Load Limits in Aircraft Design

Session Time: Two, 50-minute sessions

DESIRED RESULTS

ESSENTIAL UNDERSTANDINGS

The principles of aerodynamics allow an aircraft to fly, yet those same principles limit its ultimate performance and capabilities. (EU2)

Safe and efficient aviation operations require that pilots use math, science, and technology. (EU4)

A deep understanding of how an aircraft operates enables a pilot to fly the aircraft to its maximum capabilities in both normal and abnormal situations. (EU5)

ESSENTIAL QUESTIONS

1. How strong should an aircraft be?

LEARNING GOALS

Students Will Know

- What an aircraft load is and how the load is measured.
- Aircraft are only designed to withstand certain load limits.
- Both pilots and aircraft are subject to operational limitations.

Students Will Be Able To

- *Analyze* how G forces and load limits affect aviation operations for both humans and aircraft. (DOK-L3)
- *Explain* how aircraft design and operations take into account load limits to enhance safety. (DOK-L2)
- *Analyze* how a pilot should operate an aircraft so that it remains within its flight envelope with the aid of a Vg diagram. (DOK-L3)

ASSESSMENT EVIDENCE

Warm-up
Students will watch a video of pilots experiencing and training for G-forces and a video of structural testing on an aircraft and answer discussion questions.

Formative Assessment
Students will demonstrate what they have learned about load factors by answering several questions about the effects of G-forces on humans and aircraft and the design of aircraft to maximize safety.

Summative Assessment

Students will use what they learned about the load limits shown in a Vg diagram to describe how a pilot should operate an aircraft to avoid exceeding the load limit.

LESSON PREPARATION

MATERIALS/RESOURCES

- Load Limits in Aircraft Design Presentation
- Load Limits in Aircraft Design Student Notes
- Load Limits in Aircraft Design Student Activity 1
- Load Limits in Aircraft Design Student Activity 2
- Load Limits in Aircraft Design Student Activity 3
- Load Limits in Aircraft Design Teacher Notes 1
- Load Limits in Aircraft Design Teacher Notes 2
- Load Limits in Aircraft Design Teacher Notes 3
- Load Limits in Aircraft Design Teaching Aid

Simulating G-Forces Activity

- Small hanging scale (a scale for measuring fish or luggage is appropriate and affordable). Be sure to choose a scale that records the highest weight achieved between resets.
  AccuDial No Batteries Accurate Easy Reading Analog Compact Handheld Luggage Scale (Amazon $9.99)
  Travel Smart by Conair Compact Luggage Scale (Amazon $9.97)
- Object to serve as an approximately 1 lb. weight (such as a small bag of rice or sand)
- String or S-hook (for hanging the weight from the scale)

Teacher Demonstration: High G-Forces And A Pilot's Blood Supply

- Water balloon, half-filled with water
- String or yarn
- Smartphone or camera with slow motion video capability
- Towel or paper towels (optional)

Recommended Student Reading

- **Pilot's Handbook of Aeronautical Knowledge**
  Chapter Five, Section on Load Factors
  https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/phak/media/07_phak_ch5.pdf

LESSON SUMMARY

Lesson 1 - Turns and Turning Flight
Lesson 2 - Load Limits in Aircraft Design

In the first session, students will learn about the forces acting on an aircraft being diverted from a straight flight path, known as load. Load is measured in Gs, which is demonstrated in the warm up videos. Students will participate in an activity which simulates G-forces. They will also see a demonstration of the effect on Gs on people.

The maximum amount of load that an aircraft can sustain is known as the load limit. Students will consider how load factors influence aircraft design and certification. In a formative assessment, students will demonstrate what they have learned about load factors by answering several questions about the effects of G-forces on humans and aircraft and the design of aircraft to maximize safety.

In the second session, students will learn how to analyze a Vg diagram. Students will be assessed on their ability to analyze the limits of the flight envelope. Finally, students will be assessed on their ability to describe how a pilot should fly and operate within the limits of the flight envelope.

BACKGROUND

Aircraft being forced from a straight flight path are subject to forces known as load. The load force acting on an aircraft and everything inside it, including the pilot, is measured as G-forces or Gs. G-forces can be positive or negative. Every aircraft is designed to withstand certain positive and negative Gs, called load limits, within a range called the flight envelope. An aircraft operated outside its flight envelope can suffer structural damage or failure, and the pilots and occupants can lose consciousness when subjected to excessive loads.

Aircraft must be constructed of materials strong enough to withstand moderate G-forces yet light enough to enable efficient flight. Early aircraft were mostly made of wood and fabric, but today's aircraft are usually built of aluminum and carbon fiber. Similar to a car or boat, an aircraft has limitations for safe speeds for operation, but unlike ground transportation, exceeding the operating envelope in an aircraft can cause structural failure.

Pilots can avoid overstressing their aircraft by employing proper piloting techniques. Avoiding overly steep turns or abrupt control movements, and slowing down in turbulence are methods of ensuring the aircraft is operated within its load limits.

"Maneuvering speed" is an important value to pilots because it represents the maximum speed at which the aircraft is likely to stall before suffering structural damage. The flight envelope for an aircraft is graphed in a Vg diagram of airspeed versus load factors (Gs), and is usually found in the aircraft's Pilot's Operating Handbook. The Vg diagram provides the maneuvering speed (V_A), never-exceed speed (V_{NE}), and various stall speeds. It also shows the load factors and airspeeds that will cause structural damage or catastrophic structural failure.

Although pilots can fly in the caution range (beyond the maximum structural cruise speed), this is only advisable in smooth air. Strong wind gusts and turbulence can unexpectedly cause the aircraft to exceed its load limits, causing damage or structural failure.

MISCONCEPTIONS

Prior student experience of G-forces may be limited to roller coasters. Students may not realize that in an aircraft, improper operations, extreme turbulence, and other factors can create G-forces that exceed the aircraft's design limitations, leading to structural failure of the aircraft.

DIFFERENTIATION

To help students deepen understanding of the concepts and to help move their knowledge from short term to long term memory in the **EXPLORE** and **EXPLAIN** sections of the lesson plan, use the turn-and-talk discussion technique. With this technique, students explain to a partner what they heard and understand.

To model expected behaviors in the **EXPLORE** section of the lesson plan, perform steps 2 and 3 of the Simulating G-Forces activity before students attempt it in their small groups. Talk through the thought process as the steps are performed.

LEARNING PLAN

ENGAGE

Teacher Material: Load Limits in Aircraft Design Presentation

Slides 1-3: Introduce the topic and learning objectives of the lesson.

Slide 4: Conduct the **Warm-Up.**

Warm-Up

To introduce the importance of load limits and the effect of forces on pilots and aircraft structures, students will watch a video of pilots experiencing and training for G-forces and a video of load testing on an aircraft. Students will answer discussion questions about why G-force training is important and why manufacturers test aircraft under forces so extreme, the airplane will likely never encounter them.

- "U.S. Air Force G-Forces" (Length: 3:13)
  http://video.link/w/zBJe
- "Boeing 777 Wing Test" (Length 3:16)
  http://video.link/w/YtXe

[DOK-L2; *Explain*]

Questions

After each video, ask students to discuss the relevant question with a partner for a few minutes, and then call on volunteers to share their answers.

G-force video: Why is G-force training for pilots important

Possible responses include: pilots must learn how to "pull Gs" safely so they can continue to operate an aircraft when flying high G maneuvers, must learn methods to avoid "G-LOC".

Wing test video: Why do you think it is important engineers and manufacturers test the structural integrity of aircraft?

Possible response includes: to ensure that aircraft are designed and built to remain intact during high-load conditions, such as in turbulence or hard landings.

EXPLORE

Teacher Materials: Load Limits in Aircraft Design Presentation, Load Limits in Aircraft Design Teaching Aid, Load Limits in Aircraft Design Teacher Notes 1

Student Materials: Load Limits in Aircraft Design Student Activity 1

Slide 5: In physics, G-force is defined as an accelerating force that causes an accelerating body to be subjected to a force opposite to the acceleration. The higher the acceleration, the greater the G-forces.

An aircraft and its occupants traveling in a straight line at a steady speed experience only the force of gravity. They are said to be at 1 G. In accordance with Newton's First Law (inertia), to change direction, either vertically (a climb or dive) or horizontally (a turn), a force would need to be applied. Both the airplane and its occupants would resist that force (Newton's Third Law - equal and opposite reaction). That resistance is what is known as G-force. It is a measurement not of gravity, but of acceleration.

Slide 6: Use the table to describe a few scenarios and how many Gs a person might typically experience for each. Ensure students understand that 1 G is what a person experiences on Earth. Similarly, an aircraft at level, unaccelerated flight experiences 1 G.

Slide 7: Students were first introduced to Gs in the lesson on aerodynamic stalls in Unit 4. Use a roller coaster to explain the difference between positive and negative G-forces. That little feeling of lightness or heaviness when an elevator starts and stops is G factor. So is that motion (pull and push) upward and downward when riding a roller coaster. When someone feels as if they are getting lifted out of their seat, that's called 'negative' Gs, because they are experiencing less than one gravity (G load). An example of this is when the body feels weightless at the top of a large vertical drop.

When they get to the bottom of the roller coaster and start upward again, they feel as if they are getting pushed down into their seat; that's positive Gs, because they feel as though they weigh more than normal. In other words, they are experiencing more than one G.

A person sitting in an airplane exposed to G-forces feels as if their body weight is multiplied by the amount of G-forces experienced. A person weighing 150 pounds at 1 G (standing on Earth) would experience 450 pounds at 3 Gs.

Slide 8: Divide the class into small groups and distribute a copy of **Load Limits in Aircraft Design Student Activity 1** to each student. In this activity, students will use a small scale and weight to demonstrate G-forces. Students should perform the two tests, record the data in the table provided, and then answer the questions that follow.

Additional directions and possible responses are provided in **Load Limits in Aircraft Design Teacher Notes 1**.

Slide 9: Any force applied to an aircraft to deflect it from straight and level flight produces stress on the aircraft. The amount of this force is the load factor. Load factor is measured in Gs.

Remind students that an aircraft will experience Gs (or additional load) when it changes direction either vertically (climb or descend) or horizontally (turning).

The table on the slide depicts the load factor (measured in Gs) for various angles of bank (AOB). Students have learned that the higher the acceleration, the greater the G-forces. So, as angle of bank increases during level flight, the load factor acting on the airplane also increases; this causes more G-forces to be experienced. High G-forces are common in aerobatics and can cause humans to lose consciousness.

Slide 10: It's not only airplane structures that must be considered when dealing with load factors, but also the human body. Perform a demonstration that shows how G forces can cause a pilot to lose consciousness. Refer to **Load Limits in Aircraft Design Teaching Aid** for instructions on how to complete the demonstration.

During the demonstration, have students relate what is happening to the water in the balloon to what is happening with a pilot's blood during both low- and high-G flight.

Slide 11: Why are humans at risk of losing consciousness when exposed to high G-forces? The force pulls a person's blood into the lower extremities of the body. Reduced blood in the head can decrease vision, producing a "graying out" phenomenon in which objects seem dimmer and grayer and peripheral vision is lost. A continued reduction of blood flow can lead to blackout, or loss of consciousness.

EXPLAIN

Teacher Materials: Load Limits in Aircraft Design Presentation, Load Limits in Aircraft Design Teacher Notes 2
Student Materials: Load Limits in Aircraft Design Student Notes, Load Limits in Aircraft Design Student Activity 2

Slide 12: A load limit is how much weight (or G-force) a structure, like an aircraft, can support. Every aircraft can only support so much weight before it will break apart.

Point out that aircraft designed to withstand only 1 G would not be ideal because we experience 1 G simply standing on earth.

An aircraft's maximum Gs are usually determined when the aircraft is at gross weight, or the maximum weight for which the aircraft is certified. (This information can be found in the Pilot's Operating Handbook for a particular aircraft.)

Slide 13: Designing an aircraft with the greatest possible load limit would not be efficient. Therefore, the goal of aircraft design is to make aircraft light enough to fly (lift overcoming weight) and able to withstand a certain number of Gs.

Aircraft must be made from materials and constructed in such a way that they are strong enough to withstand the G-forces produced in flight yet light enough to enable wings of manageable size to produce enough lift to offset the weight. Few materials can meet that challenge.

In the early days of aviation, most aircraft were built of specially chosen wood, fabric, and bracing wires. Builders found that they could build a sufficiently strong airframe that was still light enough to fly. Materials such as steel or concrete were strong but just too heavy. Aluminum later became the material of choice due to its light weight and high strength. Most aircraft today are predominantly aluminum. Other modern materials are becoming more common such as carbon fiber used in the Boeing 787. The SR-71 spy airplane had part of its structure made of titanium.

Aircraft structures tend to be sparse to save weight. When the Wright Brothers built the first flyable aircraft, the wings were not a solid piece of wood, which would have been too heavy to fly. Rather it was a frame with spars, ribs, and stiffeners covered in fabric. The wing was mostly open space. It's no different for a modern jetliner. The wings of a modern jetliner may use aluminum instead of wood and fabric, but the idea is the same: build an airplane with the minimum structure needed to carry the intended load.

Slide 14: How many Gs must an aircraft be able to endure to be safe? Students have learned that 1 G is not enough, but how much is enough? The answer is determined by how the aircraft will be used (its mission).

In the first unit, students learned the FAA divides aircraft into categories and classes so that it knows which set of certification rules to apply. Aircraft with very different characteristics, such as airplanes and helicopters, must be evaluated using rules and standards appropriate to the category and class of aircraft to which they belong. The FAA has established a set of design load limits within each category that a manufacturer must demonstrate for the aircraft to be certified. Here are a few examples:

Normal category - must be able to withstand between 3.8 positive Gs and 1.52 negative Gs. This is the category in which most general aviation airplanes are certified.

Utility Category - must be able to withstand 4.4 positive Gs to 1.76 negative Gs.

Acrobatic Category - must be able to withstand between 6.0 positive Gs and 3.0 negative Gs.

Slide 15: Manufacturers are committed to producing safe aircraft. This means they must build aircraft that meet or exceed the minimum load factor requirements for a specific category. As a rule, manufacturers overdesign aircraft to provide a safety margin of at least 50 percent. This 1.5 value is called the "factor of safety" and provides, to some extent, for loads higher than those expected under normal and reasonable operation. The test represents 150 percent of the most extreme forces the aircraft will ever encounter.

However, this does NOT mean a pilot can exceed the load limit factor identified in the aircraft's handbook. If a pilot exceeds the limit by up to 50 percent, parts of the aircraft may twist or bend and the damage may be survivable. Have students recall the video in the warm-up of the Boeing 777 wing load test - which broke at 154 percent. Manufacturers have a variety of methods for stress testing aircraft components before beginning production on a new model. Computer simulations may be used but mechanical tests are also conducted. Jigs, weights, and other methods are used to put stress on the airplane or component. Additional stresses are added until the component fails by bending, breaking, or separating from the airframe. Engineers use the information they gather to make design changes aimed at improving safety.

Slide 16: Complete the **Formative Assessment**. This formative assessment will complete the first session.

Formative Assessment

Students will demonstrate what they have learned about load factors by answering several questions about the effects of G-forces on humans and aircraft and the design of aircraft to maximize safety. Provide a copy of **Load Limits in Aircraft Design Student Activity 2** to each student and give them about 10 minutes to complete the questions. This may also be provided as homework.

Correct answers are provided in Load Limits in **Aircraft Design Teacher Notes 2**.

[DOK-L2; *explain*; DOK-L3; *analyze*]

EXTEND

Teacher Material: Load Limits in Aircraft Design Presentation
Student Material: Load Limits in Aircraft Design Student Notes

Slide 17: A Vg diagram is a chart showing airspeed (velocity) vs. Gs or load factor. Each aircraft has its own Vg diagram, which is valid for a specific weight and altitude. The red lines on the graph show the limits beyond which structural damage or failure is possible. An aircraft in flight cannot exceed the limits for speed, load factor, and maximum lift capability without risking damage. In order to avoid structural damage or failure, the aircraft must operate at combinations of speed and load factor within this "envelope," which is why a Vg diagram is also known as the envelope.

Distribute a copy of **Load Limits in Aircraft Design Student Notes** to each student so they can analyze the graph more closely. Explain the basics of what is shown:

- The vertical y-axis is load factor (measured in Gs) and the horizontal x-axis is airspeed (measured in miles per hour).
- Ask students to examine the top part of the graph for positive Gs.
- The graph identifies the normal stall speed at 1 G in sustained level flight. If the pilot exceeds 1 G at this stall speed, the aircraft is operating beyond the limit and will stall. (Any speeds in the blue areas of the graph are impossible because the aircraft will stall first.)
- The aircraft can be safely operated in smooth air within the green and yellow ranges until it reaches the never-exceed speed, or V_{NE}. Operating beyond this speed will result in structural failure due to excessive speed. This is shown as a red line on the airspeed indicator.

Slide 18: Maneuvering speed is the speed at which a pilot can fully deflect one control surface (elevator, ailerons, or rudder) in smooth air without risking structural damage to the aircraft.

It is determined by the aircraft manufacturer as part of the design and testing process. Pilots use maneuvering speed to perform normal maneuvers without overstressing the aircraft. When encountering moderate or greater turbulence, pilots will slow to maneuvering speed. In severe turbulence, they may slow to well below maneuvering speed.

Slide 19: Direct students to analyze the point on the Vg diagram labeled "maneuvering speed." Remind students that this speed, also expressed as V_A, is the speed that pilots use to perform a normal maneuver without overstressing the aircraft. For this particular aircraft, the V_A shown is about 135 mph, and any loads must be less than about 4.4 Gs. Excessive speed and Gs risks structural damage. In other words, the maneuvering speed is how fast the aircraft can go to pull Gs equal to the load limit factor.

Slide 20: Maneuvering speed varies with the weight of the aircraft. The published maneuvering speed found in the Pilot's Operating Handbook is maneuvering speed at maximum gross weight for the aircraft. At lower weights, the maneuvering speed is lower. Watch the video to see how maneuvering speed changes as aircraft weight changes.

- "How Maneuvering Speed (V_A) Changes With Weight" (Length: 2:33)
  http://video.link/w/m7Be

Slide 21: Turbulence can range from light to extreme. According to the FAA's Aeronautical Information Manual, light turbulence momentarily causes slight or erratic changes in altitude or attitude. Moderate turbulence is similar to light turbulence but of greater intensity. Severe turbulence causes large, abrupt changes in attitude or altitude and the aircraft may be momentarily out of control. Extreme turbulence violently tosses the aircraft about, making it virtually impossible to control.

Pilots slow to maneuvering speed or slower to help reduce the stresses on the airframe during moderate or greater turbulence. However, in severe or extreme turbulence, such as that associated with thunderstorms, slowing down may not be sufficient to protect the aircraft from structural damage or failure.

In turbulence, pilots should slow to an appropriate speed. And, pilots should always stay well clear of thunderstorms and other violent weather.

Slide 22: Direct students to examine the yellow portion of the Vg diagram labeled "caution range" between the maximum structural cruise speed (V_{NO}) and never-exceed speed (V_{NE}). Show these corresponding speeds on the image of an airspeed indicator.

While it is permissible to fly in the caution range, it's possible to inadvertently exceed the load limit factors at these speeds, so a pilot should never exceed the V_{NO} except in smooth air. Under no circumstances should a pilot exceed V_{NE} (the red line). Unlike V_A, V_{NE} does not vary with aircraft weight.

Beyond this maximum structural cruise speed, the aircraft is not designed to withstand turbulence or strong vertical gusts at 30 fps (feet per second) or more without exceeding the load limit factor and damaging the structure.

For safety, a good rule is fly at speeds less than V_{NO} in light turbulence and speeds less than V_A in moderate or greater turbulence.

So-called V speeds will be covered in greater depth in a future lesson.

Slide 23: Direct students to analyze the red line labeled "accelerated stall" on the Vg diagram and blue portions of the diagram. The curved red lines show maximum lift capability. Explain that this aircraft is capable of developing no more than positive 1 G at 64 mph, 2 Gs at 92 mph, 3 Gs at 112 mph, and 4.4 Gs at 137 mph. Any load factor outside these lines is not aerodynamically possible because the aircraft will stall first.

It is similar for negative Gs, except that structural damage will occur at slower airspeeds and smaller negative load factors.

Slide 24: Point out that structural damage is shown in orange and structural failure is shown in red on the Vg diagram. This is because they are slightly different. Structural damage describes when a component is bent or warped, but can be repaired. When structural damage occurs, a pilot may be able to recover, but the repairs are costly. Structural failure is a catastrophic event, meaning the pilot will be very unlikely to recover. A wing or stabilizer separating from the airframe constitutes structural failure.

Slide 25: The way a pilot operates an aircraft can affect its structural integrity. In an earlier lesson on weight and balance, students learned about the importance of operating an aircraft within its weight and balance limitations. Overloading or improperly loading an aircraft can put excessive stress on the airframe and flight controls. Pilots should never operate an aircraft outside of its acceptable weight and balance range. In addition, pilots should only perform maneuvers for which the aircraft is rated, always operate within the airspeed limitations, slow to lower speeds in turbulence, and use smooth control inputs especially when fully deflecting control surfaces.

EVALUATE

Teacher Materials: Load Limits in Aircraft Design Presentation, Load Limits in Aircraft Design Teacher Notes 3
Student Material: Load Limits in Aircraft Design Student Activity 3

Slides 26-29: Quiz the students on questions related to load factor for the Private Pilot Knowledge Test.

Slide 30: Conduct the **Summative Assessment.**

Summative Assessment

In this activity, students will use what they learned about the load limits shown in a Vg diagram to describe how a pilot should operate an aircraft to avoid exceeding the load limit. For each question, students should should reference V_S, V_A, V_{NO}, or V_{NE}, and give the appropriate speed in mph.

[DOK-L4; *evaluate]*

Summative Assessment Scoring Rubric

- Follows assignment instructions
- Responses show evidence of the following:
  Understanding of how to interpret a Vg diagram.
  Understanding of important airspeeds and limits.
  Understanding of the rationale for the maneuvering speed.
- Contributions show in-depth thinking including analysis

Points	Performance Levels
9-10	Accurately and clearly describes what a pilot should do in each scenario
7-8	Correctly describes what a pilot should do in each scenario with minor gaps in understanding
5-6	Partially describes what a pilot should do in each scenario with major gaps in understanding
0-4	Shows little or no evidence of understanding of what a pilot should do

GOING FURTHER

Use the following video to help students understand maneuvering speed.

- "How Is Maneuvering Speed Determined?" (Length: 7:23)
  http://video.link/w/Oxaf

STANDARDS ALIGNMENT

NGSS STANDARDS

Three-dimensional Learning

HS-PS2-2 - Use mathematical representations to support the claim that the total momentum of a system of objects is conserved when there is no net force on the system.

- Science and Engineering Practices
  Using Mathematics and Computational Thinking
  Planning and Carrying out Investigations
  Analyzing and Interpreting Data
  Obtaining, Evaluating, and Communicating Information
- Disciplinary Core Ideas
  PS2.A Forces and Motion
  PS2.B Types of Interactions
- Crosscutting Concepts
  Cause and Effect

COMMON CORE STATE STANDARDS

- **RST.9-10.1** - Cite specific textual evidence to support analysis of science and technical texts, attending to the precise details of explanations and descriptions.
- **RST.9-10.3** - Follow precisely a complex multistep procedure when carrying out experiments, taking measurements, or performing technical tasks, attending to special cases or exceptions defined in the text.
- **RST.9-10.4** - Determine the meaning of symbols, key terms, and other domain-specific words and phrases as they are used in a specific scientific or technical context relevant to grades 9-10 texts and topics.
- **WHST.9-10.9** - Draw evidence from informational texts to support analysis, reflection, and research.

REFERENCES

https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/phak/media/07_phak_ch5.pdf
https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/phak/media/21_phak_glossary.pdf
http://www.boldmethod.com/learn-to-fly/aerodynamics/va-designed-maneuvering-speed-what-does-it-protect/
https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_90-23G.pdf