Unified Treatment for Impact - Probabilistic & Deterministic

John C. Halpin, JCH Consultants, Dayton, OH
Keith T. Kedward, Dept. Mech. Eng., U. of California at Santa Barbara, CA
Paolo Feraboli, Dept. Aero. & Astro., U. Of Washington, Seattle, WA
Hyonny Kim, School Aero. & Astro., Purdue University, West Lafayette, IN

Introduction

- **Birdstrike:**
  - **Safety of Flight threat**
    - **Certification to proven level of impact resistance**
    - **FAR 25, 27 & 29, tolerance to complete flight,--**
- **Hail stone strike threat**
  - **Durability threat (local damage requiring deferred repair)**
- **Impact threats usually determines minimum gage dimensions for:**
  - **Transparencies**
  - **Cockpits**
  - **Leading edges of empennages & wings**
  - **Radomes**
  - **Engine nacelles**
- **Impact threat environments need better definition**

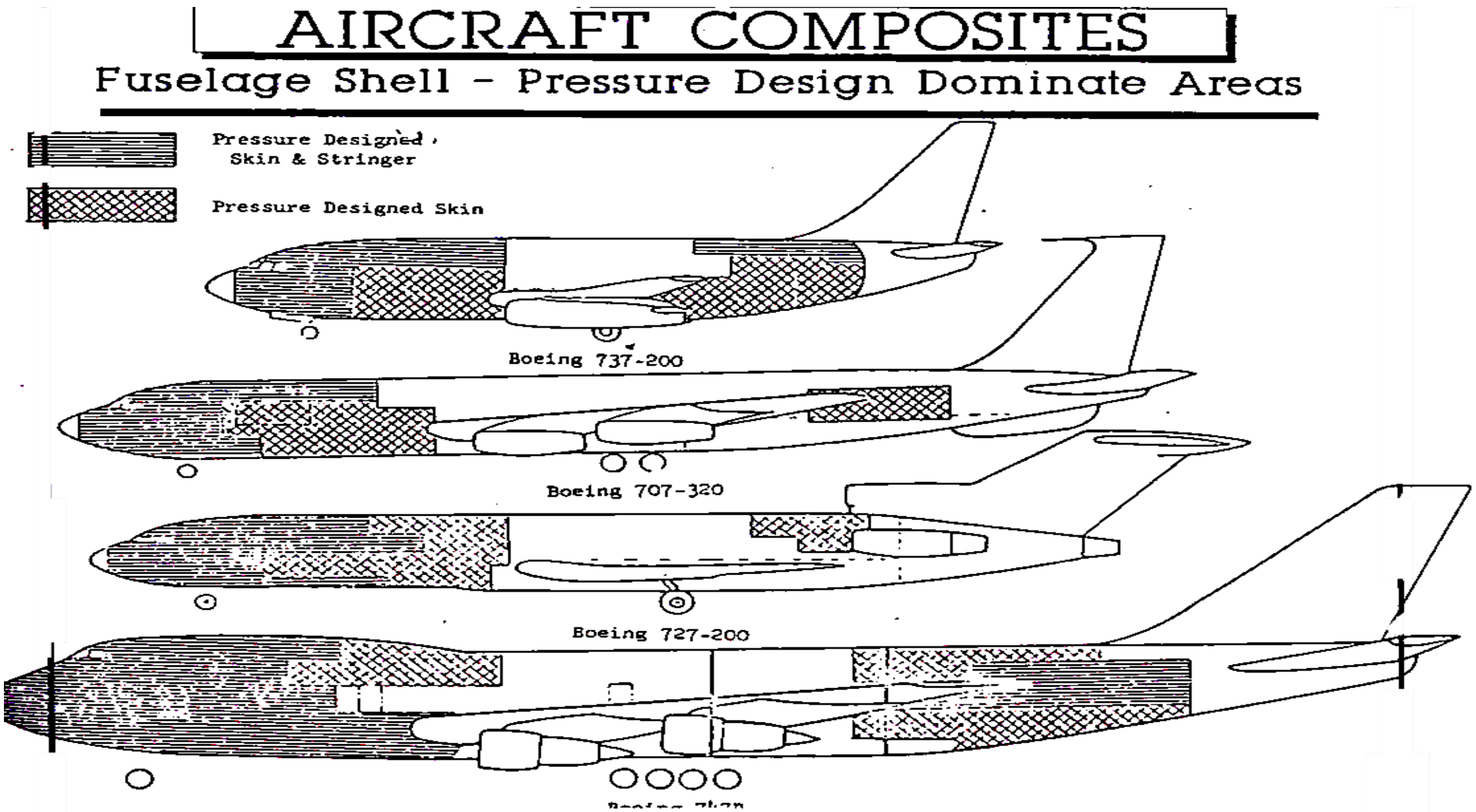
Focus: Impact Events Occurring During Airborne Operations, Characterizing the In-flight Risk Environment for Birdstrike and Hail & Ground Hail Strike on Parked Aircraft.

- **Two criteria topics;**
  - **Probability of an impact initiating a small local delamination or disbond that may or may not grow with usage (occurrence per average a/c usage for one design life); the Durability Energy Threshold.**
    - **The Durability Limit may correlate with the quasi-static delamination initiation.**
  - **The second is an impact that induces significant damage per the FAR-25 based on the design life for the expected production run (total expected fleet size), the Damage Tolerance Energy Impact threshold.**
    - **The penetration condition may correlate with quasi-static punch shear thresholds.**
  - **Example; one design life could be 100,000 hours and the total fleet usage for say 1000 a/c could be 7×10^7 hours.**
- **Illustrate procedures to estimate damage threshold criteria as a function of laminate design characteristics.**

Fuselage Structure Vulnerable to In-flight Impact Threats Sized by GAG Pressurization Cycles, Not by Compression After Impact.

(John E. McCarty, 1989 Lecture Notes - Davos, Switzerland)

AC-107A Damage Tolerance

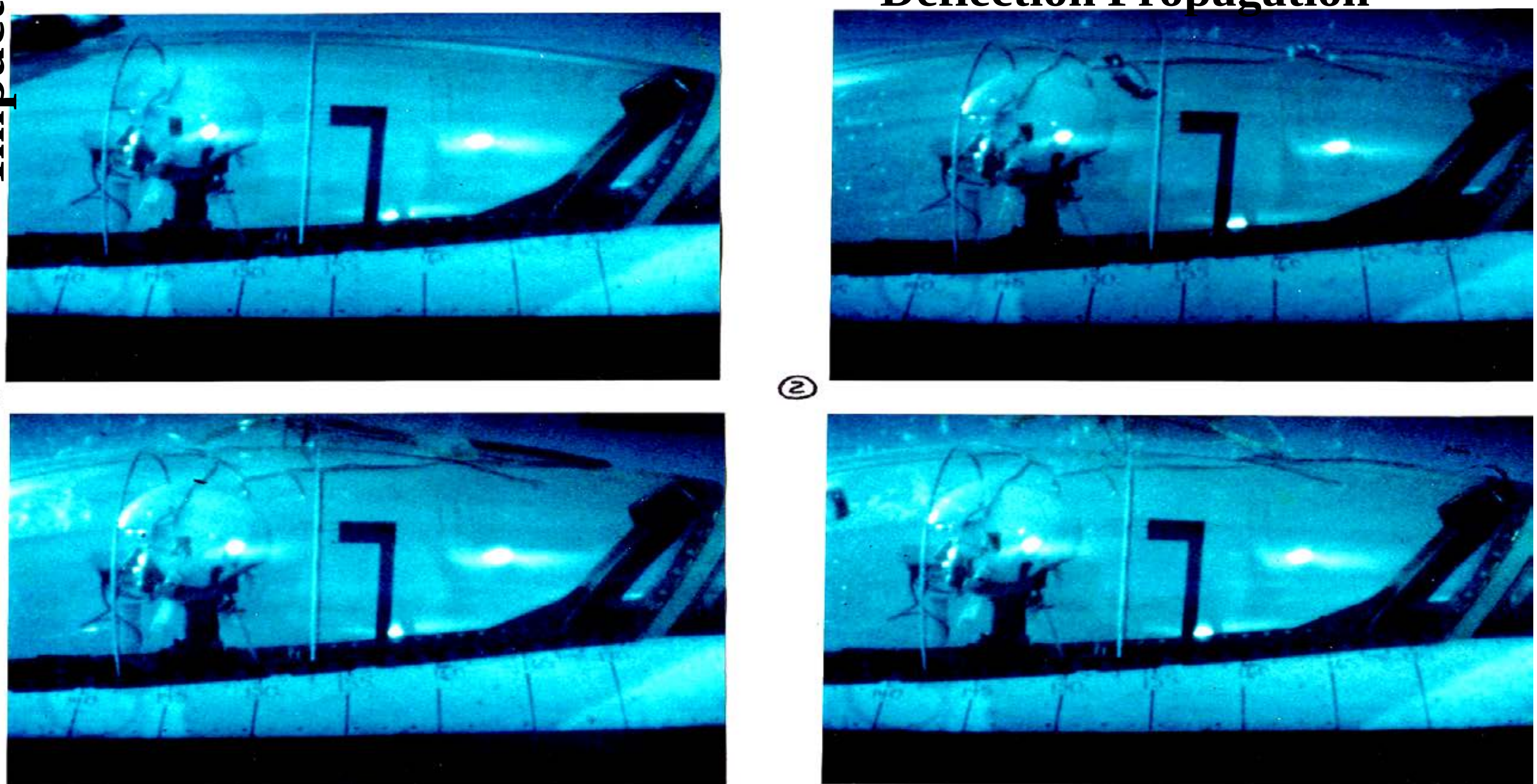


Deflection Wave - Crown Break

(Thickness 3/4inch; V=346kts; & W=4.1lbs)

Impact

Deflection Propagation



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Similarities: Incident from Canadian Aviation; “Sharing the Skies” & Helicopter Test & Simulation in Italy

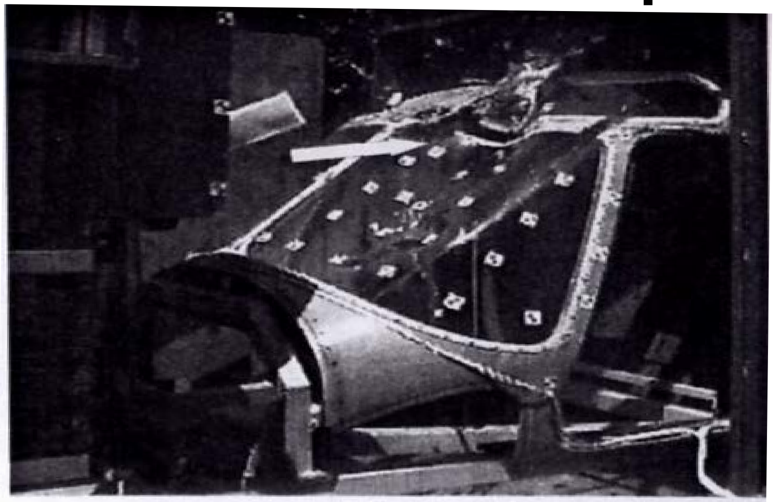


Figure 3: Shot on the helicopter cockpit

i - failure of the joints between the crossbeam and the transparencies
ii - fracture at the root of the crossbeam
iii - fracture at the middle of the deflected crossbeam

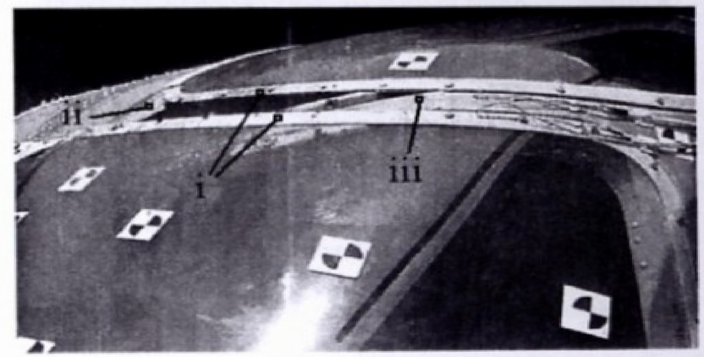


Figure 4: Damages induced on the helicopter cockpi

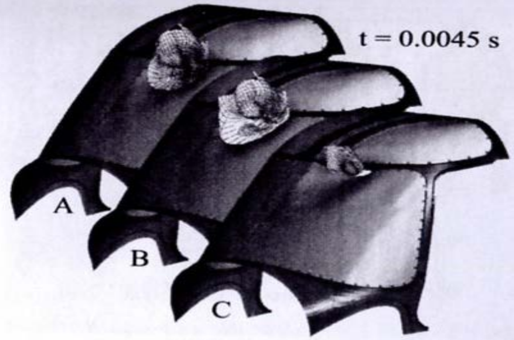


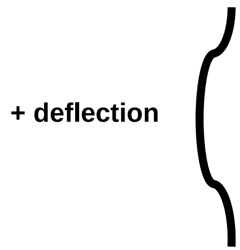
Figure 21: Numerical damages in the analyses of the shot on obtained with three different bird models

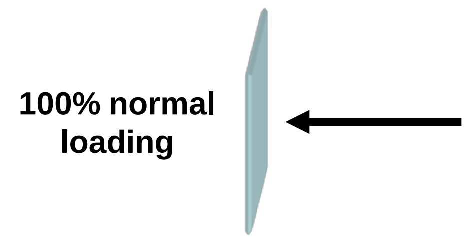
Behavior of the bird In “C” recognized the shear strength of the bird and the resulting concentration of the loads on a small contact area.

Plate 11 The windshield on this B737 was severely damaged as a result of a collision with a bird a 10,000 ft. ASL and 250 kts. The captain was injured from debris when the bird penetrated the fuselage above the windshield.

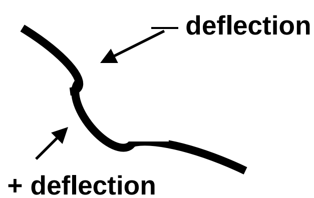
Vehicle Geometric Features Strongly Influence Structural Response to Impact: Oblique Angles Produce Quasi Static Deflection Waves. Deflection Wave Dependent on Impactor Characteristics (IE. Shear Strength of Bird Versus Fragmentation of Ice)

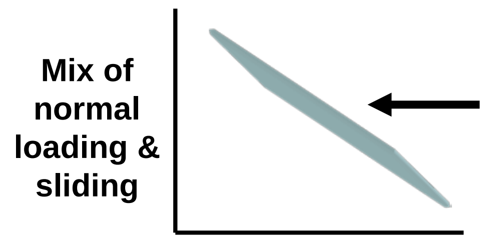
Deflection, Rebound or Penetration (Energy Loss)



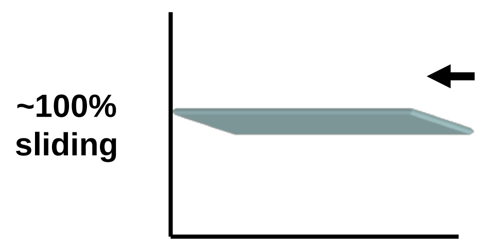


Less Deflection but Bow Wave Moving in Direction of Impact, May Interact With Structural Discontinuity, Rebound or Penetration (Energy Loss).



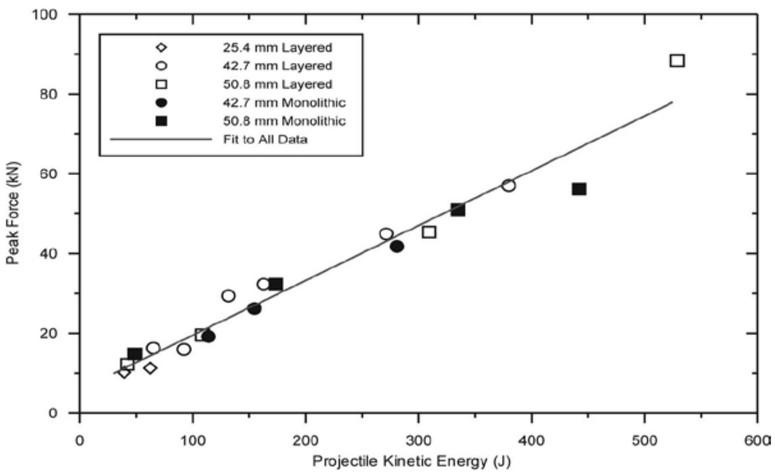


Shearing Motion



Characterizing & Qualifying a Model for Impactor Response is Necessary for Accurate FEM Simulation: Hail Ice Example.

(Ice fragments on impact, birds have hydrodynamic behavior modified for shear strength of bird material)



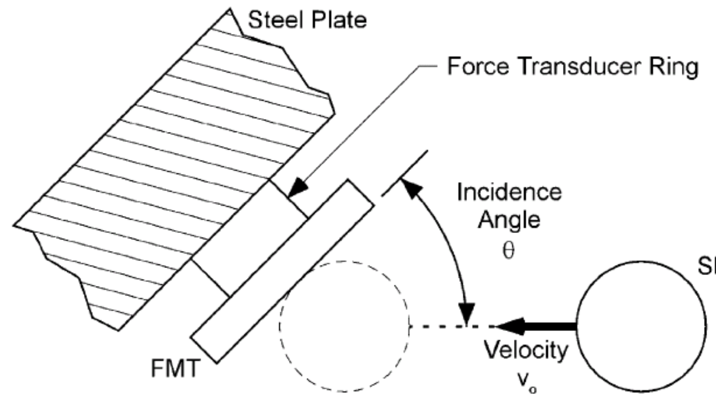


Fig. 11. Incidence angle definition for SHI impacting FMT.

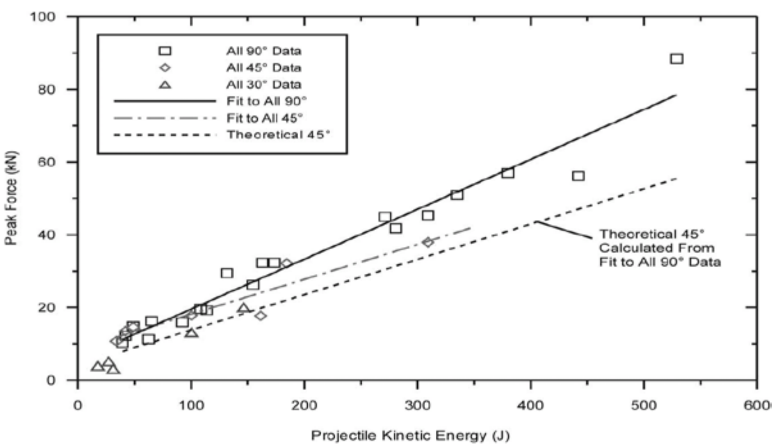


Fig. 12. Peak force for impacts onto FMT at 90, 45 and 30° incidence angles.

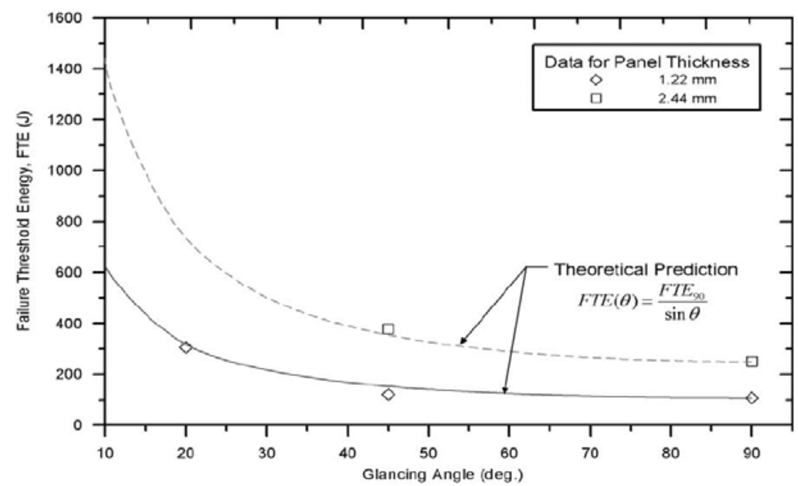


Fig. 23. Effect of glancing angle on FTE.

An Easyjet Boeing B737 (August, 2003) From Geneva and Ran Into Severe Hail,(Pilot Described As "Clear Air Hail") Resulting in Severe Damage to the Aircraft Upon Which the Aircraft Returned to Geneva. No Operational Control/dispatch System Tasked With Reviewing the Weather Conditions and Providing This Information to the Crew.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

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Characterizing Birdstrike (Hail strike) Events:

(Number of impacts within a volume element)

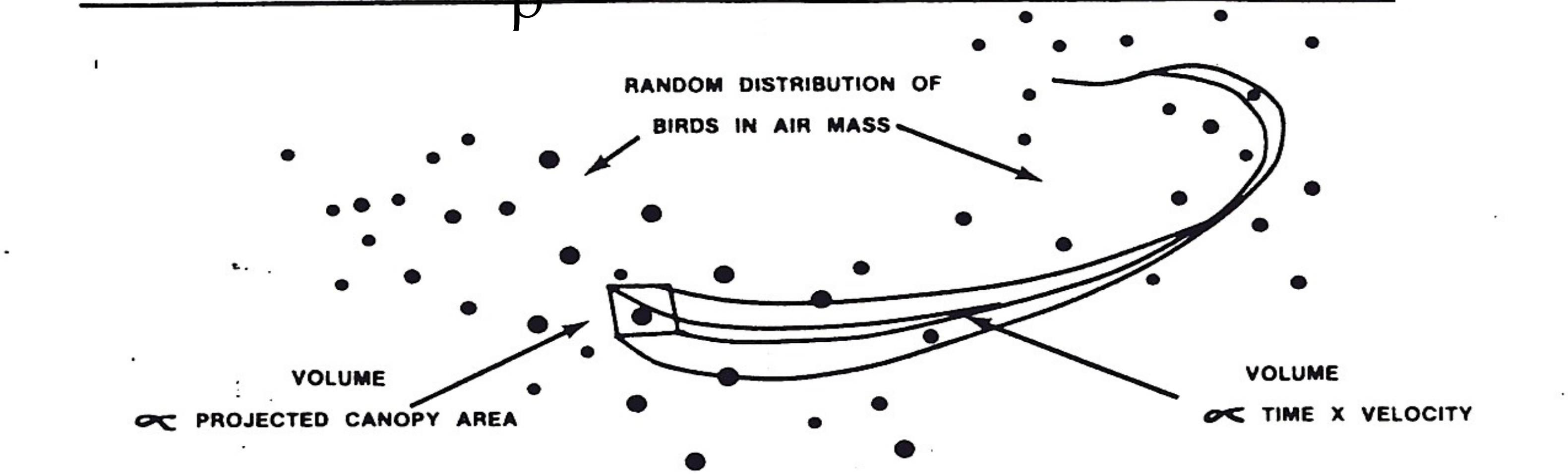
NUMBER OF BIRDS IMPACTING ENCLOSURE EQUALS THE PRODUCT OF

= PROJECTED AREA (PA) X

VELOCITY (V) X

TIME (T) X

ρ DENSITY OF BIRDS IN FLIGHT ENVELOPE



Operational Impact Rate (OIR) Characterizes The Operating Environment

OPERATIONAL IMPACT RATE (OIR) EQUALS

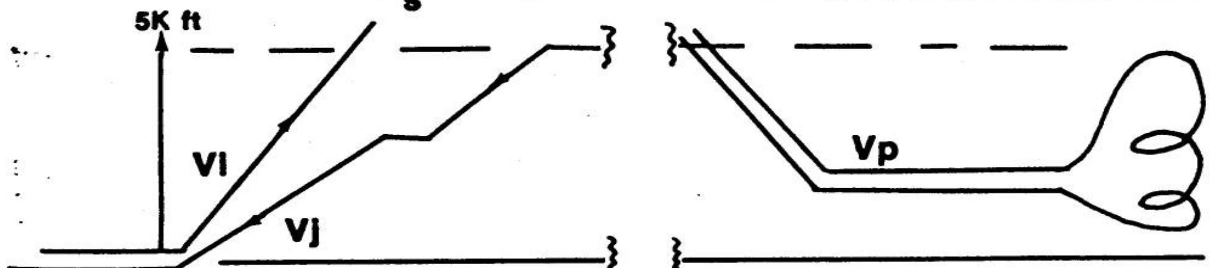
$$\frac{\text{NUMBER OF BIRDS IMPACTING ENCLOSURE}}{\text{TOTAL OPERATIONAL HOURS}} =$$

WHERE

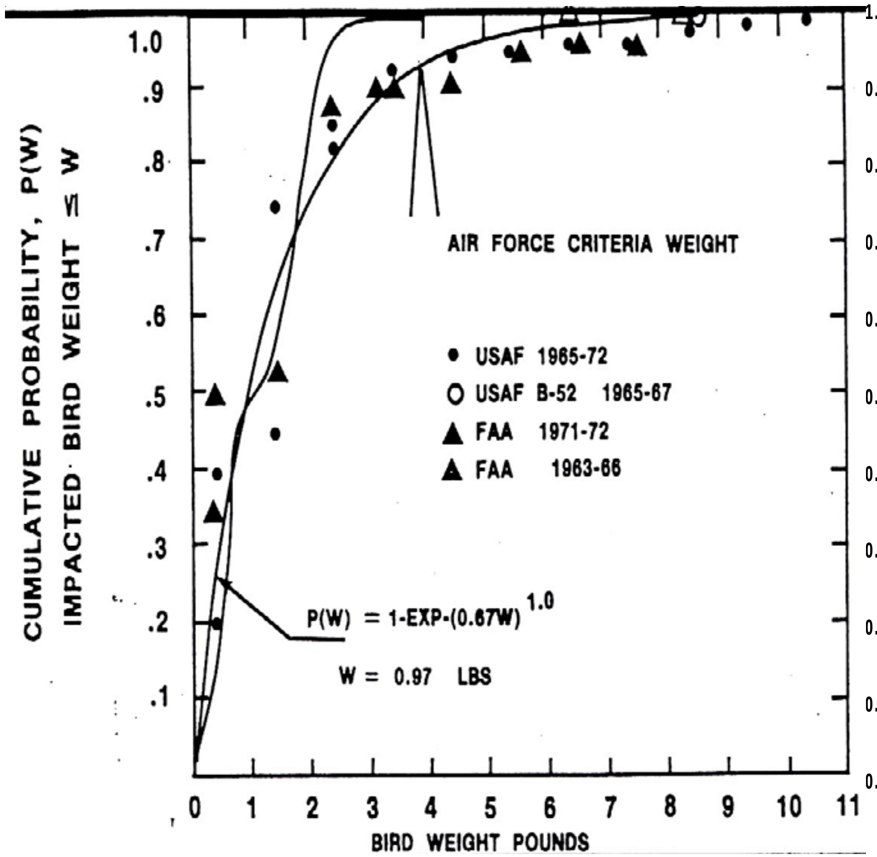
$$PA \times V \times \frac{\text{TIME IN BIRD ENVIRONMENT}}{\text{TOTAL FLIGHT HOURS}} \times \rho \text{ BIRDS}$$

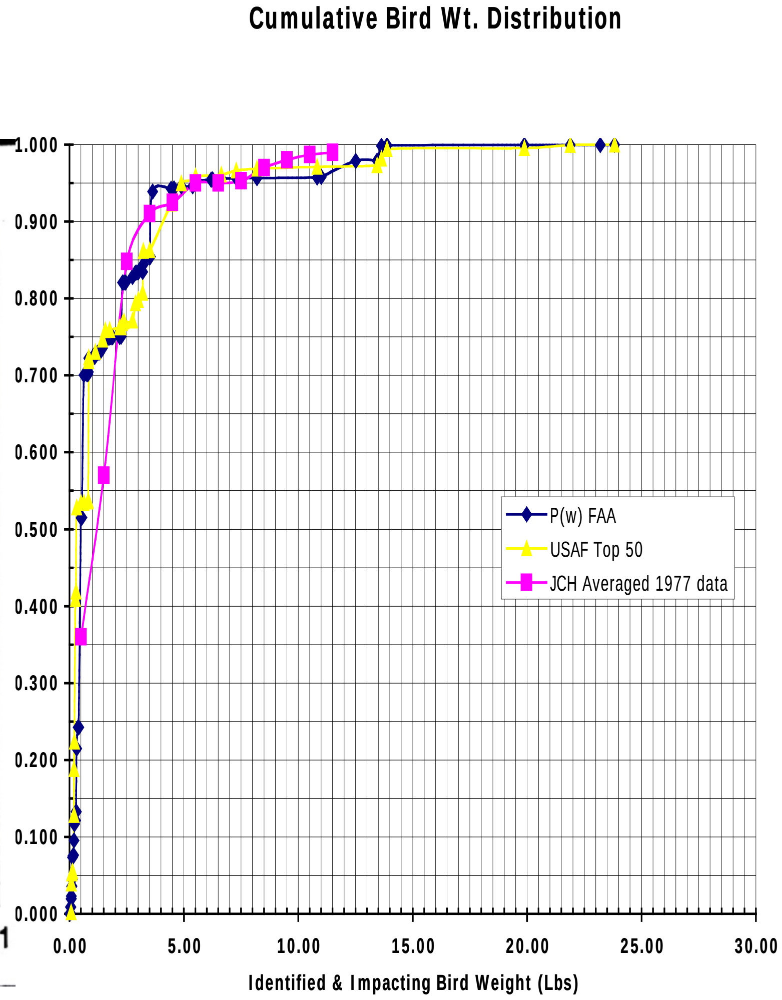
VEHICLE CHARACTERISTICS (PA × V) — USAGE (V × TIME IN BIRD ENVIRONMENT / TOTAL FLIGHT HOURS) — ENVIRONMENT (ρ BIRDS)

$$t_s = t \text{ (LOW ALTITUDE)/TOTAL FLIGHT HOURS}$$



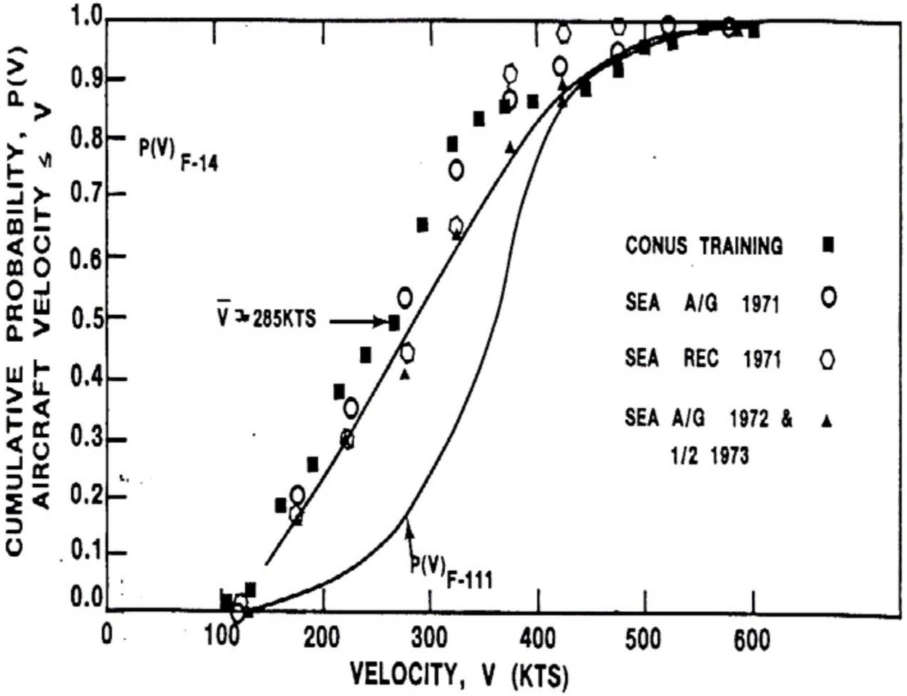
Comparison of Reported Impacting Bird weight Data: Current FAA data 1990 - 2005



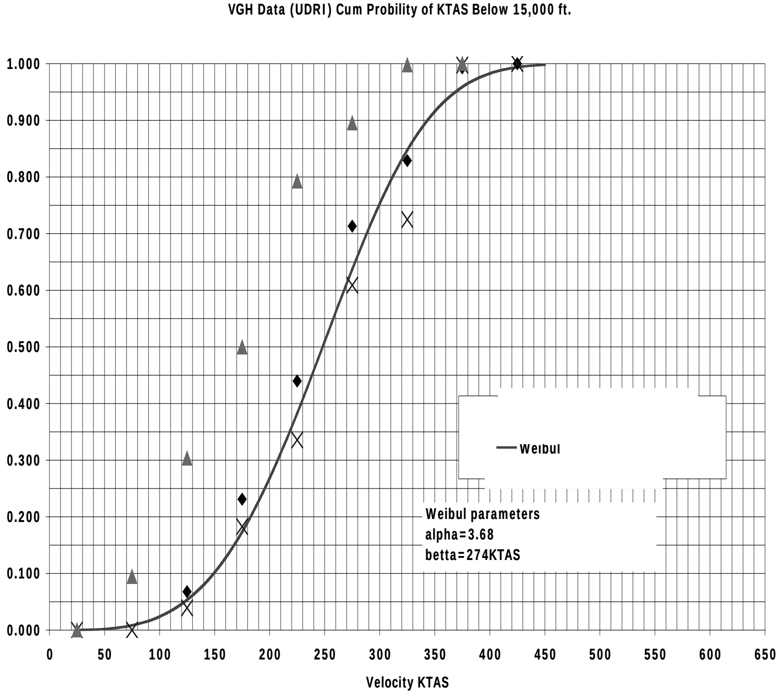


Historical (VGH) Low Altitude Usage

Fighter A/C Usage



Civil A/C Usage



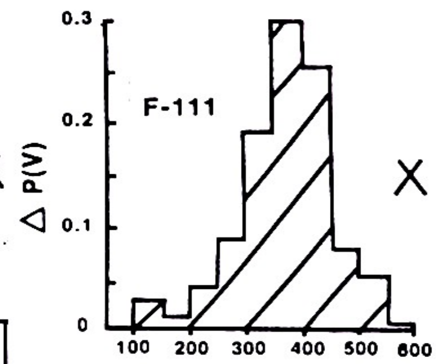
Fraction of Time in Threat Environment: 25 to 45%+ Mil; CIVIL 7 to 45%

Application of Methodology for an Earlier Risk Assessment: F-111Failure Threshold Energy Level

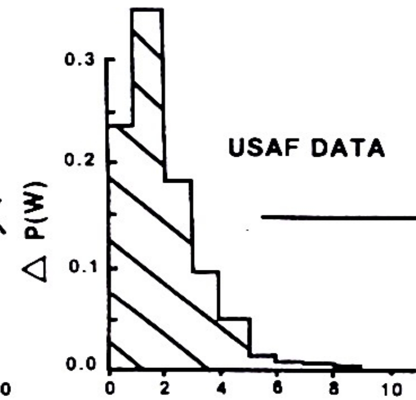
TOTAL NUMBER BIRDS IMPACTING CANOPY

[OIR x FORCE USAGE
I.E. F-111(TAC)
100 x 0.389=38.9]

X



X



FAILURE CRITERIA
I.E. KE=7.1 FT LBS (F-111)
200 KTS - 4 LB BIRD

IMPACTING KINETIC ENERGIES FT-LBS x 10 -3

A/C VELOCITY (KTS)	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5
110 - 160	0.4	1.2	2.0	2.8	3.7	4.5	5.3	6.1
160 - 210	0.8	2.3	3.8	5.3	6.9	8.4	9.9	11
210 - 260	1.2	3.7	6.2	8.6	11	14	16	18
260 - 310	1.8	5.4	9.0	13	16	20	24	27
310 - 360	2.5	7.5	13	18	23	28	33	38
360 - 410	3.3	9.9	17	23	30	36	43	50
410 - 460	4.2	13	21	30	38	46	55	63
460 - 510	5.2	16	26	37	47	58	68	79
510 - 560	6.4	19	32	45	57	70	83	96

BIRD WEIGHTS

A/C VELOCITY (KTS)	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5
110 - 160	0.3	0.4	0.2	0.1	0.1	0.0	0.0	0.0
160 - 210	0.1	0.2	0.1	0.0	0.0			
210 - 260	0.4	0.5	0.3					
260 - 310	1.0	1.2						
310 - 360	2.2							
360 - 410	3.3							
410 - 460	2.7							
460 - 510	0.9							
510 - 560	0.1							

14 NO DAMAGE
25 DAMAGING

EXPECTED NUMBER (WEIGHT/VELOCITY) BIRD STRIKES

← CANOPY CAPABILITY

Kinetic Energy Matrix **Impact Matrix**

Comparison: F-111
Historical Data versus Projections

• THE F-111 HISTORY (1969-1976)	
• F-111 A/D/E/F FT. HRS	388,628
• NORTON SAFETY CENTER REPORTS	
	39 CANOPY STRIKES
	23 MAJOR PENETRATION/ LOST (6 LOST)
	5 MINOR DAMAGE (< $100)
	11 NO DAMAGE
• BASED ON ACTUAL DATA	38. 9 CANOPY STRIKES
• THE ANALYTICAL METHODOLOGY PROJECTS	
	25 PENETRATION /LOST
	14 NO DAMAGE

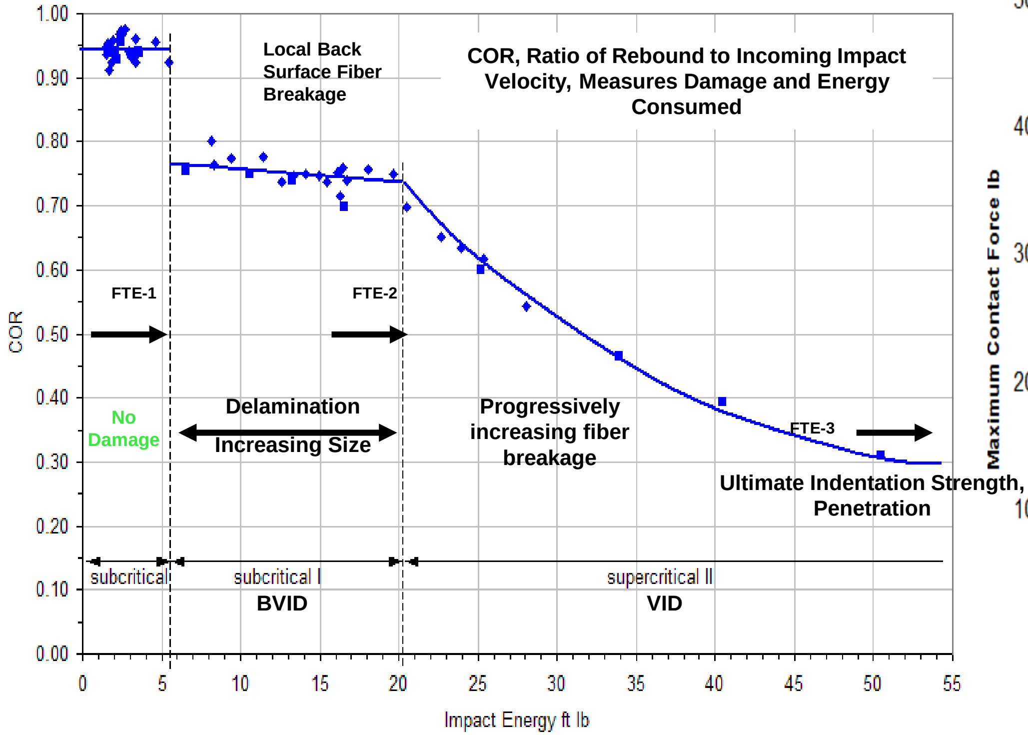
Risk Assessment Procedure

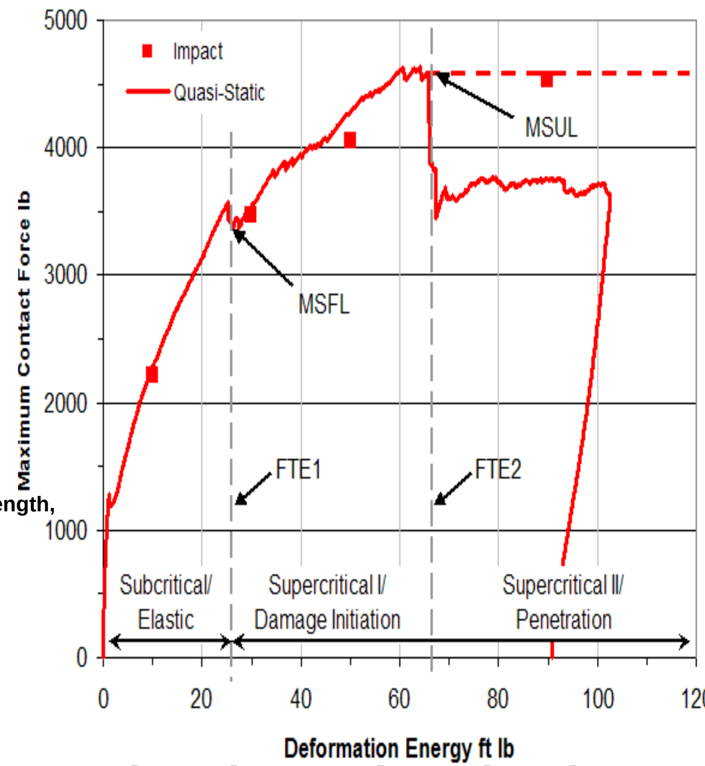
1. Estimate total number of impacts in operational life
2. Estimate distribution of impacting weights and velocities
   - Defines matrix of potential impact kinetic energy levels
3. Define failure criteria in terms of impacting kinetic energy levels
   - Failure modes, IE FTE-1, & FTE-2
   - Impact locations
4. Identify number of impacts exceeding critical energy thresholds
5. Project operational consequences for:
   - Average aircraft in fleet
   - Risk for total fleet
6. Project optimum design criteria for weight and risk

•Steps 1 & 2 for birdstrike & hail ice requires probability of mass or size and operational usage in threat environment;

•Steps 3+ completes procedure.

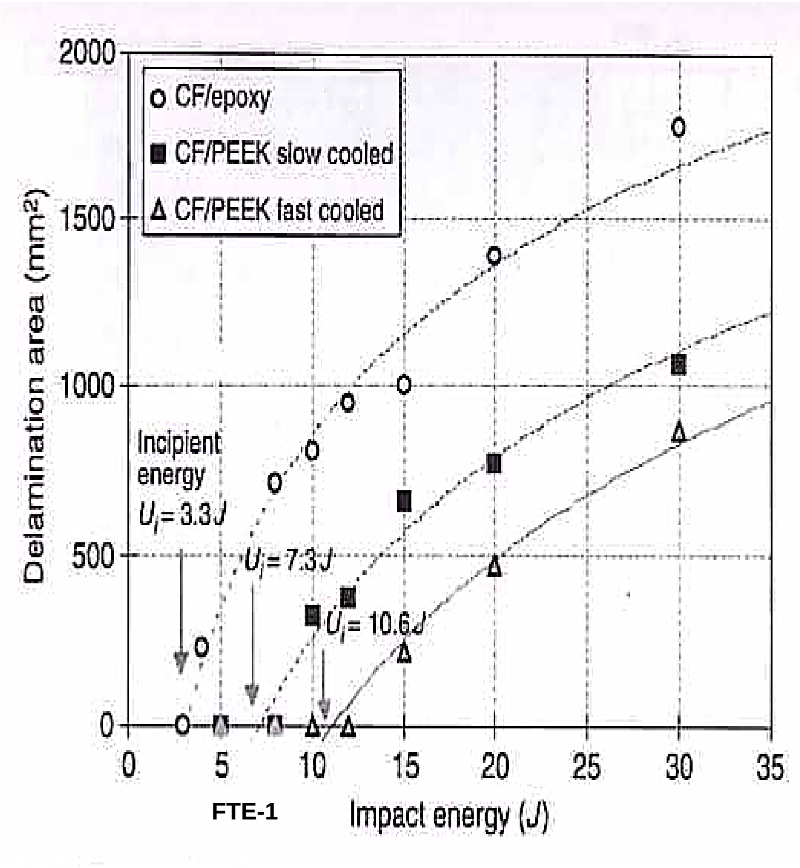
Examples of Progressive Deterioration, & Failure Threshold Energies, FTE, for a Graphite Epoxy Panel. (FTE, Incoming Kinetic Energy Initiating a Damage Level.)



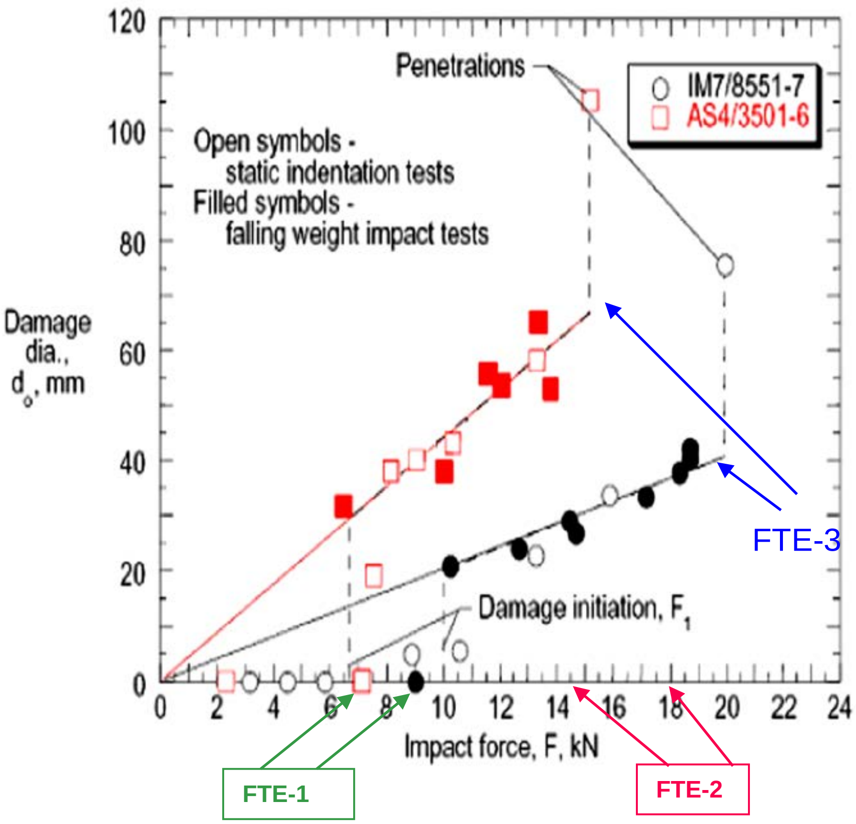


Quasi-static COR & Indentation to Determine the Entire Kinetic Energy Range (FTE-1, FTE-2, FTE-3)

Example: Variation of Threshold Energy, FTE-1 & FTE-2 With Thickness & Toughness



Courtesy of Peter Miller, U of W Seattle



Geometry of Structure Has Strong Influence on Number of Impacts on Specific Features, % Projected Area, Energy (or Force) Transferred During Impact Event, & Glancing Angle.

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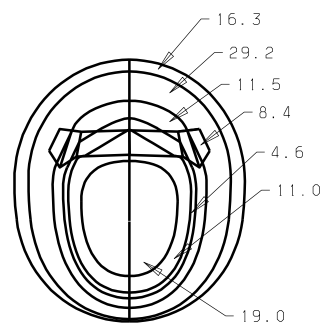
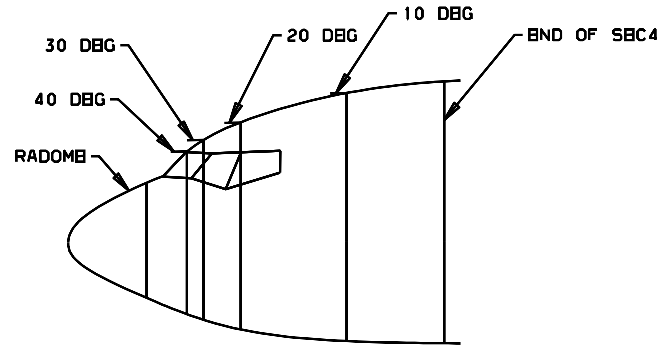
are needed to see this picture.



% Of Projected Frontal Area

UP
OUTBD
NOSE VIEW



Impacts Occur on Oblique Surfaces, of Various Angles

UP
AFT
SIDE VIEW

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are needed to see this picture.

For birdstrike "glancing" changes to a shearing action.

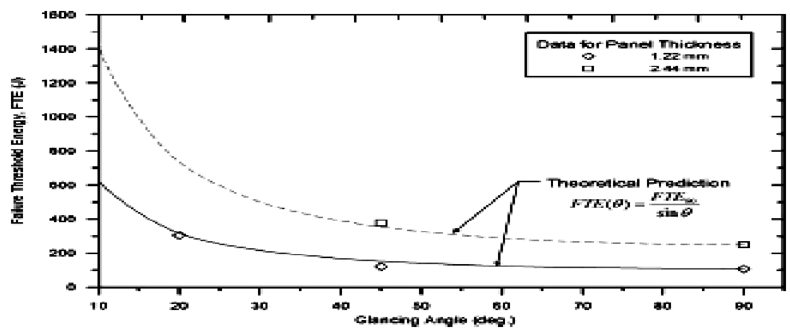
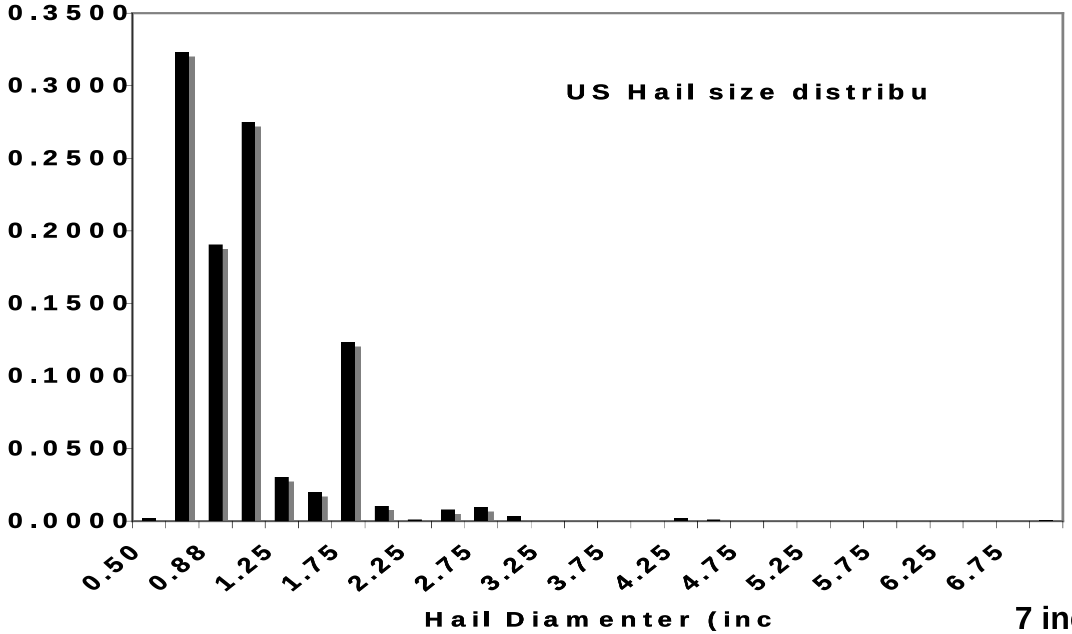


Fig. 23. Effect of glancing angle on FTE.

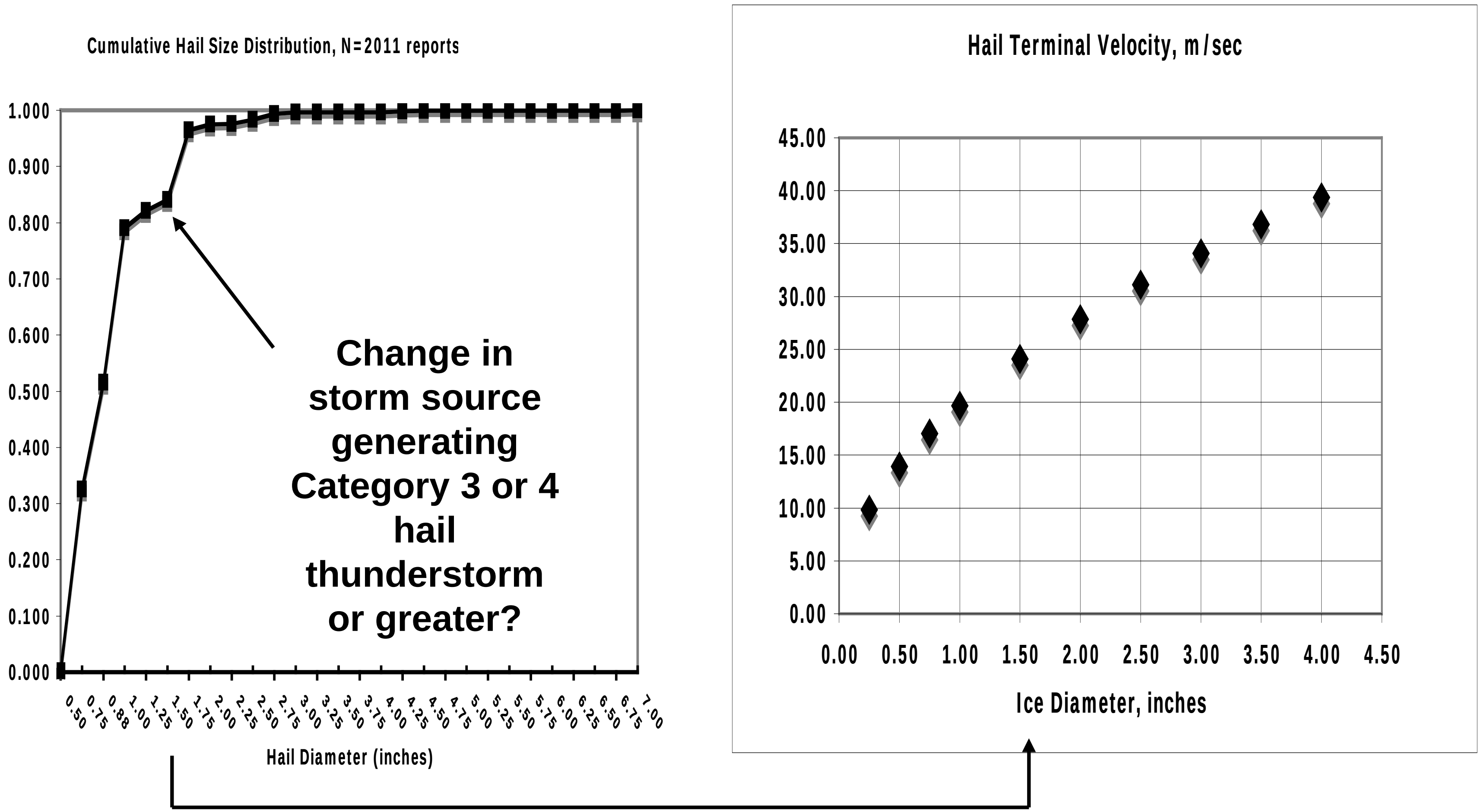
Preliminary US Nail Size Data (2011 reports): Maybe Two or Three Distributions, Changing at Hail Size ~ 1.25 to 1.5 Inches



Tornado systems typically produce extreme size hail; i.e. 7 inches.

7 inch. 1 in 30 years, 06/03 Nebraska, Incremental P(n) = 0.0005

Aerodynamics of Hail, Size & Shape Influences Terminal Velocities, V_T
Hail size from NOAA data base, all US states.



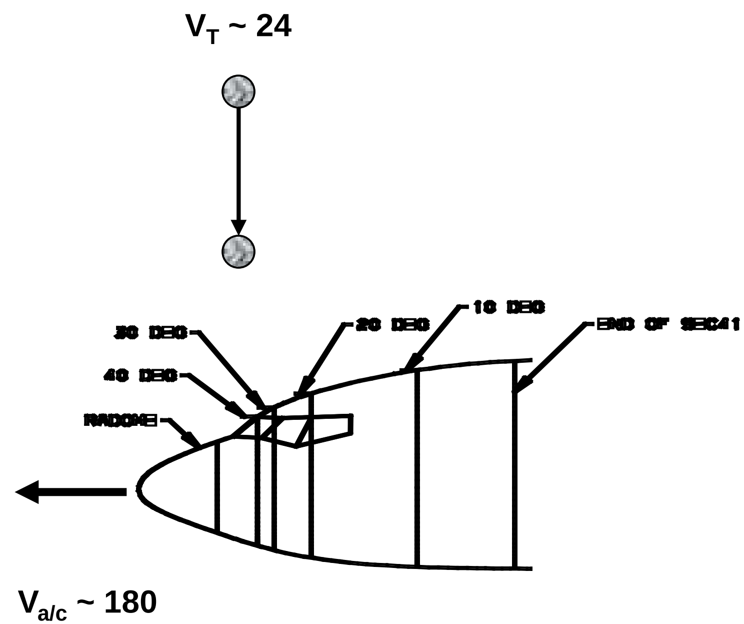
Determination of Velocity Vector Components for Hail Impact & Resulting Energy Components

Example calculation:

- Hail (1.5 inch dm.), V_T ~ 24 m/sec (47kts)
- A/C horizontal velocity ~ 180 m/sec (350KtAS)
- total relative velocity ~ 182 m/sec (354kts) at - 7.6 deg. from horizontal

1. **Resolved impact velocity vector(s)**
   - perpendicular to window, 40 deg. to horizontal ~ 134 m/s (260 kts)
   - Shearing (sliding) component parallel to surface ~ 122 m/s (237 kts)
2. **The Kinetic Energy components transferred to surface; Hail (1.5 inch dm. & weighs .057lbs (26 grams),**
   - Total KE ~ 423 J (312 ft-lb)
   - Normal component ~ 317 J (234 ft-lb)
   - Shearing (sliding) component parallel to surface ~ 289 J (213 ft-lb)

Impact scenario is high-velocity/dynamic event which would exceed FTE-1 in carbon/epoxy panels less than 0.125 in. thickness.*



Impacts Occur on Oblique Surfaces, of Various Angles

* ref: Kim, Welch, Kedward, *Composites Part A 2003*

Hail Considerations

- **Ground Hail strike on parked A/C**
  - **Projected horizontal surface area**
  - **Probability of hailstorm at airport locations & mass density (per unit area)**
  - **Hail size distribution, & terminal velocities, V_T**
- **In-flight Risk Environment for Hail strikes**
  - **Vector addition of A/C velocity & V_T**
    - **Velocity components normal to impacted surface(s)**
  - **Probability of hailstorm during flight operations & mass density distribution**
  - **Hail size, & terminal velocities, V_T**
- **Limited data base for in-service hail strikes**
  - **Hail Damage reporting procedure would be helpful, airframe and engine**
  - **Birdstrike reporting procedures, useful model**
  - **Correlation with NOAA & METAR sever weather data base?**
  - **Correlation with lighting strike & engine ice ingestion?**
- **Repeat Impact Considerations: impact rate – number hits per unit area**

Data Needs: Operational Usage &Threat Environment(s)

- **Operational usage, data strong influence on risk**
  - **Impact Energy and Force is a function of velocity, v^2**
    - **Moderate velocities in threat environment compliment optimum fuel consumption**
  - **Recognized by pilot & ATC communities**
  - **Limited VGH data for civil aircraft, UDRI data base**
- **Useful FAA data base for reported impacting bird mass**
  - **Cumulative mass distribution**
  - **Needs improvement (voluntary, detailed damage assessment?)**
    - **No linkage to damage & repair actions**
    - **Primary focus; wildlife management at airfields**
- **Hail ice environment**
  - **NOAA**
    - **Sever storm data base from 1950**
    - **Probabilistic weather prediction under development**
    - **Correlation with METAR data, & other a/c weather related threats (lighting?)**
  - **Data base for hail ice risk assessment needs development**
    - **History of events**
    - **Are their different size distributions associated with storm categories**
- **International cooperation to define risk environment**

Summary

- **Bird (& hail) impact events represents a Kinetic Energy state characterized by the joint contribution of mass and velocity:**
  - **Provides a basis for a unified treatment for a variety of impact related environments;**
    - **FOD,**
    - **Birdstrike, &**
    - **Hail ice**
  - **Conservation of energy and momentum permits converting a scalar kinetic energy into directional (tensorial) dynamic force components, most impacts involve complex vehicle geometries.**
- **Airworthiness increasingly dependent on numerical simulation:**
  - **FE models for impacting object must recognize characteristics of individual threats**
  - **Material Characteristic(s) needed to identify response to impact event(s) {FTE's}**
  - **Dynamic & Quasi static test and scaling procedures fundamental to practical development and certification efforts**
- **"Treat environment" data bases requires attention**

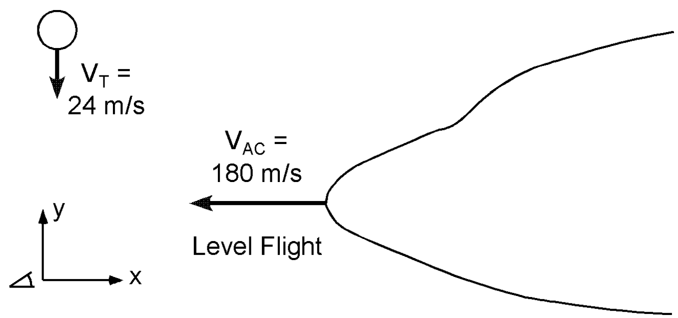
Appendix

Additional slides & some references

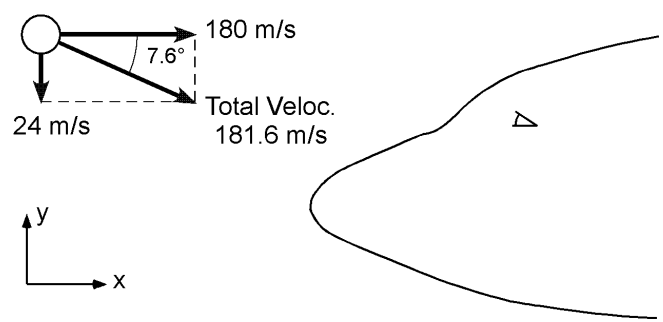
Determination of Velocity Vector Components for Hail Impact & Resulting Energy Components

Resolving Projectile Velocity and Angle with Respect to Aircraft

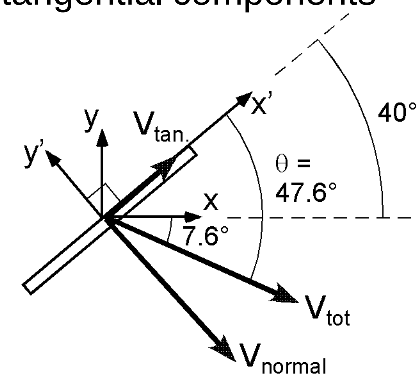
For observer fixed in global reference frame, aircraft moving in –x dir. and ice sphere moving in –y dir.



For observer on the aircraft, the ice sphere appears to be moving in +x dir. at 180 m/s and down in –y dir. at 24 m/s.



Impact onto windshield oriented at 40 deg. from horizontal – resolving normal and tangential components



Components	Velocity (m/s)	KE (J)
Total	181.6	428.7
Normal (y' dir.)	$V_{tot}\cos\theta$ = 131.4	$KE\cos\theta$ = 317
Tangential (x' dir.)	$V_{tot}\sin\theta$ = 122.5	$KE\sin\theta$ = 280

* ref: Kim, Welch, Kedward, *Composites Part A 2003*

Reference List

- P. Feraboli, “Forceful Measures, Energetic Solutions”, 21st ASC Technical Conference, Dearborn, MI, September 2006.
- P. Feraboli, K.T. Kedward, “Enhanced evaluation of the impact response of composite plates”, AIAA Journal, 42/ 10, 2004.
- P. Feraboli, “Some Recommendations for the characterization of the impact performance of composite panels by means of drop tower impact testing”, J. Of Aircraft, Fall 2006
- P. Feraboli, “Damage resistance characteristics of thick-core honeycomb composite panels “, 47th AIAA SDM, No. 2006-2169, 2006.

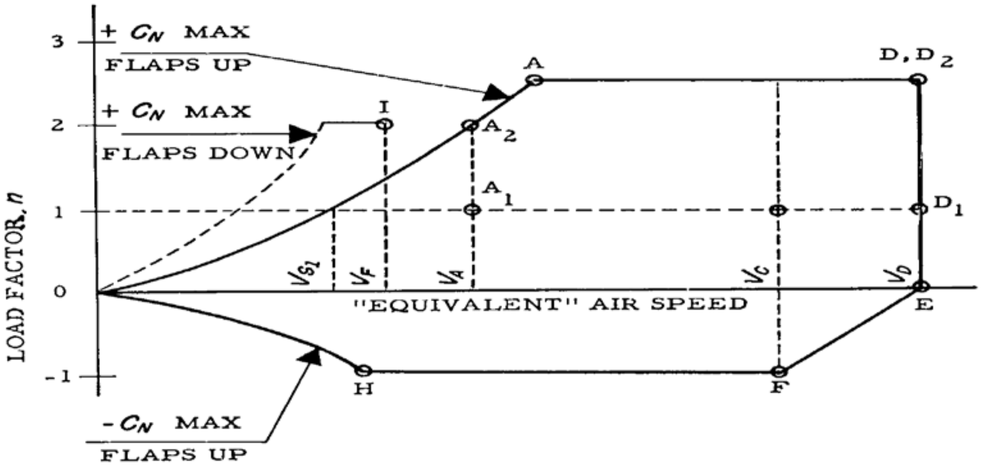
FAA Requirements for Airframes

- **Transport Category Aircraft - FAR25**
- **Part 25.571 Damage- Tolerance & Fatigue Evaluation of structures**

  (a) General, ---

  (e) Damage- Tolerance (discrete source) evaluation. The airplane must be capable of successfully completing a flight during which likely structural damage occurs as a result of:

  1. Impact with a 4-pound bird when the velocity of the airplane (relative to the bird the airplane's flight path) is equal to V_c at sea level, ---



FAA Requirements for Airframes (cont.)

- **Transport Category Aircraft - FAR25**
- **Part 25.571 Damage- Tolerance & Fatigue Evaluation of structures**

(a) General, ---

(e) Damage- Tolerance (discrete source) evaluation.

- **Part25.631 Bird strike Damage - Empennage**

  The empennage structure must be designed to assure capability of continued safe flight and landing of the airplane after impact with an 8 pound bird when the velocity of the airplane (relative to the bird along the airplane's flight path) is equal to V_c at sea level, ---

- **Part 25.775 Windshields and Windows**

(b) Windshields panels directly in front of the pilots in the normal conduct of their duties, and the supporting structures for these panels, must withstand, without penetration, the impact of a 4 pound bird when the velocity of the airplane (relative to the bird along the airplane's flight path) is equal to V_c at sea level, ---

NOTE: V_c was interpreted as most probable P(v) from VGH data, not max velocity in the altitude velocity envelope diagram.

Sources of Data

$$\mathbf{OIR = Pa \cdot v \cdot t_s \cdot \rho_{Bird\ Environment}}$$

Where:

OIR $\rightarrow$ Historical operational usage

Pa $\rightarrow$ Vehicle geometry

V $\rightarrow$ Vehicle tracking program, VGH

t_s $\rightarrow$ Vehicle tracking program, VGH

$\rho_{Bird\ Environment}$ *(# & mass/unit volume)* not directly measurable

W_{Bird} $\rightarrow$ Historical Data (USAF, FAA, others)

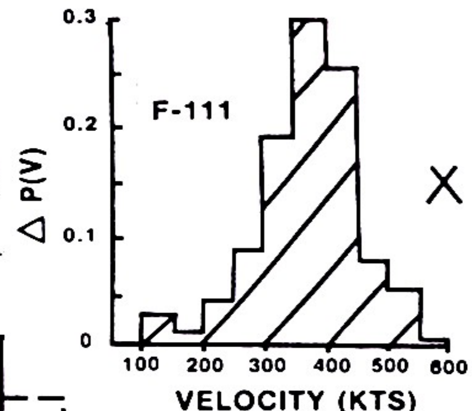
Note: Historical data allows for a scaling process as bird population environment (density in airspace) is independent of vehicle and operational usage.

Alternative approaches limited by data bases.

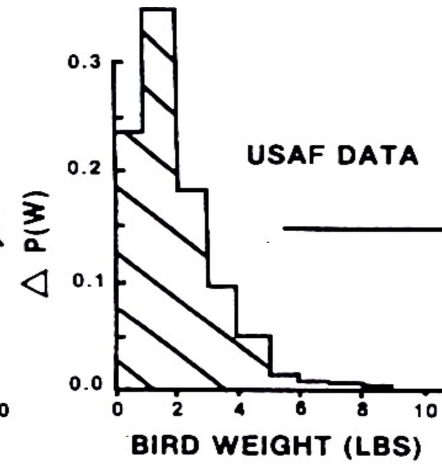
Application of Methodology To Composite Structure: FTE-1,& -2 Used With Defined Velocity and Impacting Mass Distributions (Similar to Canopy) to Define Impact Tolerance Capabilities

TOTAL NUMBER BIRDS IMPACTING CANOPY

[OIR x FORCE USAGE
I.E. F-111(TAC)
100 x 0.389=38.9] X



X



FAILURE CRITERIA
I.E. KE=7.1 FT LBS (F-111)
200 KTS - 4 LB BIRD

IMPACTING KINETIC ENERGIES FT-LBS x 10 -3

A/C VELOCITY (KTS)	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5
110 - 160	0.4	1.2	2.0	2.8	3.7	4.5	5.3	6.1
160 - 210	0.8	2.3	3.8	5.3	6.9	8.4	9.9	11
210 - 260	1.2	3.7	6.2	8.6	11	14	16	18
260 - 310	1.8	5.4	9.0	13	16	20	24	27
310 - 360	2.5	7.5	13	18	23	28	33	38
360 - 410	3.3	9.9	17	23	30	36	43	50
410 - 460	4.2	13	21	30	38	46	55	63
460 - 510	5.2	16	26	37	47	58	68	79
510 - 560	6.4	19	32	45	57	70	83	96

BIRD WEIGHTS

A/C VELOCITY (KTS)	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5
110 - 160	0.3	0.4	0.2	0.1	0.1	0.0	0.0	0.0
160 - 210	0.1	0.2	0.1	0.0	0.0			
210 - 260	0.4	0.5	0.3					
260 - 310	1.0	1.2						
310 - 360	2.2							
360 - 410	3.3							
410 - 460	2.7							
460 - 510	0.9							
510 - 560	0.1							

14 NO DAMAGE
25 DAMAGING

EXPECTED NUMBER (WEIGHT/VELOCITY) BIRD STRIKES

← CANOPY CAPABILITY

Factors Determining Optimum Weight and Risk

- **Failure Threshold Energy, FTE, Levels**
  - **Independent of threat environment,**
  - **Determined by material, design details**
  - **Estimate from literature, *development testing*, scaling, and *design simulation* (I. E. Quasi-static Interlaminar Shear threshold,--)**
- **"Allowable" Deflection, sometimes used for internal functional impairment considerations.**
- **Individual Threat Environments & FTE, independent of design**
  - **Bird strike**
  - **Hail Ice (on-ground, & in flight)**
  - **FOD**
- **Operational Usage of aircraft is significant factor(independent of FTE's & usually the threat)**
- **Dependent on projected exposed areas**
- **Impact Energy external to airframe determined by threat mass & velocity;**
  - **Impacting force & INTERNAL LOADS a function of**
    - **Impacting diameter & impactor material characteristics (ILS)**
  - **Incident angles determined by design geometry**
    - **Oblique impacts will increase the "apparent" FTE for design feature**

Failure Threshold Energy Level(s) :
Quantifying the Role of Quasi Static Testing & Scaling

- **Impact and Quasi-Static Experiments**
  - **Explore broad velocity spectrum using identical target configuration:**
    - **High Velocity – e.g., in-flight bird, ice, rotating blades**
    - **Intermediate Velocity – e.g., ground hail, FOD**
    - **Low Velocity – e.g., tool drop, vehicle collision**
    - **Quasi-Static indentation**
  - **Measure FTE-1, FTE-2, seeking relationship across velocity spectrum via analyses**
    - **simple models guided and verified by high fidelity numerical simulation – DETERMINE EQUIVALENCY FACTORS/RELATIONSHIPS between all cases**
    - **relationships defined in terms of target geometry, material properties, projectile parameters**
- **Scaling Effects**
  - **Must be able to account for wide variety of target configurations and projectile variations**
  - **Projectile/target interaction parameter should be defined**
    - **indentation stiffness (local/dynamic, global/static), target/force-pulse dynamics comparison**
  - **Represent impact events (across velocity spectrum) with UNIFYING parameter, e.g., effective contact force (could be time dependent), accounting for difference in local contact conditions between projectile and target**
    - **e.g., 200 ft-lb impact produced by following cases will have different force profiles:**

      Bird
Ice
Drop Weight

      → Determine Quasi-Static equivalent to find FTE-1 and FTE-2

Kinetic Energy Levels As Function of A/C Speed and Impacting Weight; 4 Pounds and 350 KTAS Are a Typical Mil Transport Requirement. Interface Between Green & Black Can Be Used to Identify Impact Tolerance Capability

$$KE = \frac{1}{2}\left(\frac{w}{g}\right)V^2$$

Weight(lbs)/Bird; Velocity(kts) A/C	2	4	6	8	10	12	14	16	18	20	22	24	Velocity (m/sec)
100	887	1,774	2,661	3,548	4,435	5,322	6,209	7,096	7,983	8,870	9,757	10,644	51.4
125	1,386	2,772	4,158	5,544	6,930	8,316	9,701	11,087	12,473	13,859	15,245	16,631	64.3
150	1,996	3,991	5,987	7,983	9,979	11,974	13,970	15,966	17,961	19,957	21,953	23,949	77.2
175	2,716	5,433	8,149	10,866	13,582	16,298	19,015	21,731	24,448	27,164	29,880	32,597	90.0
200	3,548	7,096	10,644	14,192	17,740	21,288	24,836	28,384	31,932	35,480	39,027	42,575	102.9
225	4,490	8,981	13,471	17,961	22,452	26,942	31,433	35,923	40,413	44,904	49,394	53,884	115.7
250	5,544	11,087	16,631	22,175	27,718	33,262	38,806	44,349	49,893	55,437	60,980	66,524	128.6
275	6,708	13,416	20,124	26,831	33,539	40,247	46,955	53,663	60,371	67,078	73,786	80,494	141.5
300	7,983	15,966	23,949	31,932	39,914	47,897	55,880	63,863	71,846	79,829	87,812	95,795	154.3
325	9,369	18,738	28,106	37,475	46,844	56,213	65,582	74,950	84,319	93,688	103,057	112,426	167.2
350	10,866	21,731	32,597	43,462	54,328	65,194	76,059	86,925	97,790	108,656	119,522	130,387	180.0
375	12,473	24,947	37,420	49,893	62,366	74,840	87,313	99,786	112,259	124,733	137,206	149,679	192.9
400	14,192	28,384	42,575	56,767	70,959	85,151	99,343	113,534	127,726	141,918	156,110	170,302	205.8
425	16,021	32,042	48,064	64,085	80,106	96,127	112,148	128,170	144,191	160,212	176,233	192,255	218.6

Analytical Methodology

- **Based, initially, on Historical Birdstrike Data:**
  - **Operational impact rate**
  - **Bird weight distribution**
- **Correlates & Predicts Operational Impact Rates Based on Operational Usage:**
  - **A/C velocities**
  - **Time below 15,000 feet**
  - **Projected frontal area**
- **Develops Risk and Damage Assessments Based on:**
  - **Structural response; &**
  - **Failure criteria**
- **Bird (& hail) impact events represents an energy state characterized by the joint contribution of mass and velocity: Kinetic Energy**
- **Can be extended to Hail Ice and other impact environments**

Impact Failure Threshold Energy, FTE, Levels to Be Identified and Used in Risk Assessment for Composite Structures

(Potential damage threshold criteria as a function of laminate design characteristics)

- **Sub -critical**
  - **Elastic response**
  - **No damage**
- **1st Supercritical regime**
  - **Delamination damage, energy dissipation**
  - **Barely Visible Impact Damage, BVID**
- **2nd supercritical regime**
  - **Backside fiber breakage, through thickness cracking & penetration**
  - **Visible Impact Damage, VID**
  - **Potential loss of pressurization & penetration into structure**