

Prezentacija predavanja

**NUMERIČKE METODE U ANALIZI UDARNIH OŠTEĆENJA
ZRAKOPLOVNIH KONSTRUKCIJA**

Prof. dr. sc. Ivica Smojver
Fakultet strojarstva i brodogradnje Sveučilišta u Zagrebu

NUMERIČKE METODE U ANALIZI UDARNIH OŠTEĆENJA ZRAKOPLOVNIH KONSTRUKCIJA

Sažetak predavanja

Rad predstavlja pregled 30-godišnjih istraživanja u području numeričke analize kompozitnih konstrukcija, posebice zrakoplovnih, u okviru AeroDamage.Lab na Fakultetu strojarstva i brodogradnje Sveučilišta u Zagrebu. Početkom 1990-ih započet je rad na numeričkom modeliranju kompozitnih konstrukcija razvojem lju-skastog konačnog elementa s 9 čvorova primjenjivog u analizi višeslojnih kompozita, pri čemu je razvijen MATLAB program. U sljedećoj fazi istraživanja proveden je razvoj numeričkih algoritama za analizu raslojavanja pri udaru kompozitnih ploča udaračima male brzine/mase. To dovodi do jedva vidljivih vanjskih oštećenja (BVID) te je veza između pojave pukotina u matrici i međuslojnih raslojavanja primijenjena u razvoju odgovarajućih algoritama. Udari u kompozitne konstrukcije predstavljaju poseban problem zbog inherentne osjetljivosti krhkog materijala pri takvoj vrsti opterećenja. Stoga je za simulaciju oštećenja pri udaru korišten u početnom periodu istraživanja Abaqusov ugrađeni model inicijacije i propagacije oštećenja. U ovom modelu koristi se Hashinov kriterij popuštanja kao kriterij inicijacije oštećenja. Nakon toga, oštećenje u kompozitu je modelirano korištenjem principa *Continuum Damage Mechanics*. Kako bi se dodatno povećala pouzdanost numeričkog modeliranja oštećenja u kompozitnim konstrukcijama, unutar istraživačke skupine AeroDamage.Lab razvijen je višerazinski pristup. Takav pristup povezuje računalno vrlo učinkovit poluanalitički mikromehanički model *High Fidelity Generalized Method of Cells (HFGMC)* i Abaqus/Explicit solvera za simulacije na razini čitave konstrukcije. Trenutni fokus istraživanja je na modeliranju samozacjeljujućih polimernih kompozita, budući da su dokazali svoju primjenjivost u kompozitnim konstrukcijama tako što mogu samozacijeliti oštećenja matrice kao i delaminacije. Razvijen je konstitutivni model koji je numerički verificiran LVI, HVI, DCB i 3PB testovima.

O predavaču

Prof. Ivica Smojver djeluje na Zavodu za zrakoplovno inženjerstvo Fakulteta strojarstva i brodogradnje Sveučilišta u Zagrebu. Prije toga radio je na Zavodu za tehničku mehaniku istog fakulteta kao i Tehničkoj vojnoj akademiji u Zagrebu, Katedra raketne tehnike. U razdoblju od 2004. – 2018. bio je voditelj Katedre za aerodinamiku te Katedre za zrakoplovne konstrukcije. Voditelj je Projektnog laboratorija za numeričko modeliranje oštećenja u zrakoplovnim konstrukcijama od 2009. (AeroDamage.Lab). Znanstveni interesi uključuju primjenu metode konačnih elemenata u analizi kompozitnih zrakoplovnih konstrukcija; analizu ponašanja zrakoplovnih konstrukcija pri udarnim opterećenjima; primjenu višerazinskih metoda u analizi pojave oštećenja u kompozitnim konstrukcijama; numeričko modeliranje kao i samoobnavljajuće kompozitne konstrukcije. Prof. Smojver podučava predmete u području avionskih konstrukcija te mehanike kompozitnih zrakoplovnih konstrukcija na studijima zrakoplovstva i strojarstva na FSB-u, kao i predmete iz područja raketne tehnike na Sveučilišnom vojnom studiju. Kao voditelj brojnih projekata ima više od 60 radova u referentnim publikacijama i zbornicima radova, te je imao pozvana predavanja, među ostalim institucijama i u NASA Glenn Laboratory, Airbus, Bombardier, TsAGI (Rusija) INCAS (Rumunjska) i dr. Od 2018. obnaša dužnost voditelja Preddiplomskog vojnog studija Vojno inženjerstvo Sveučilišta u Zagrebu. Među ostalim članstvima, prof. Smojver je *Senior Member* u *American Institute of Aeronautics and Astronautics* (AIAA), član *European Association of Computational Mechanics*, predstavnik Hrvatske u *Programskom odboru za transport Obzora 2020 te Obzora Europe*. 4 godine je obnašao dužnost supredsjedatelja u *Advisory Council for Aeronautical Research and Innovation in Europe - Member States Group (ACARE – MSG)* te je bio predstavnik RH u *Clean Sky 2 States Representatives Group*. Član je *Materials Technical Committee* u *American Institute of Aeronautics and Astronautics* od 2022.



SUVREMENE METODE U PROJEKTIRANJU I ANALIZI INŽENJERSKIH KONSTRUKCIJA
HAZU, Zagreb, 20.10.2023.





100 godina Fakulteta
strojarstva i brodogradnje
Sveučilišta u Zagrebu
100 Years of Faculty of
Mechanical Engineering
and Naval Architecture
University of Zagreb



Numeričke metode u analizi udarnih oštećenja zrakoplovnih konstrukcija

Ivica Smojver

Fakultet strojarstva i brodogradnje Sveučilišta u Zagrebu,
Zavod za zrakoplovno inženjerstvo

Projektni laboratorij za numeričko modeliranje oštećenja:
zrakoplovnim konstrukcijama - AeroDamageLab

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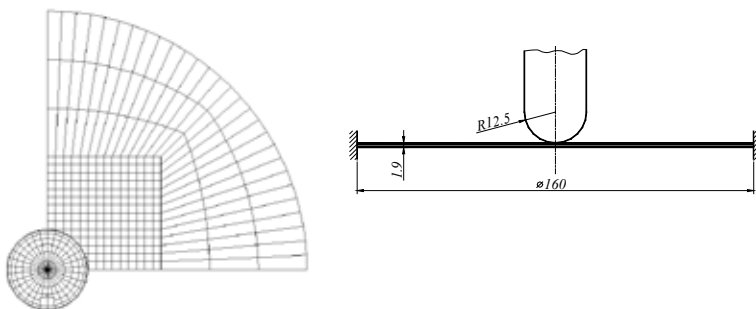
Contents

- Impact damage in composite plates – matrix cracks and delaminations
- Application of numerical methods in high strain-rate problems
- Multiscale Analyses of Composite Structures
- Crashworthiness Applications
- Low-Velocity Impact Loading Analyses
- High-Velocity Impact Loading Analyses
- Modelling of advanced composites: ACCESS project
- Conclusions

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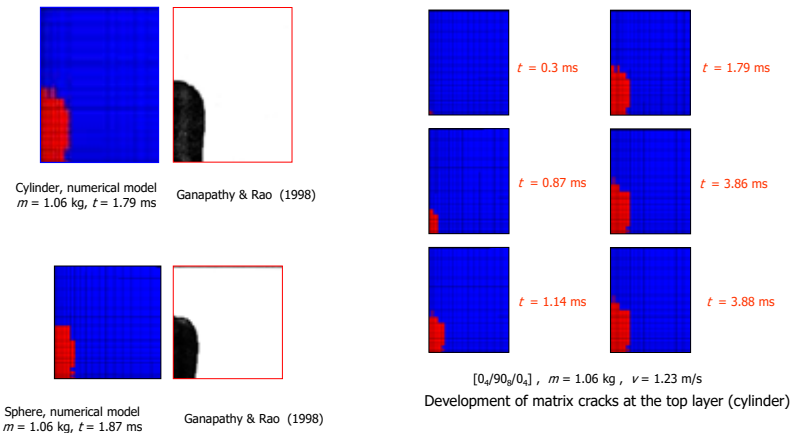
Impact damage in composite plates – matrix cracks and delaminations

- geometry of the impactor and the clamped circular glass/epoxy plate



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Projected area of matrix cracks

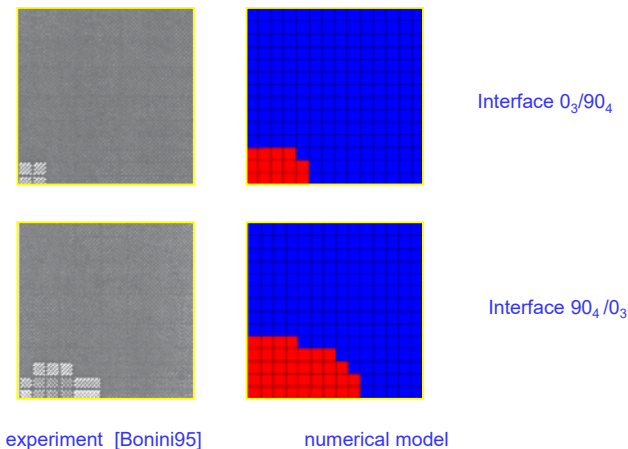


Dissertation: Ivica Smojver (1999)

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Delaminations

$[0_3/90_4/0_3]$, $m = 2.3 \text{ kg}$, $v = 5 \text{ m/s}$



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Application of numerical methods in high strain-rate problems

- Examples:

High velocity impact
Crashworthiness applications
Ballistic perforation



- Problems:

- Extreme material deformations**

Excessive FE distortion
Complex contact conditions

- Strain-rate dependent constitutive models**

Failure and damage models

Simulation: Outboard Flap penetration

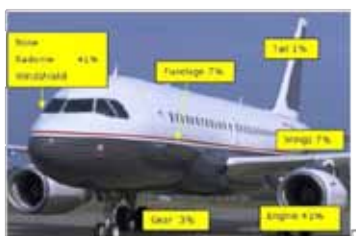
Reliable numerical solutions

- **AeroDamageLab** – established in 2009 within the Technology project TP-07/0120-30
„Numerical Modelling of Damage in Aeronautical Structures“

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Example: Bird strike simulation

- major threat to aircraft safety



Statistical distribution of impact damage



Outboard Flap penetration – Airbus A319/320

- **Numerical solution:**

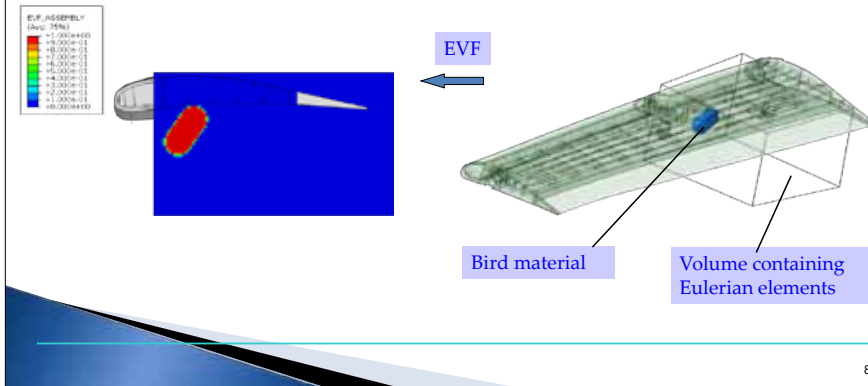
- finite element method
 - nonlinear explicit transient dynamic analysis (Abaqus/Explicit)
 - very detailed finite element models
 - multiple failure and damage models

- Lagrangian model
 - Coupled Eulerian Lagrangian CEL
 - Smoothed Particle Hydrodynamics SPH

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Coupled Eulerian Lagrangian bird model

- Modeling of fluids and solids that undergo extreme deformation
- Multi material finite element formulation – Eulerian Volume Fractions (EVF)
- General contact is used to couple the Eulerian and Lagrangian models
- Eulerian finite element model – EC3D8R elements



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Importance of Bird material: Accurate modelling of impact forces

- bird strike - soft body impact
- hydrodynamic modelling of bird replacements – EOS materials

- Hugoniot pressure: $p_H = \rho_0 U_s (U_0) U_0$ ρ_0 - initial density
 U_0 - impact velocity
 U_s - shock velocity

- stagnation pressure: $p = \frac{1}{2} \rho_0 U_0^2$

- linear Mie-Grüneisen (Us-Up) equation of state :

$$U_s = c_0 + s U_p \quad \text{- linear relation between shock and particle speeds} \quad \begin{matrix} c_0 - \text{speed of sound} \\ s - \text{material constant} \end{matrix}$$

$$p = \frac{\rho_0 c_0^2 \eta}{(1 - s \eta)^2} \left(1 - \frac{\Gamma_0 \eta}{2} \right) + \Gamma_0 \rho_0 E_m \quad \text{- pressure to density relation}$$

$$\eta = 1 - \rho_0 / \rho \quad \text{- nominal volumetric compressive strain}$$

$$\Gamma_0 \quad \text{- material constant - "Grüneisen gamma"}$$

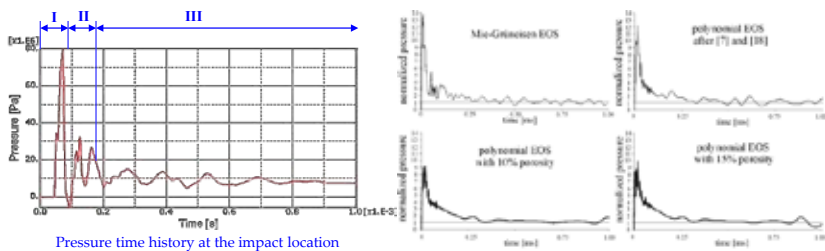
$$E_m \quad \text{- internal energy per unit mass}$$

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Bird modeling: • cylinder with hemispherical ends

- length to diameter ratio equal to 2
- bird material density = 938 kg/m³

Material model validation:



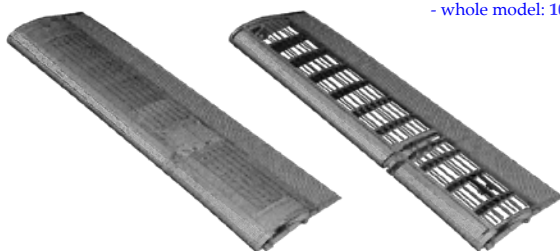
Pressure time history at the impact location

- I Shock wave stage (Hugoniot pressure)
- II Pressure release stage
- III Stagnation pressure stage

- VUMAT EOS material
- modelling of porosity effects
- more realistic modelling of impact pressures

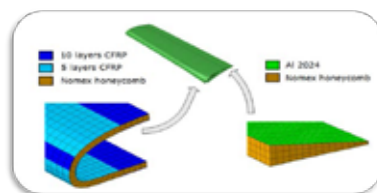
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Finite element model



- whole model: 109585 elements

- 69696 conventional shell (S4R & S3R)
- 16020 continuum shell (SC8R)
- 23665 solid elements (C3D8R)
- 204 beam elements (B31)



- CFRP skin, gradually variable skin thickness (14 - 41 layers)
- Typical layup: [45/0/-45/90/-45/0/45]_s
- layer thickness: 0.125 mm (1.75 - 5.125 mm)
- spars and ribs made of Aluminum alloy
- leading and trailing edge sandwich structures
- kinematic constraints: SC8R & S4R elements

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Structural damage modeling

Composite materials:

- Hashin's damage initiation criterion
- 4 failure modes:
 1. fibre rupture in tension
 2. fibre buckling and kinking in compression
 3. matrix cracking under transverse tension and shearing
 4. matrix crushing under transverse compression and shearing

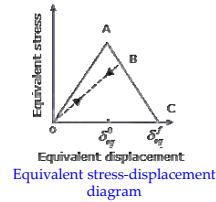
- Degradation of material stiffness – damage parameters

$$\mathbf{C}_d = \frac{1}{D} \begin{bmatrix} (1-d_f)E_1 & (1-d_m)v_{21}E_1 & 0 \\ (1-d_f)(1-d_m)v_{12}E_2 & (1-d_m)E_2 & 0 \\ 0 & 0 & (1-d_s)G_{12}D \end{bmatrix}$$

$$D = 1 - (1-d_f)(1-d_m)v_{12}v_{21}$$

$E_1, E_2, G_{12}, v_{12}, v_{21}$ – unidirectional CFRP ply properties

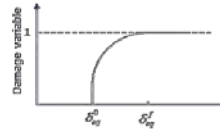
d_f – fibre damage parameter
 d_m – matrix damage parameter
 d_s – shear damage



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- Damage evolution: parameter of a particular failure mode evolves as

$$d = \frac{\delta_{eq}^f (\delta_{eq}^f - \delta_{eq}^0)}{\delta_{eq}^f (\delta_{eq}^f - \delta_{eq}^0)}$$



Damage variable as a function of equivalent displacement

Aluminium alloys (Al 2024 & Al 7075):

- Elastoplastic material model
- Shear failure criterion:

$$\bar{\epsilon}^{pl} = \bar{\epsilon}_0^{pl} + \int_0^t \sqrt{\frac{2}{3}} \dot{\epsilon}^{pl} : \dot{\epsilon}^{pl} dt$$

– damage parameter:

$$\omega = \frac{\bar{\epsilon}_0^{pl} + \sum \Delta \bar{\epsilon}^{pl}}{\bar{\epsilon}_f^{pl}}$$

– suitable for high strain rate dynamic problems

$\bar{\epsilon}_0^{pl}$ – initial value of equivalent plastic strain

$\dot{\epsilon}^{pl}$ – the equivalent plastic strain rate

$\bar{\epsilon}_f^{pl}$ – strain at failure

$\Delta \bar{\epsilon}^{pl}$ – plastic strain increment

- Cowper-Symonds strain rate dependent model (VUMAT)

$$\sigma(\epsilon, \dot{\epsilon}) = \left[a + b(\epsilon^{pl})^n \right] \left[1 + \left(\frac{\dot{\epsilon}}{D} \right)^{1/p} \right]$$

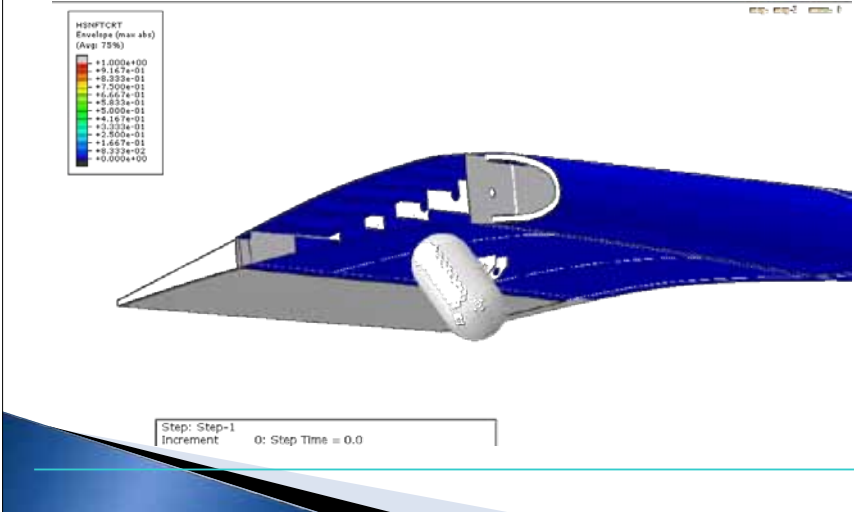
a, b [MPa]
 D [s⁻¹]
 p, n [-] } – material parameters for CS model (yield stress)

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Results – bird impact in flap structure

Hashin's fiber tensile failure criterion (cross – sectional view)

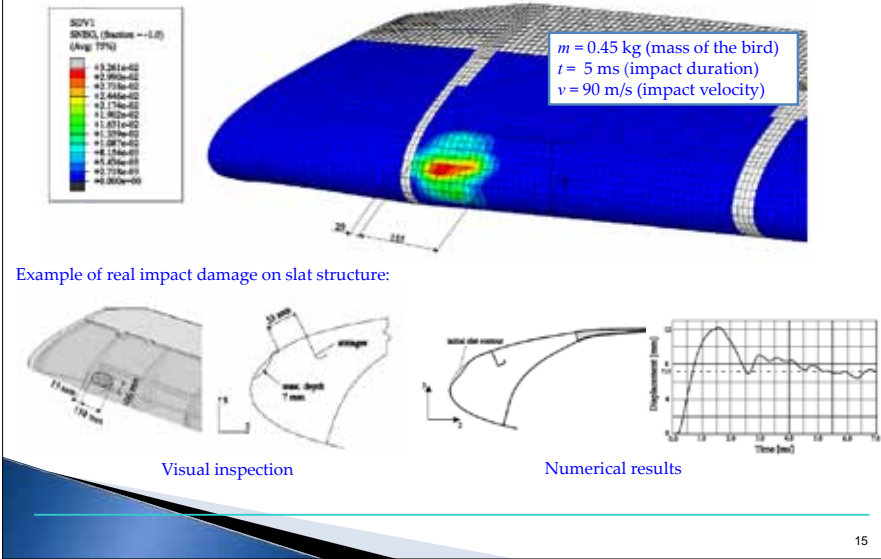
$m = 1.81\text{kg}$ (mass of the bird)
 $t = 5\text{ ms}$ (impact duration)
 $v = 100\text{ m/s}$ (impact velocity)
EVF = 0.5

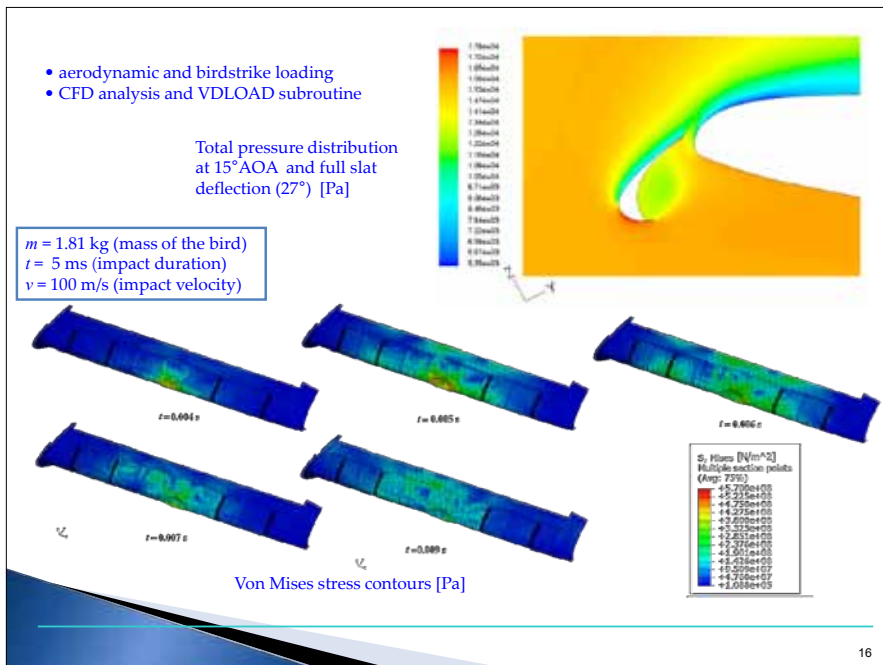


Results – bird impact in metallic slat structure

Equivalent plastic strain [-]

$m = 0.45\text{ kg}$ (mass of the bird)
 $t = 5\text{ ms}$ (impact duration)
 $v = 90\text{ m/s}$ (impact velocity)





Multiscale Analyses of Composite Structures

Problem:

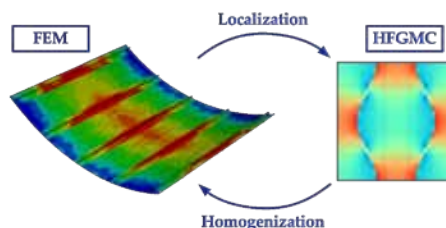
Numerical modelling of failure and damage of laminated composite structures:

- failure modes of composite materials are closely related to the material microstructure
- analyses on the constituent level using micromechanical principles
- modelling of damage effects on the micro-level
- in order to solve engineering problems analyses have to be performed on two length scales

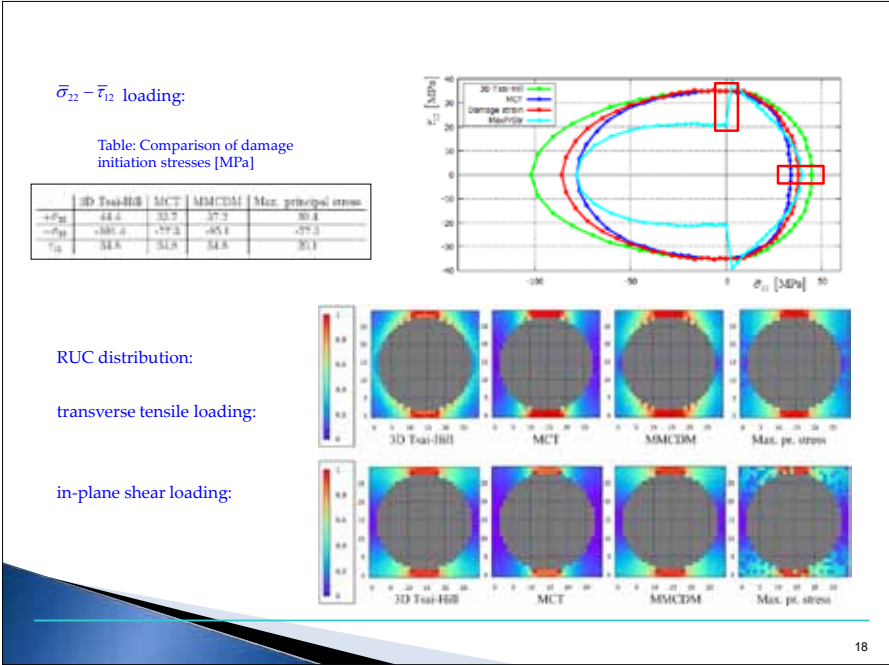


Solution:

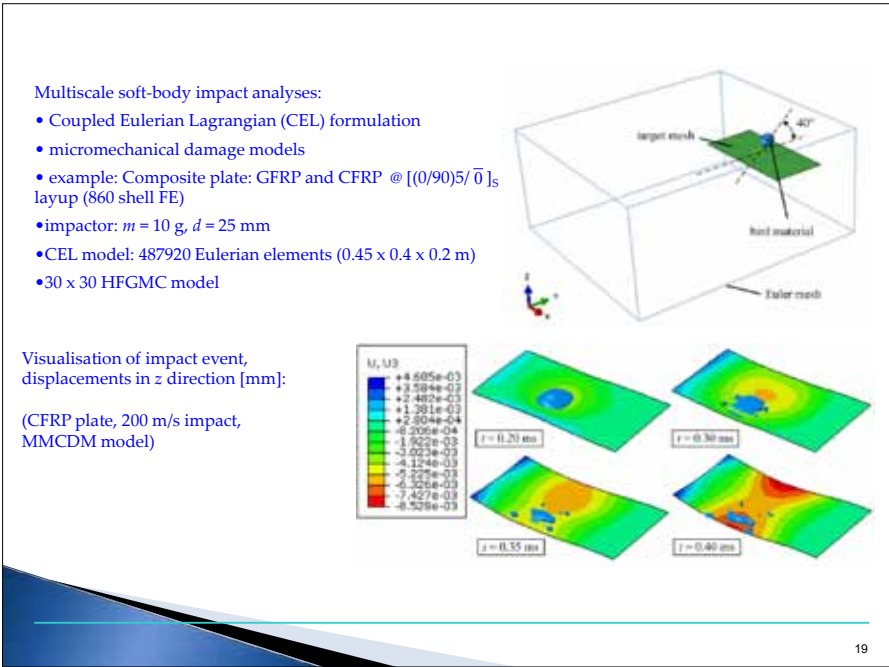
- High Fidelity Generalized Method of Cells (HFGMC)
- Abaqus/Explicit
- multiscale approach



Dissertation: Darko Ivančević
(2015)



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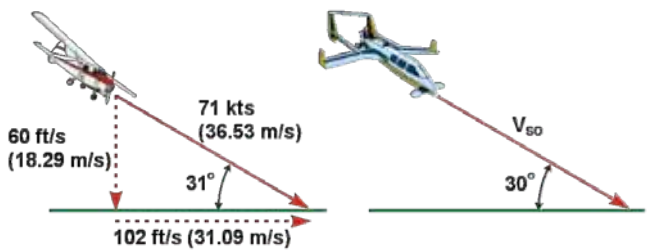


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Crashworthiness Applications

Crashworthiness analysis of a small aircraft fuselage structure

- AGATE requirements (Advanced General Aviation Transport Experiments)
- Taking into account the influence of the whole structure, stalling speed and type of impacted surface

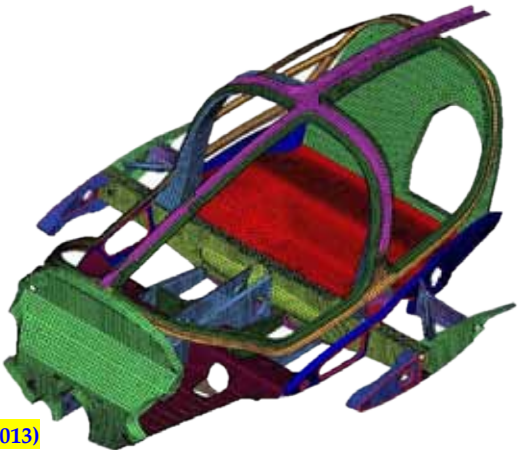


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Analysis

- Final model

Total number of elements	41354
Total number of nodes	55195
Beam elements	344
4-noded shell elements	39378
3-noded shell elements	1632
Total number of shell elements	41010
Number of 3D elements	0



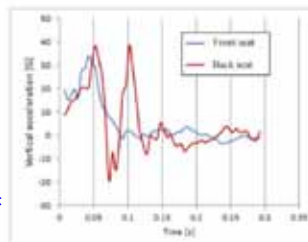
MEng Thesis: Kristina Šarović (2013)

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- Results of analysis with MPC connecting engine as concentrated mass

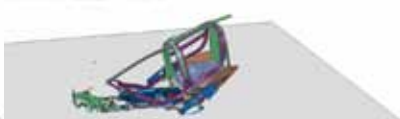
vertical acceleration at the passenger locations:



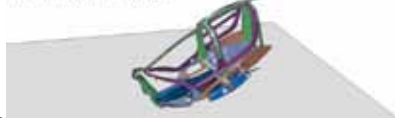
Increment 0 : t = 0 s



Increment 112652 : t = 0.05 s



Increment 55676 : t = 0.025 s



Increment 168356 : t = 0.075 s

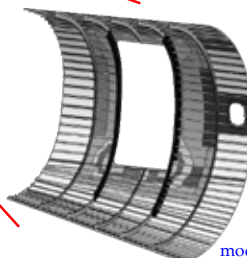
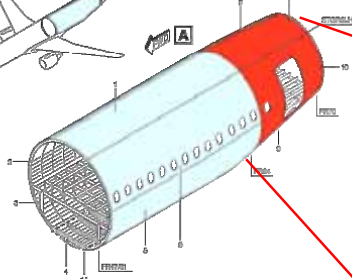


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Low-Velocity Impact Loading Analyses

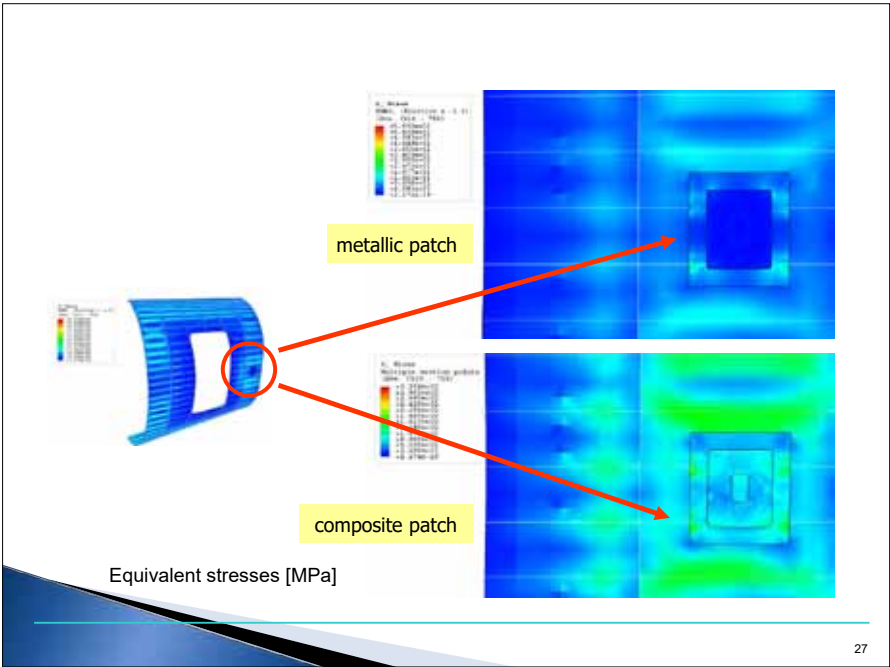
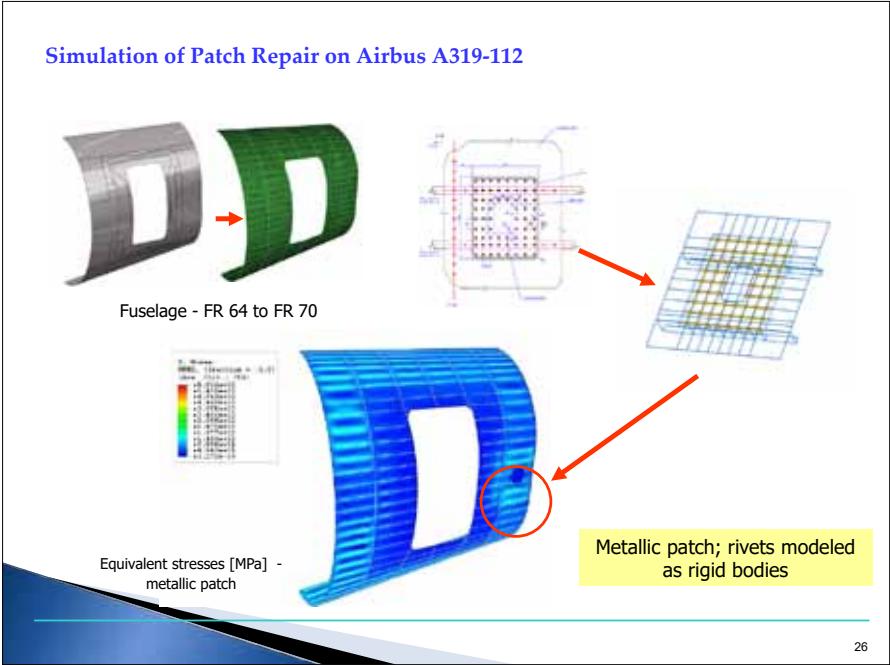
Applications:

- ground equipment impact damage on fuselage structure



modelled structure

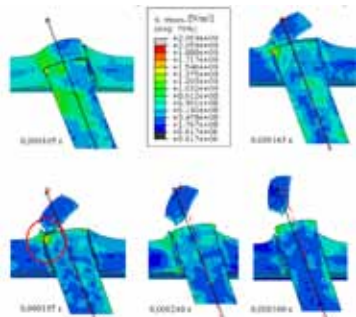
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High-Velocity Impact Loading Analyses

Applications:

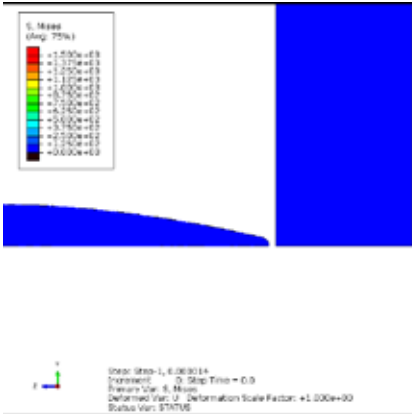
- numerical simulation of impact on armour plates
- high-velocity perforation phenomena



Impact - 330 m/s @ 20deg angle

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Impact of a realistic 12.7 mm anti-aircraft ammunition - Von Mises stress distribution in [MPa]



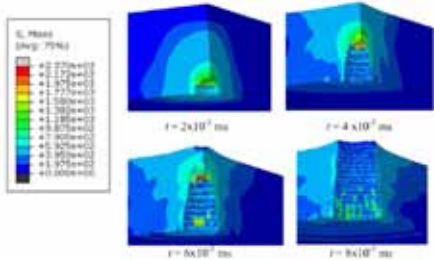
$t_p = 20$ mm (plate thickness)
 $v = 903$ m/s (impact velocity)
 $t = 0.14$ ms (impact duration)

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Effect of design parameters on perforation resistance:

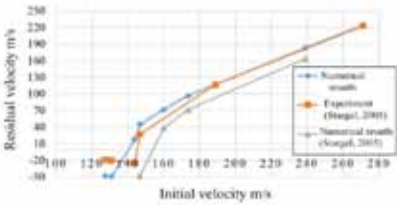
- material
- aircraft skin thickness
- curvature

$t_p = 10 \text{ mm}$ (plate thickness)
 $v = 903 \text{ m/s}$ (impact velocity)



Von Mises stress [MPa] distribution

$t_p = 2.03 \text{ mm}$ (plate thickness)
 $R = 111.6 \text{ mm}$ (curvature radius)



ballistic curves

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Modelling of advanced composites: ACCESS project

- ACCESS: **A**dvan**C**ed **C**omposit**E** **S**elfhealing **S**imulation
- funded by the Croatia Science Foundation
- project duration: 10/2018 – 10/2022
- objective: development of a numerical methodology for modelling of advanced composite structures with self-healing capabilities
- **intrinsic self-healing capability** - Surlyn copolymer
- numerical methodology for self-healing composites will be based on multiscale concepts, since the failure modes of composite structures appear at different length scales

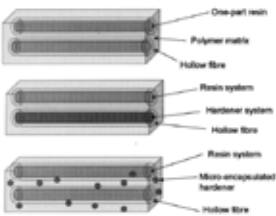


Figure: Schematic of self-healing composite materials [Bleay 2001]



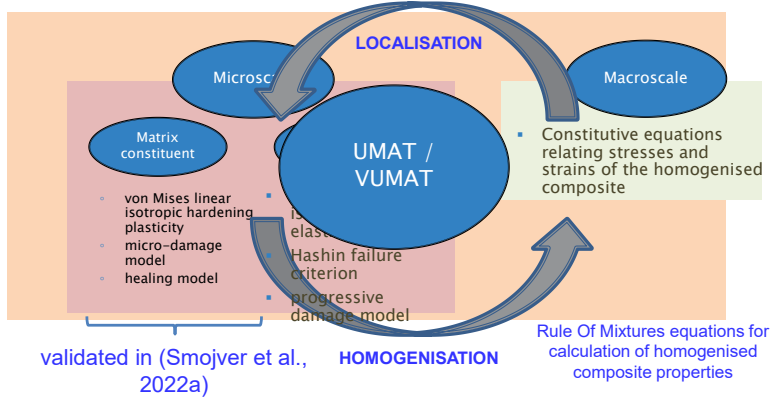
Figure: Application of Hollow Glass Fibres in CFRP composites [Williams 2007]

S.M. Bleay, L. Humberstone:
Mechanical and electrical assessment of
hybrid composites containing hollow
glass reinforcement, Composites
Science and Technology 59 (9), 1321-
1329 (1999)

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Constitutive model description

Voigt (iso-strain) and Reuss (iso-stress) approximations



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Constitutive model description

Matrix constituent at the microscale

Micro-damage-healing model, after (Darabi et al. 2012)

$$\dot{\phi} = \Gamma^{nd} \left(\frac{\bar{\gamma}}{Y_{th}} \right)^q (1 - \phi)^2 \cdot e^{k \bar{\epsilon}_{eff}}$$

$$\dot{h} = \Gamma^h (1 - h)^m (1 - \phi)^m$$

$$\phi_{eff} = \phi (1 - h)$$

$\phi, \dot{\phi}$ – damage variable; damage rate

Γ^{nd} – damage viscosity parameter, 1/s

$\bar{\gamma}$ – damage driving force, Pa

Y_{th} – threshold damage force, Pa

q, k – damage model parameters

$\bar{\epsilon}_{eff}$ – effective (equivalent) strain

$h, \dot{h}$ – healing variable; healing rate

Γ^h – healing viscosity parameter, 1/s

m – healing model parameter

ϕ_{eff} – effective damage variable

Plasticity model

Von Mises linear isotropic hardening plasticity

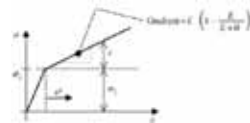


Fig. 3: Stress-strain diagram for linear strain hardening

$$\sigma_y = \sigma_{y0} + r(\epsilon^p)$$

$$r(p) = \int H \cdot d\epsilon^p$$

Dissertation: Dominik Brezetić (2023)

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Constitutive model description

- Reinforcing fibres at the micro scale
 - Hashin failure criterion + progressive damage model

$$\phi_f^t = \frac{\delta_{eq}^f (\delta_{eq}^{T/C} - \delta_{eq}^0)}{\delta_{eq}^{T/C} (\delta_{eq}^f - \delta_{eq}^0)}$$

δ_{eq}^0 initial equivalent displacement;
 δ_{eq}^f equivalent displacement at which the material has failed;
 $\delta_{eq}^{T/C}$ current equivalent displacement for the case of tension or compression

- Homogenisation

$$E_{11} = E_{11}^f V^f + E^m (1 - V^f)$$

$$\frac{1}{E_{22}} = \frac{V^f}{E_{22}^f} + \frac{1 - V^f}{E^m}$$

$$\nu_{12} = \nu_{12}^f V^f + \nu^m (1 - V^f)$$

$$\frac{1}{G_{12}} = \frac{V^f}{G_{12}^f} + \frac{(1 - V^f)}{G^m}$$

- Localisation

- Voigt (iso-strain) assumption

$$d\epsilon_{11}^m = d\epsilon_{11}^f = d\epsilon_{11}$$

- Reuss (iso-stress) assumption

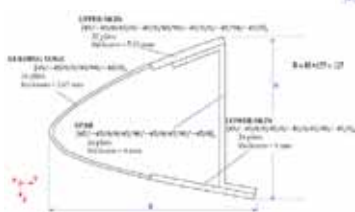
$$(1 - V^f) \cdot d\epsilon_{ii}^m + V^f \cdot d\epsilon_{ii}^f = d\epsilon_{ii}, \text{ where } i = 2, 3;$$

$$(1 - V^f) \cdot d\gamma_{ij}^m + V^f \cdot d\gamma_{ij}^f = d\gamma_{ij}, \text{ where } i, j = 1, 2, 3.$$

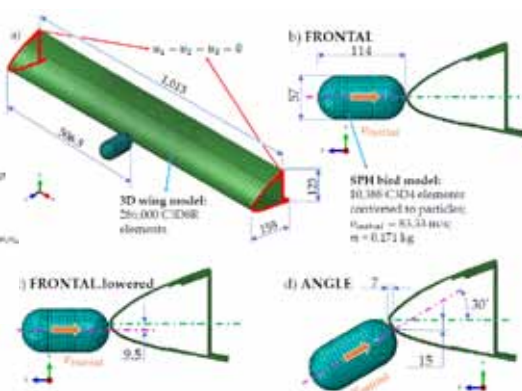
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Composite aircraft wing bird strike

- EponTM 828EL + PCL
- UD T700 carbon fibre

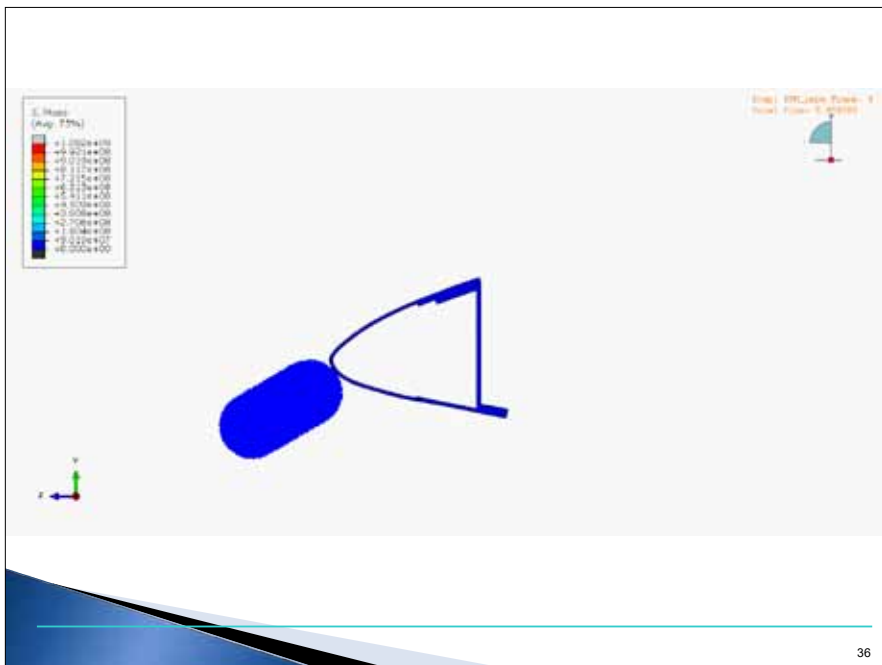


Schematic representation of composite aircraft wing structure with layup sequences, thicknesses and the main material coordinate system.

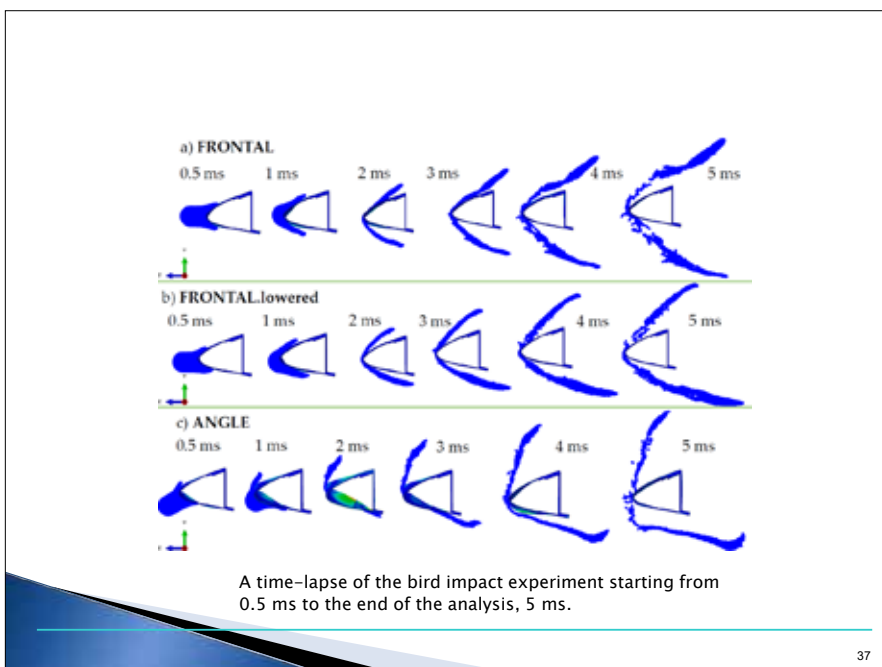


Abaqus model of the bird impact experiment with composite wing structure and SPH bird model, for three different initial configurations, dimensions in mm.

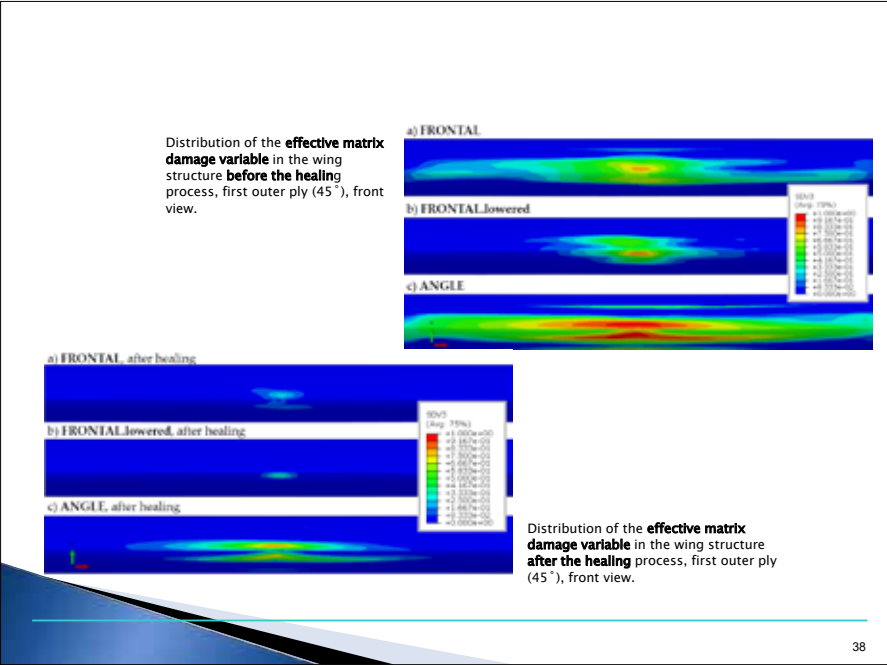
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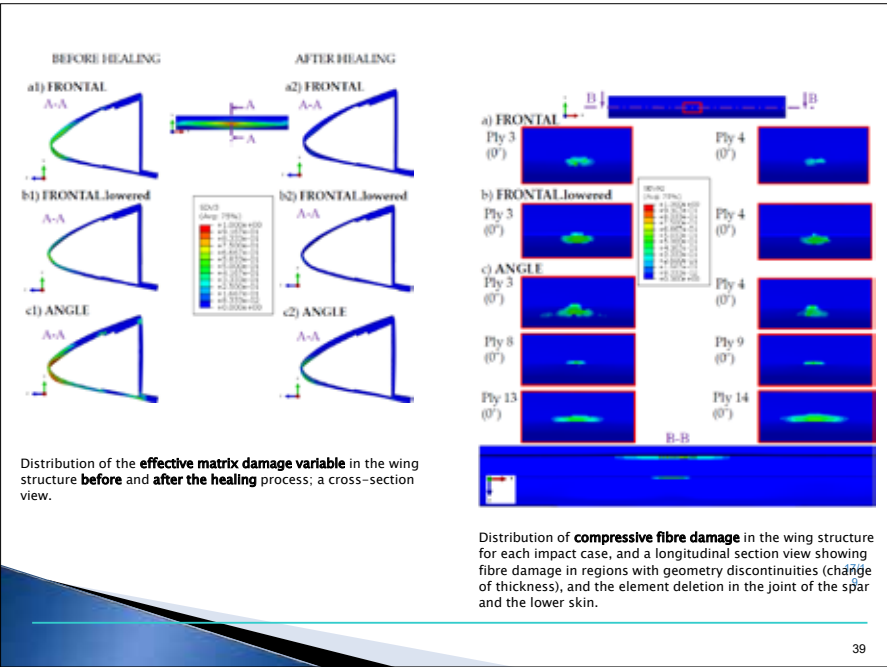
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Conclusions

- importance of accurate impactor modeling
 - impactor material behavior
 - numerical impactor model (CEL or SPH)
- realistic simulation of the structural behavior of aeronautical structures:
 - detailed finite element models
 - complex failure models
- wide range of problems: various impact velocities, material behavior and overall numerical approaches
- common elements: complex contact conditions
 - nonlinear and anisotropic material behavior
 - complex damage and failure models
- numerical methodology: Abaqus/Explicit & FORTRAN subroutines

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ivica.smojver@fsb.hr



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