a pilot who ignores the value of the maneuvering speed.

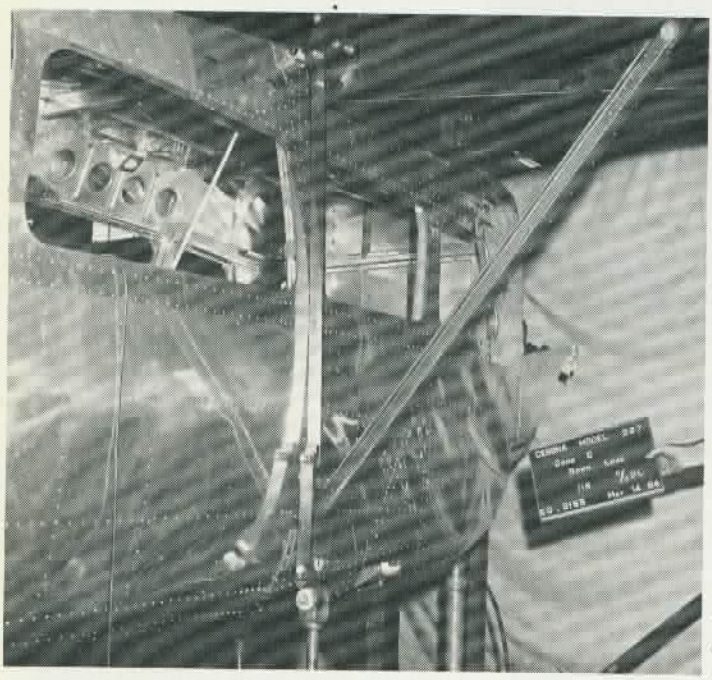
A little known fact about wing flaps is that when they are lowered, the structure is no longer stressed to be safely flown at its normal g limits. In almost all aircraft, the use of full flaps requires that a pilot observe some specified, reduced load factor. Most Bonanzas, for example, are limited to a 2-g load with the flaps down (4.4-g's with flaps retracted). So if a pilot is making an approach in heavy turbulence and expects full utilization of all controls, the flaps should remain retracted, irrespective of the approach speed.

Engineers hammer a Skymaster's gear savagely during drop tests, seeking to measure exactly how much force it will take to cause structural failure.

Some pilots have the mistaken notion that if a wing is designed for a 4-g limit, for example, it cannot be damaged until a minimum load of 6 g's is imposed. They assume that minor trespasses slightly above 4 g's won't hurt the wing. This is true to the extent that damage to the wing won't be *visible*. But overstressing has a cumulative and detrimental effect on the service life of an aircraft. This is a positive and irreversible fact. A wing (or any structural member) that is overstressed repeatedly over a period of time will fatigue. The effect of accumulated overstress is the formation of cracks which always precede actual structural failure. This is why periodic inspections are so vital to aircraft safety. Fatigue damage can be sighted visually through the inspection

The picture isn't out of focus: Piper engineers are shaking the daylights out of an engine mount to measure how much vibration it can survive.





Laborious testing procedures, and not arbitrary decisions, establish where the limits will be set on new designs.

Hydraulic pressure hauls at a Cessna fuselage to test amount of down load needed to break wing attach structure.

ports of a wing. But the pilot should cooperate by flying the aircraft so as to abide by the limitations. Modern airplanes are tough. The construction materials used frequently exceed the minimum strength required by some large percentage. But a pilot who abuses his aircraft can break it if he tries hard enough. And exceeding the limiting load factor doesn't necessarily mean that the wing can't take the load. Some other part of the airframe such as the tail assembly might be the weakest link in the chain.

Another limitation is the red line airspeed, or the never exceed speed. It is fairly self-explanatory, but there are some mistaken notions as to what takes place when this speed is exceeded. There is a safety margin built in by the manufacturer. A pilot could exceed the red line airspeed by as much as 10% without encountering any adverse effects. But, he would again be reducing the safety margin, especially if turbulence, even light turbulence, is encountered at such a high airspeed. Beyond the 10% margin (220 mph, for example, in the case of a 200 mph red line), a pilot can anticipate flutter. This is an aerodynamic phenomenon that is similar to a flag fluttering in a strong wind. When an airplane is forced to fly fast enough, some part of the airplane will eventually begin to flutter, just like a flag. And once it starts, whoa Nellie, watch out. Flutter is considered to be catastrophically divergent, which means that once it begins, the condition worsens on its own accord, even after the pilot reduces airspeed. Flutter is much like a nuclear chain reaction in slow motion. It takes considerable effort to get it started, but once the process begins . . . .

It is another tribute to airframe manufacturers that no modern, certificated light airplane has ever encountered flutter. Also, pilots easily understand the red line limitation and are careful to avoid airspeeds which are even close to it.

It is interesting to note that flutter is generally the first adverse condition to occur at speeds well above the red line. Many pilots believe that this limitation is imposed because the structure is not strong enough to withstand such high airspeeds. Not

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true. Most airplanes could be dived at breathtaking speeds if it were not for flutter, a phenomenon of nature about which manufacturers can do very little. They merely tell us how to avoid it.

There are a few airplanes, however, mostly of the older and fabric variety, that demonstrate minor structural failures at ultra-high speeds (more than 10% above the red line) before flutter has a chance to occur. These failures generally consist of a front window blowing (in or out), or a side window being sucked out, or a piece of fuselage fabric ripping off.

The yellow arc on an airspeed indicator is the range of airspeeds which should be avoided in turbulent air. One reason for this, of course, is the effect of encountering gusts at high speed. The airplane encounters loads similar to those experienced by a high-speed motorboat racing across choppy water. Another is the tendency for a pilot to overcontrol the aircraft in turbulence at high speeds. A third reason not normally thought of is horizontal gusts. That's right, horizontal gusts. Not all gusts come from above and below the aircraft. Some come from in front of or behind the aircraft as well. The ones which strike the aircraft head-on are significant at high airspeeds. Assume a pilot is flying in turbulent air at 180 mph – in the yellow arc – about 20 mph below the red line of 200 mph. Suddenly he is confronted with a head-on 30 mph gust. The airspeed increases in response and in proportion to the gust, to about 210 mph – 10 mph above the red line. This is one major reason for the yellow arc. It is placed on the instrument by the manufacturer for the pilot's protection. To be safe, all a pilot has to do is heed the aircraft limitations.

This is a good time to discuss other problems associated with an overweight aircraft. Suppose Hiram Hotshot stuffs his airplane with freshly caught fish and takes off weighing 3,300 pounds, fully 300 pounds beyond the maximum allowable. (This is done more frequently than one might imagine.) Now instead of each square foot of wing lifting 15 pounds, the wing loading is increased to 3,300 pounds divided by 200 square feet, or 16½ pounds per square foot. Hiram expects the resulting decrease in performance – and gets it. What he doesn't expect soon follows. To avoid a hill at the end of the runway, he wracks the overburdened aircraft into a steep bank and hauls back on the wheel to counter a strong and sudden turbulent downdraft on the leeward side of the hill. He feels the increased g load in the seat of his pants but is relieved to see that his g-meter indicates no more than 4 g's. Ah, ignorance is bliss. Remember, those 4 g's are acting on more weight than is normal. Each square foot of wing is being called upon to lift four times its wing loading, or 66 pounds per square foot. This, multiplied by the area of the wing, 200 square feet, results in the total load on the wing, 13,200 pounds. This is more than 1,200 pounds beyond the design load limit of the wing. No, the wing won't break. It won't even bend very much. Wings are built quite strongly, you know. But, this is an instance of overstress, a contribution to fatigue, a small chip taken from the trunk of an oak tree.

"Aha," you say, "but since Hiram just took off, his airspeed is probably below the maneuvering speed and he can't possibly pull this much of a g-load." And "aha to you," I say, "because if Hiram is flying that slowly in such a configuration and so close to the granite, then the aircraft must have stalled and conditions would be far worse than described." No, Hiram wasn't that dumb. He lowered the nose and built up airspeed to avoid the stall and in doing so, overstressed the airframe. The point is this: in such a situation, Hiram could not have avoided being squeezed into a pickle jar. He established the criteria before takeoff by overloading his Gilded Buzzard Mark IV.

More bad news follows when Hiram decides to land and off-load some of the excess weight. Landing overweight imposes excessive strain on the landing gear. For any given rate of descent at touchdown, the load on the landing gear varies with the square of the aircraft weight. Since Hiram is 300 pounds, or 10% overloaded, the landing gear must absorb 21% more shock. He must be careful and touch down smoothly or he'll overstress the gear in the same way he overstressed the wing. No, the gear won't fall off. It probably won't even be visibly damaged. Just more fatigue.

The shock absorbing ability of the landing gear varies directly with the length of the shock struts. A shock strut inflated to only half of its normal length can only absorb half of its normally-rated shock load. This means that the stiff landing gear components must absorb the rest, a load to which they should not be subjected.

If an airplane is landed with one or more flat shock struts, its owner should prepare for an expensive appointment with the A & P. The landing gear itself has virtually no shock absorbing ability. If touchdown is made with a fairly high sink rate, the airplane will bounce along the runway like a car with faulty shock absorbers. Finally, something will break. If the aircraft is overloaded to begin with, the damage will be more extensive.

Some airplanes, by the way, are limited in their weight carrying abilities not by wing strength, but by landing gear strength.

There is an apparent paradox involving flying a given airplane at heavy weights versus light weights. In every case except one, a pilot is far better off with a lightly-loaded airplane. The single exception is during flight in turbulence. A sharp-edged vertical gust has less effect on a heavy airplane than on a light one. In other words, the heavier an airplane is loaded, the less it is affected by a given gust. The margin of safety is increased. But, and this is a big but, this is true only if the pilot leaves the elevator alone. As soon as he starts honking on the yoke, the effects of being in a heavy airplane become adverse.

It is hard to appreciate why a heavy airplane offers more safety in turbulence. The situation is similar to a heavily-laden ship at sea. The ship can weather a storm that would destroy it if it were riding empty. Also, a swept, low-aspect ratio wing withstands gusts better than a straight, high-aspect ratio wing.

There are numerous other limitations that define the safe operating envelope of an aircraft, too many to discuss in a single article. These include center of gravity limitations (with which most pilots are familiar), gear and flap speed limits, rpm red lines, oil and fuel pressure limits, and a host of others. The point is that aircraft and engine limitations are not arbitrary figures tossed into a manual. They are meaningful limits, determined by arduous testing. When observed, they provide wide margins for error, which is one reason why the modern light airplane is such a safe means of transportation. □