

RELIABILITY-BASED DESIGN OPTIMIZATION OF GROUND VEHICLES

**2006 DoD Maintenance Symposium and Exhibition
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The University of Iowa

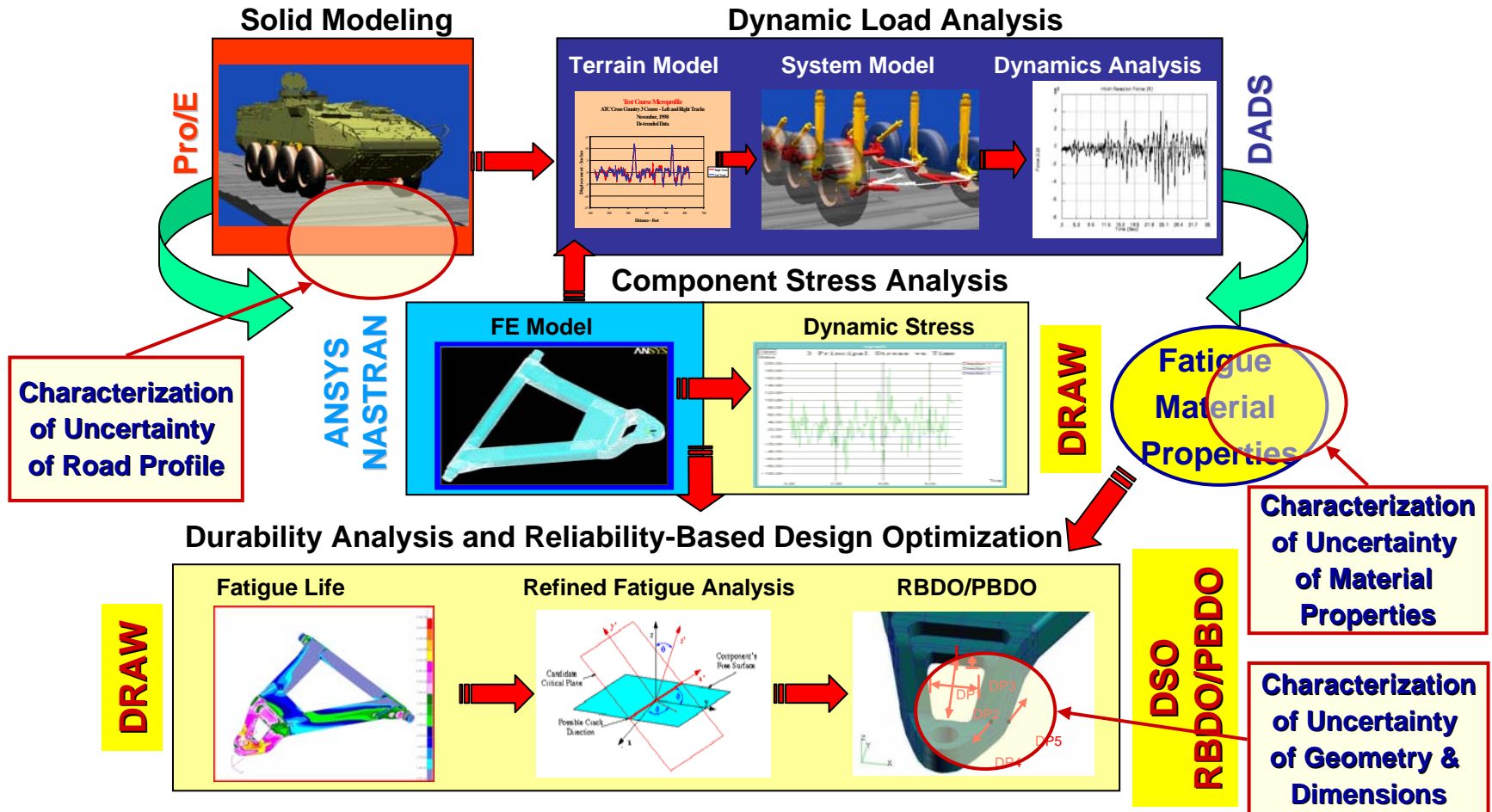
David Gorsich

UA Army TARDEC

MOTIVATION

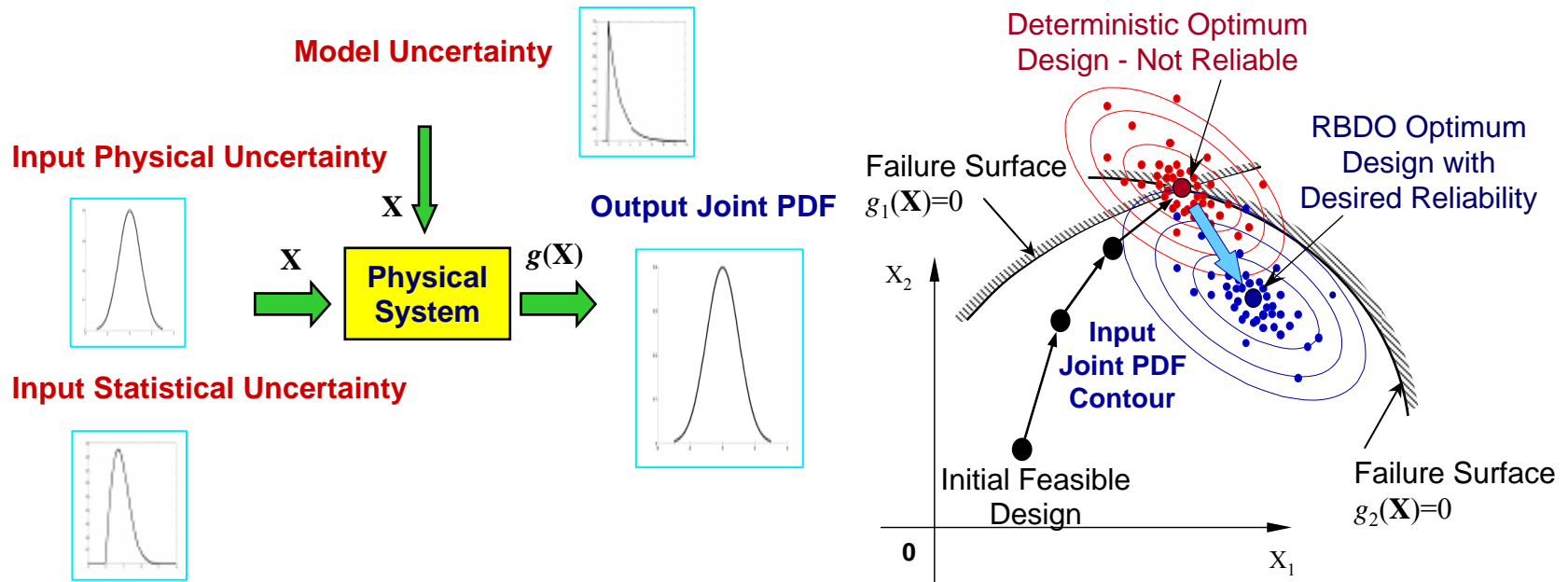
- Army Vehicles - **Rapid deployability, mobility, survivability, and sustainability.**
- Rapid deployability and mobility - **Lighter ground vehicles.**
- Sustainability - **Ultra-reliable components** that remain operationally effective for a sustained mission period with **minimal maintenance or repair.**
- Challenge - **Weight-minimized (or up-loaded) vehicles** would be much more **susceptible to manufacturing and operational variability.**
- **Reliability approach to design optimization** is required for **weight reduction initiatives (or up-loaded vehicles).**

ARMY VEHICLE DURABILITY OPTIMIZATION & RELIABILITY



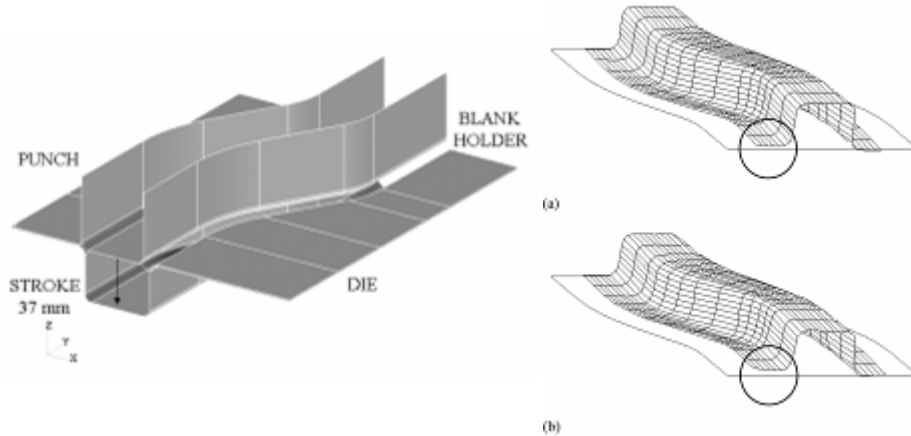
- How to Optimize the Vehicle Design to Minimize/Reduce the Weight?
- Under These Uncertainties, How to Achieve the Component Level Reliability?
- Under These Uncertainties, How to Achieve the System Level Reliability?

DESIGN OPTIMIZATION UNDER UNCERTAINTY



- Due to competitive demand, designs are pushed to the limit of the design constraints using **deterministic optimization**, leaving little or no room in manufacturing variability \Rightarrow Leads to higher manufacturing costs, which hinders product marketability.
- Uncertainty-based design optimization methodology provides not only optimum design, but also a reliability \Rightarrow **6- σ Design for Manufacturing**.

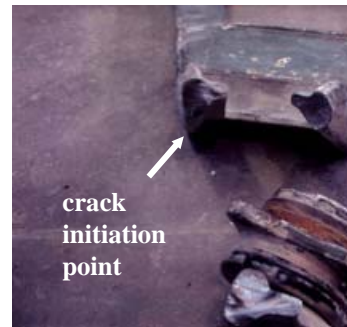
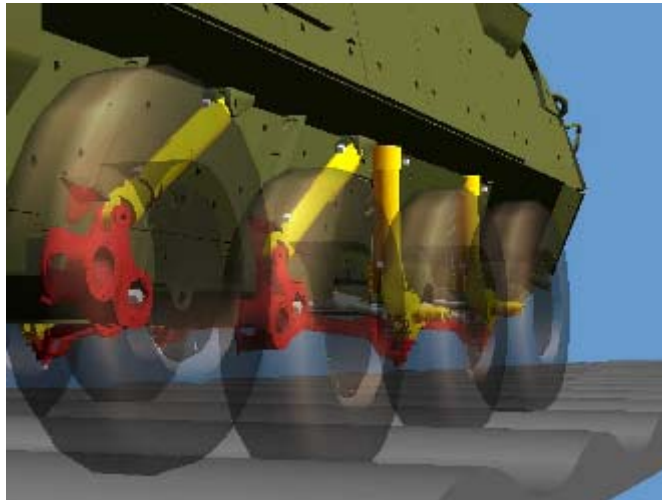
APPLICATIONS OF PROBABILISTIC METHODS AND RELIABILITY



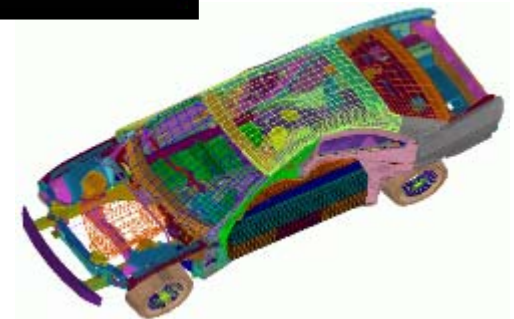
Manufacturing Process



Noise, Vibration, & Harshness

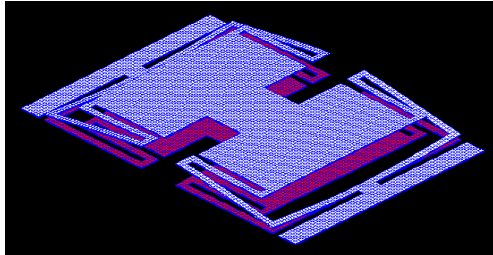


Durability



Crashworthiness

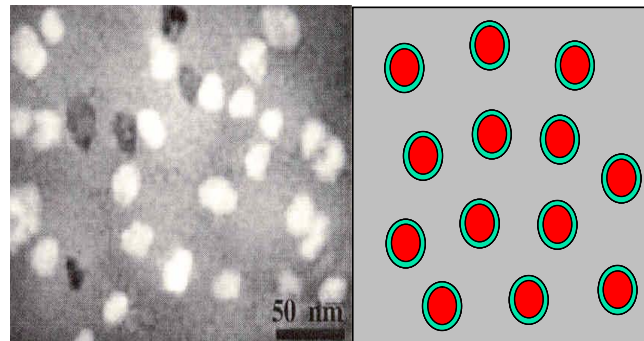
APPLICATIONS OF PROBABILISTIC METHODS AND RELIABILITY (cont')



Materials design to be an integral part of the system design process

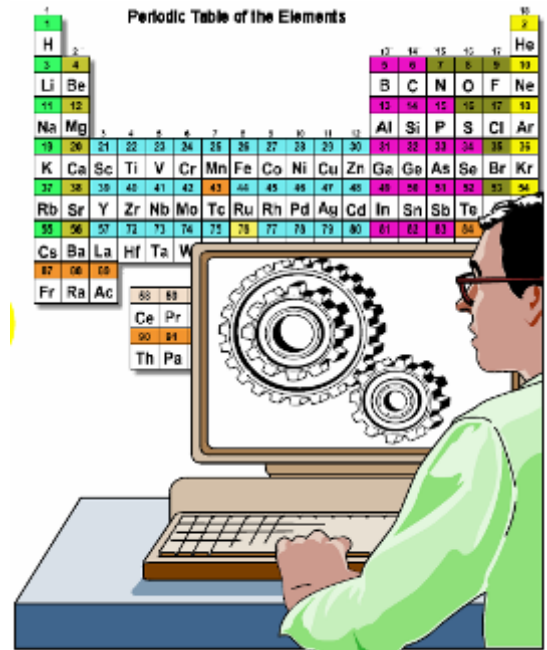
MEMS

*Smaller Scale
Requires More
Reliability!*

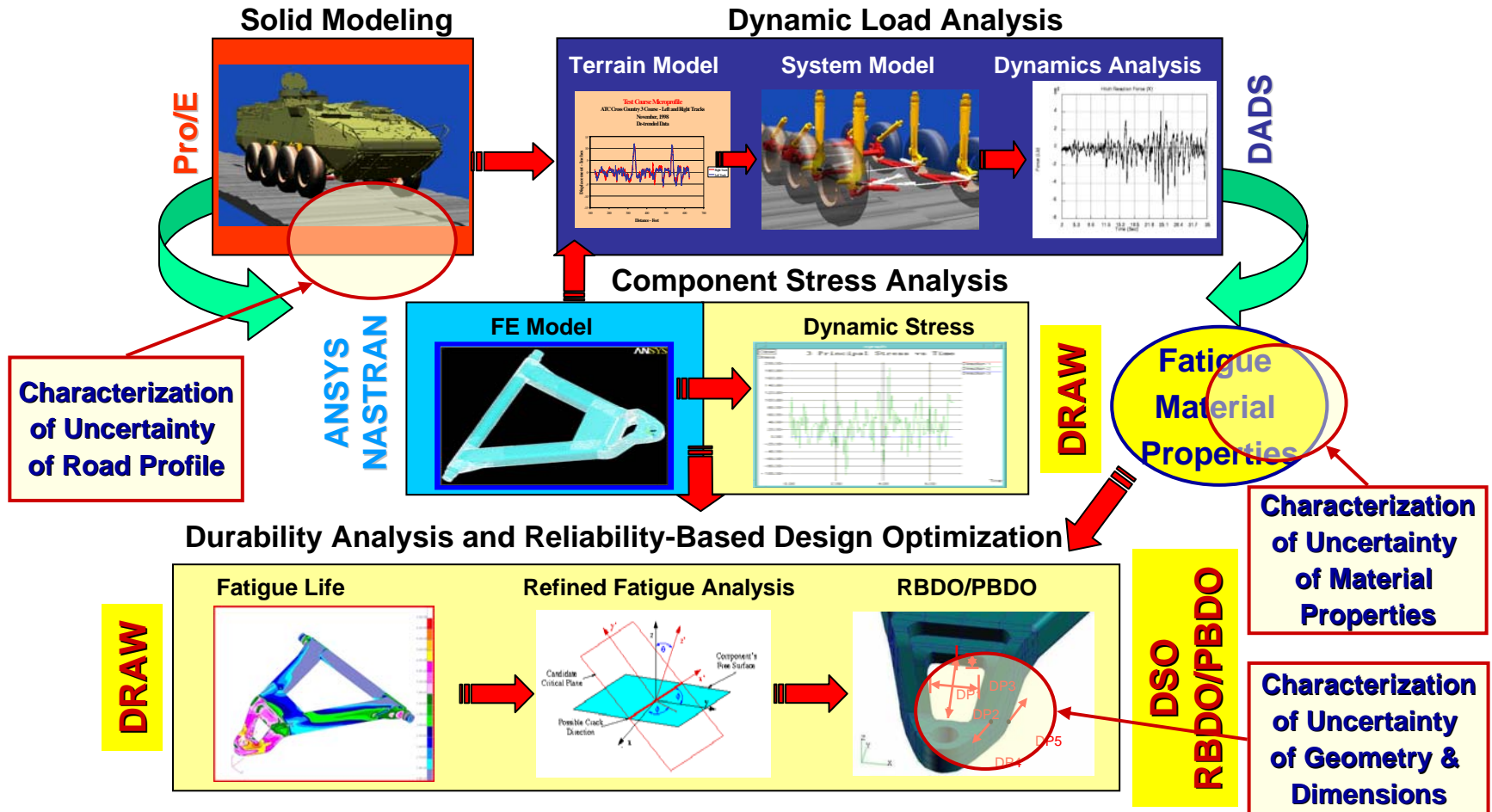


- = α -Al Single Crystal
- = solute enriched Al-Ni-Y
- = amorphous aluminum

New Materials
*Nano- & Micromechanics-
Based Material Modeling*



ARMY VEHICLE DURABILITY OPTIMIZATION & RELIABILITY

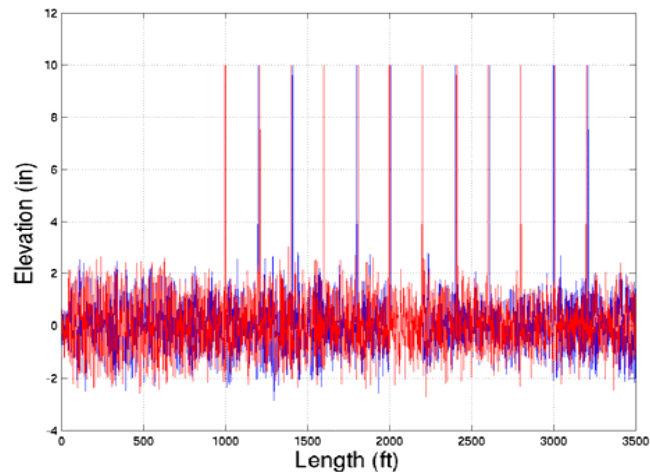


- How to Optimize the Vehicle Design to Minimize/Reduce the Weight?
- Under These Uncertainties, How to Achieve the Component Level Reliability?
- Under These Uncertainties, How to Achieve the System Level Reliability?

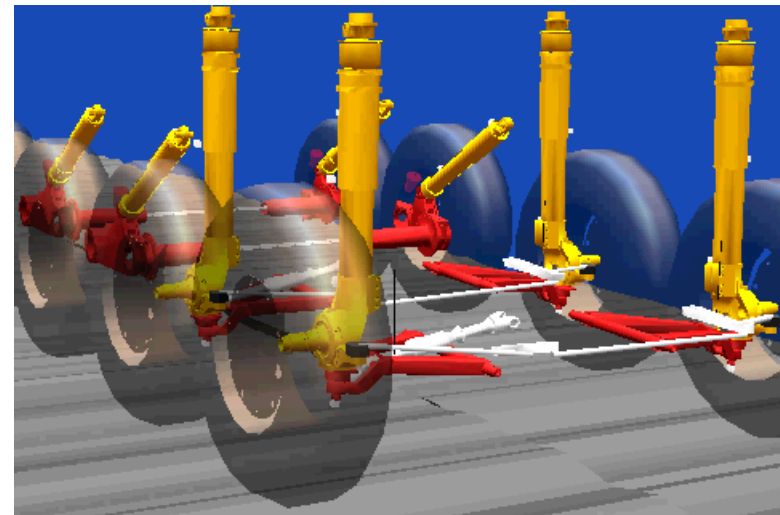
STRYKER DURABILITY ANALYSIS AND RBDO

Dynamic Analysis Used DADS

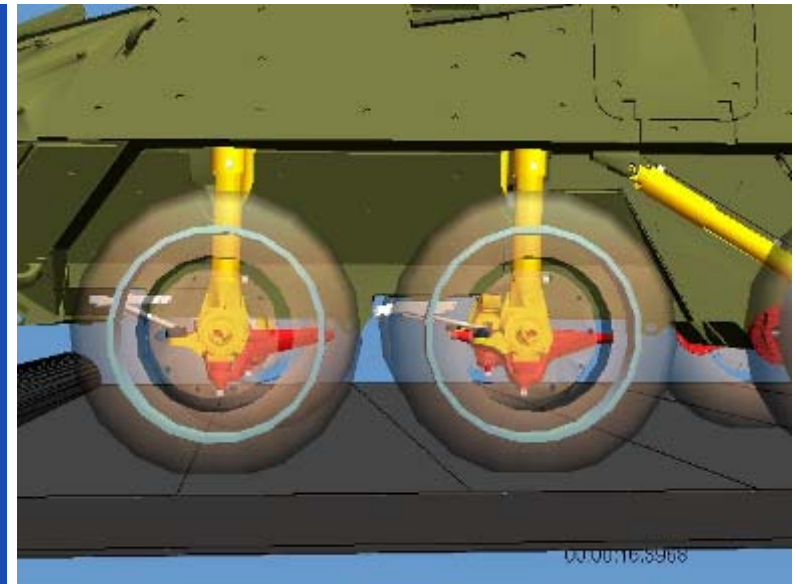
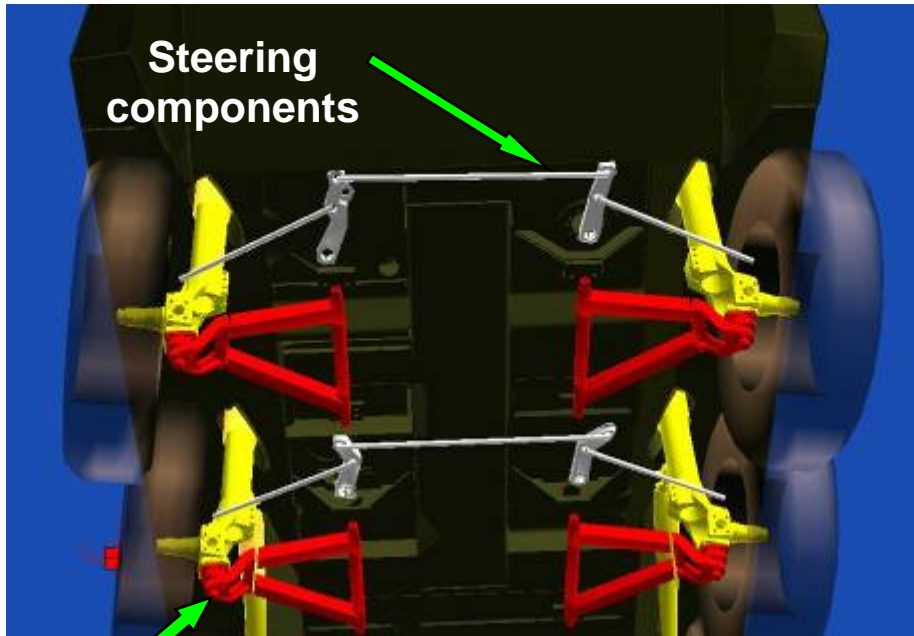
- Vehicle traversing simulated terrain
- Determines force/acceleration time history at all locations of vehicle
- Input into FEA & fatigue analysis



10"HR Terrain Profile

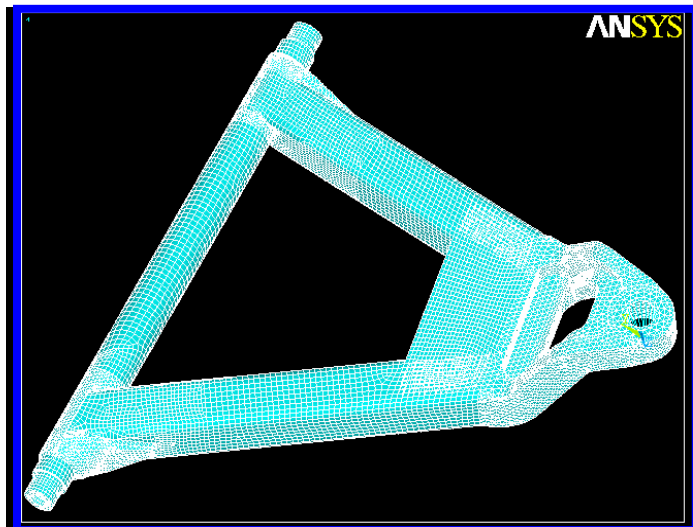


A-ARM & STEERING COMPONENTS



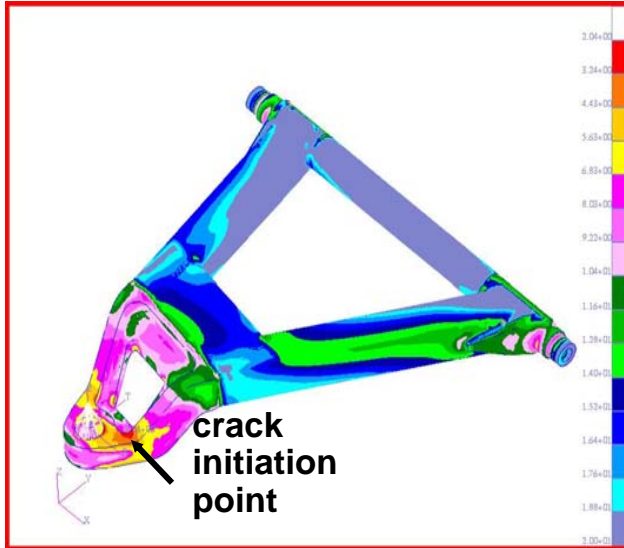
10"HR Terrain

A-Arm

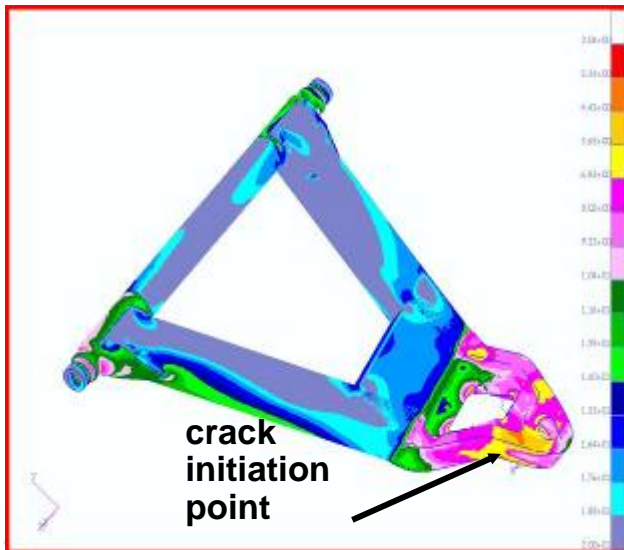
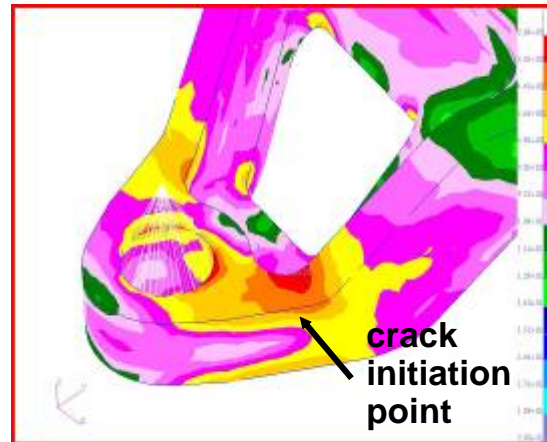


Number of Nodes	63,625
Element Type and Number:	15,751
Triangular Element	42,170
8-Node Solid Element	27,634
4-Node Solid Element	192
Rigid Beam	
Total Number of Element	85,747
Total Degree of Freedom	215,451

VALIDATION OF A-ARM FATIGUE FAILURE SIMULATION (10"H-R)



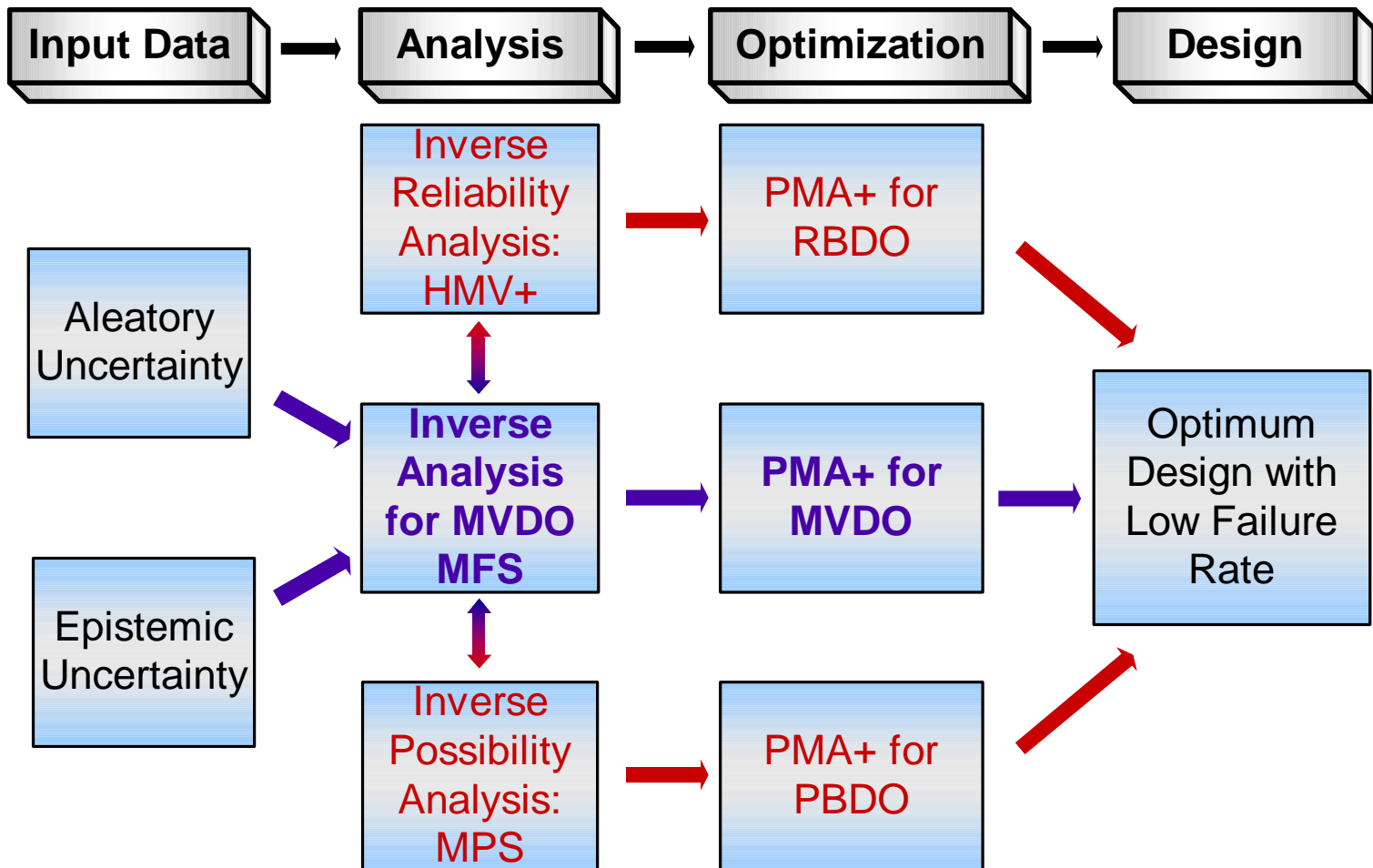
**Life Contour at
Critical Region**



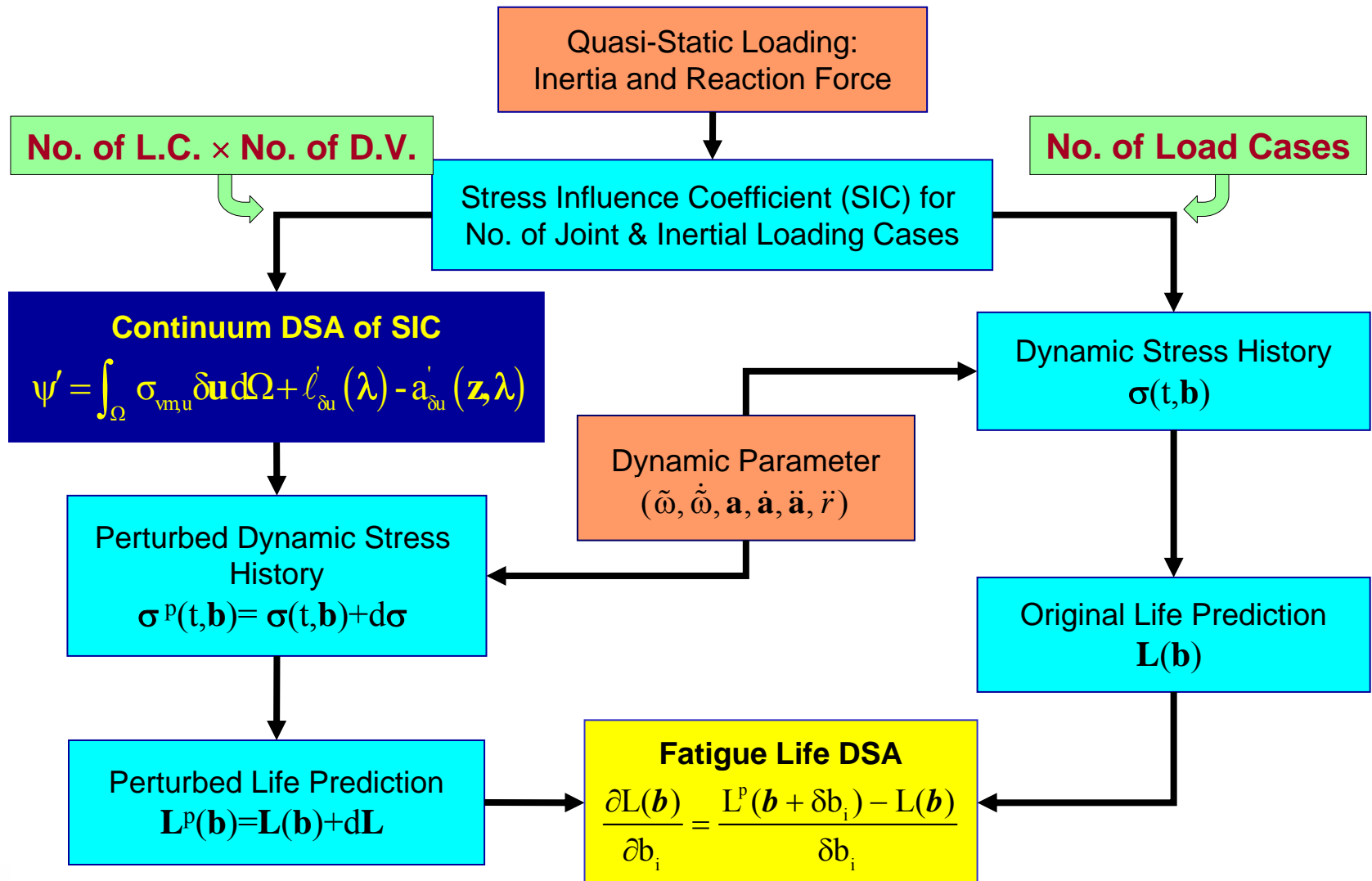
**Fatigue failure
simulations for three
terrains
(10HR, 6WB & BB)
identified hot spot at
the same location.**



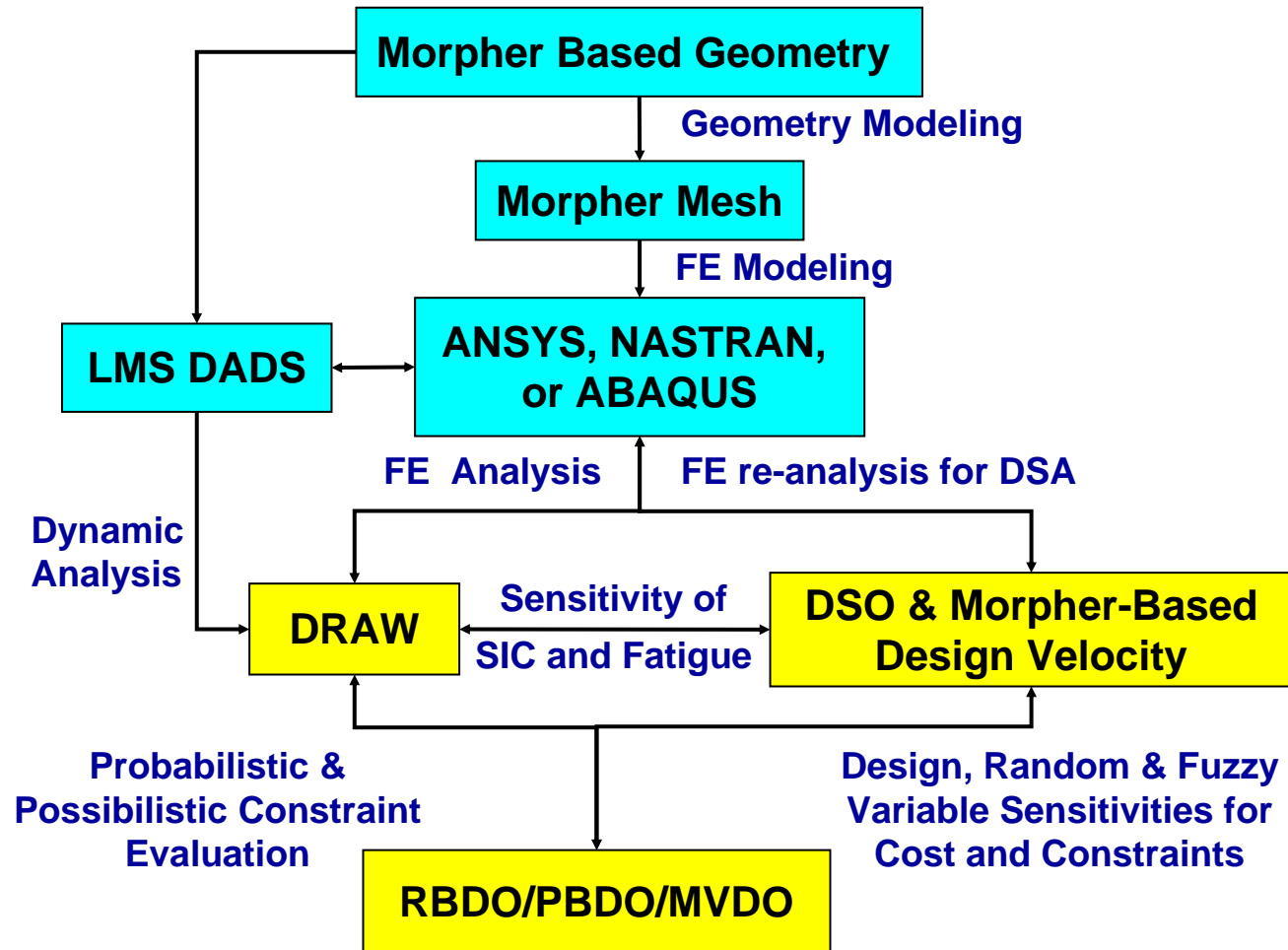
PMA-BASED RBDO, PBDO, & MVDO (INTEGRATED SOFTWARE SYSTEM)



DURABILITY SENSITIVITY ANALYSIS (DSO SOFTWARE)



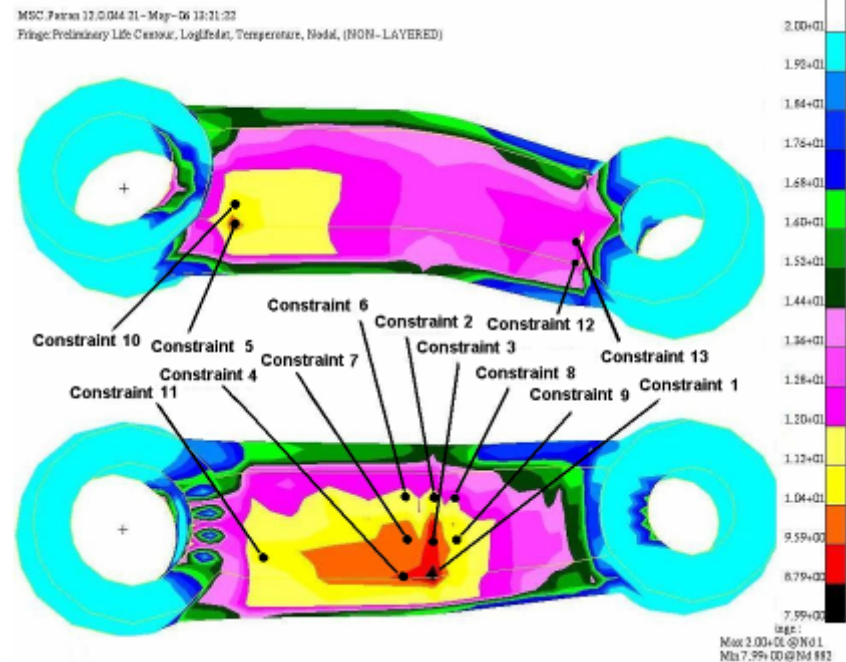
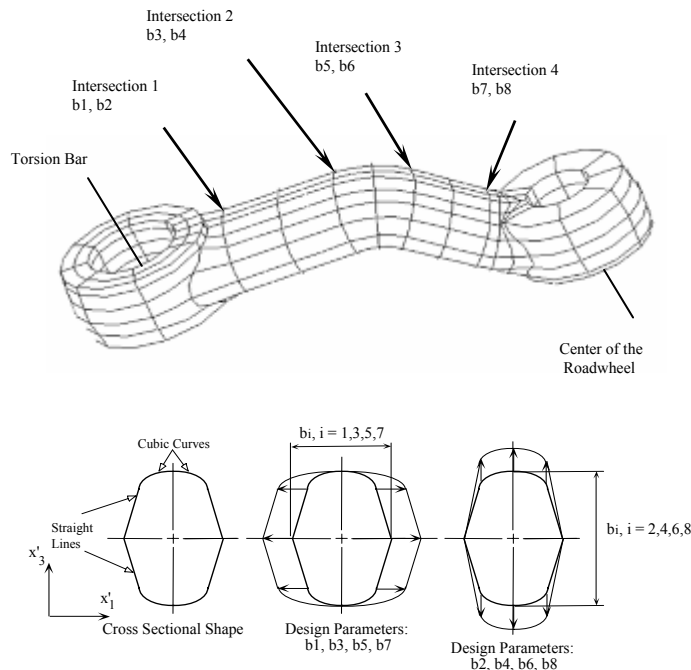
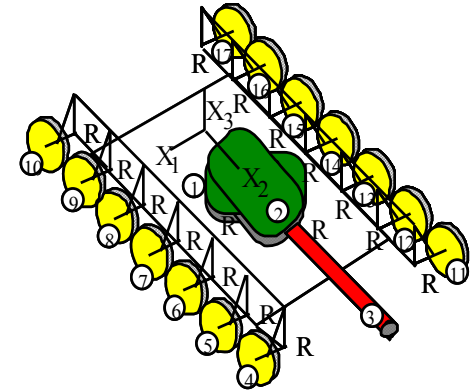
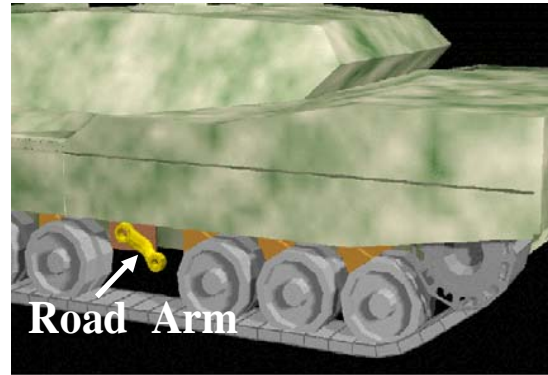
INTEGRATED DURABILITY RBDO/PBDO/MVDO SOFTWARE SYSTEM



Software Develop at Iowa

MORPHER-BASED RBDO, PBDO, & MVDO FOR DURABILITY OF M1-TANK ROAD ARM

- **Predict fatigue life** of tracked vehicle **road arm**
- **Use morpher-based shape design** parameterization for longer fatigue life with higher reliability using **RBDO, PBDO, and MVDO**



ROAD ARM RBDO, PBDO, & MVDO FORMULATIONS

Minimize Weight (\mathbf{d})

subject to $G_i(X) = 1 - \frac{L(X)}{L_t} \leq 0, \quad i = 1 \sim np$

$d_L \leq \mathbf{d} \leq d_U, \quad \mathbf{d} \in R^n$

$L(X)$: Crack Initiation Fatigue Life

L_t : Crack Initiation Target Fatigue Life (=5 years $\approx 7.9E6$)

RBDO Formulation

Minimize Weight (\mathbf{d})

Subject to $P(G_i(\mathbf{X}(\mathbf{d})) > 0) \leq \Phi(-2), \quad i = 1, \dots, 10$

$\mathbf{d}^L \leq \mathbf{d} \leq \mathbf{d}^U$

PBDO & MVDO Formulations

Minimize Weight (\mathbf{d})

Subject to $\Pi(G_i(\mathbf{X}(\mathbf{d})) > 0) \leq 0.02275, \quad i = 1, \dots, 10$

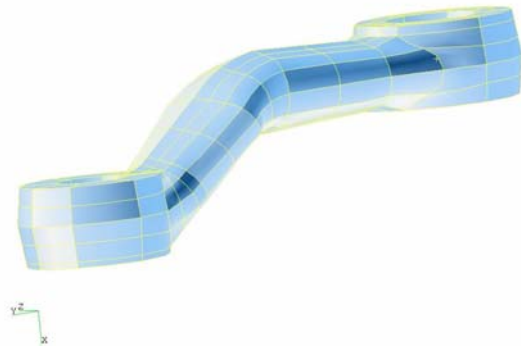
$\mathbf{d}^L \leq \mathbf{d} \leq \mathbf{d}^U$

Parameter	d_L	Mean	d_U	COV	
Design/Random/Fuzzy (Geometric Tolerance)	b_1, X_1	1.35	1.75	2.15	1%
	b_2, X_2	2.64955	3.24955	3.74955	1%
	b_3, X_3	1.35	1.75	2.15	1%
	b_4, X_4	2.57031	3.17031	3.67031	1%
	b_5, X_5	1.3563	1.7563	2.1563	1%
	b_6, X_6	2.43767	3.037671	3.53767	1%
	b_7, X_7	1.35166	1.75166	2.15166	1%
	b_8, X_8	2.50849	2.908494	3.40849	1%
	Fatigue Material	Mean	COV		
Random/Fuzzy (Material Parameter)	X_9	Cyclic Strength Coefficient, K'	197E3	3%	
	X_{10}	Cyclic Strength Exponent, n'	0.12	3%	
	X_{11}	Fatigue Strength Coefficient, σ'	177E3	3%	
	X_{12}	Fatigue Strength Exponent, b	0.073	3%	
	X_{13}	Fatigue Ductility Coefficient, ϵ'_f	0.41	3%	
	X_{14}	Fatigue Ductility Exponent, c	0.6	3%	

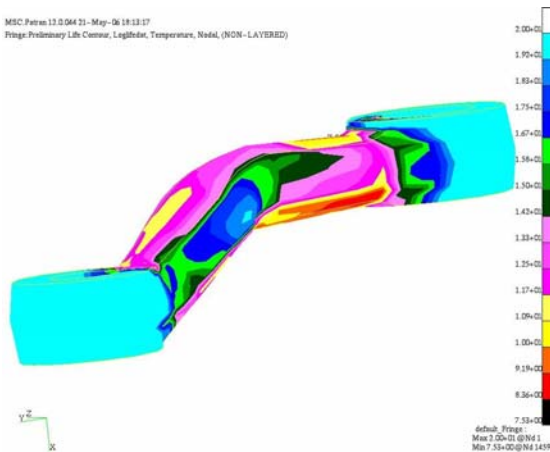
ROAD ARM DURABILITY RBDO/PBDO/MVDO RESULTS

	Initial	DDO	RBDO	PBDO	MVDO
d1	1.7500	1.5885	1.6811	1.7923	1.7637
d2	3.2496	2.6496	2.6496	2.6496	2.6496
d3	1.7500	1.9222	1.9542	2.0089	1.9842
d4	3.1703	2.5703	2.5703	2.5703	2.5703
d5	1.7563	1.4765	1.5404	1.6290	1.6053
d6	3.0377	3.2919	3.3658	3.5048	3.4353
d7	1.7517	1.6303	1.7290	1.8431	1.8145
d8	2.9085	2.5085	2.5085	2.5085	2.5085
Cost	515.093	464.563	476.191	492.436	487.040
Active Constraints IDs		1,3,5,8,12	1,3,5,8,12	1,3,5,8,13	1,3,5,8,12
NFE	1	11	97	272	172

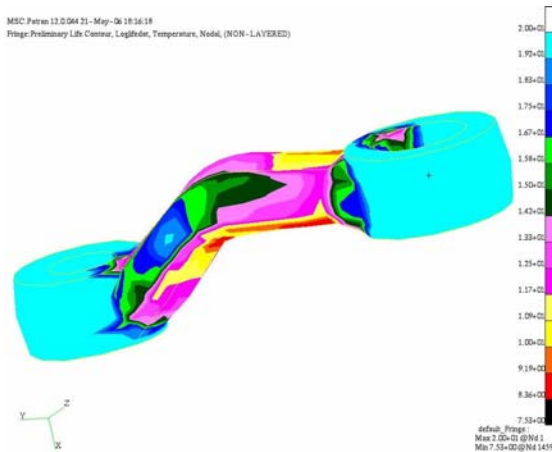
MORPHER-BASED RBDO OPTIMIZED SHAPE AND FATIGUE LIFE CONTOUR



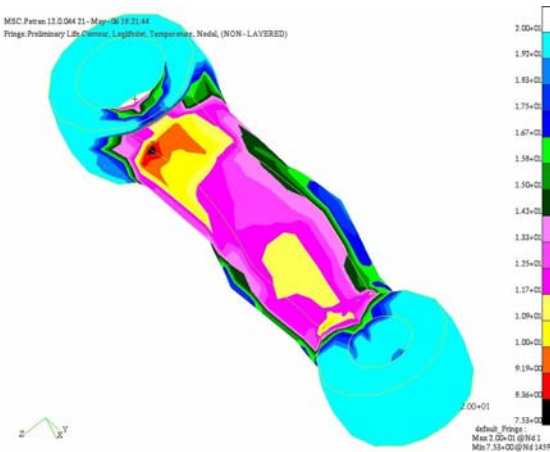
MSC Patran 12.0.064 21 - May-06 18:13:17
Fringe: Preliminary Life Contour, LogMidln, Temperature, Nodal, (NON-LAYERED)



MSC Patran 12.0.064 21 - May-06 18:16:18
Fringe: Preliminary Life Contour, LogMidln, Temperature, Nodal, (NON-LAYERED)



MSC Patran 12.0.064 21 - May-06 18:21:44
Fringe: Preliminary Life Contour, LogMidln, Temperature, Nodal, (NON-LAYERED)



HPC-BASED GROUND VEHICLE RELIABILITY PREDICTION AND OPTIMIZATION PROJECT

- Assessment of HMMVW A-Arm durability for up-armored HMMVW
- Parallelization of Durability Analysis, RBDO, PBDO, MVDO Processes
- Deterministic design optimization of HMMVW A-Arm and to improve durability for up-armored HMMVW
- RBDO/PBDO/MVDO of A-Arm for improved durability and reliability
- Validation of RBDO/PBDO/MVDO results using TARDEC's Physical Simulation Durability Testing Facility

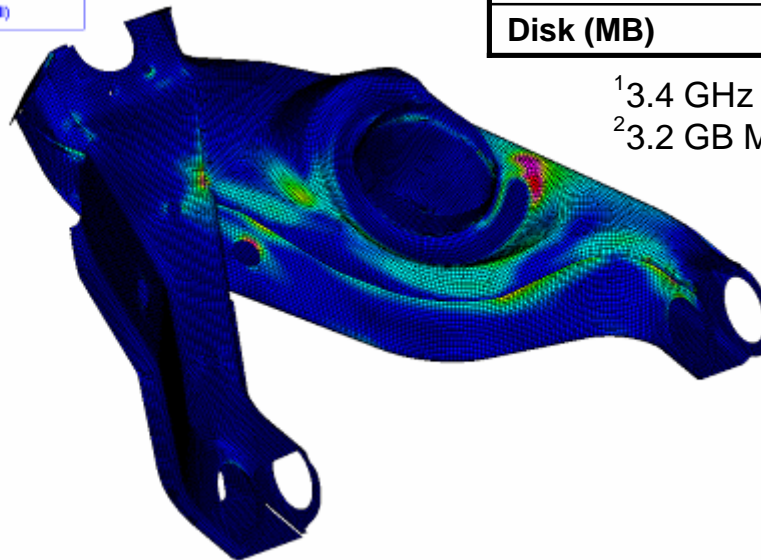
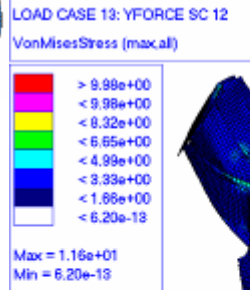
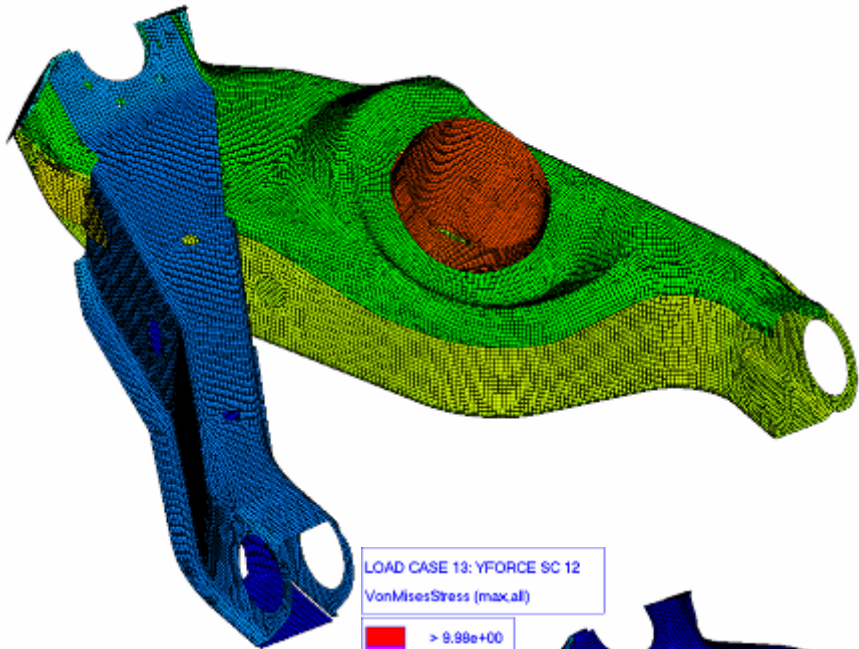
WHY PARALLELIZATION OF RBDO/PBDO/MVDO PROCESSES USING HPC?

- Each RBDO, PBDO, or MVDO design iteration requires an optimization process to carry out an **MPP search**. If we carry out **RBDO, PBDO, or MVDO for durability**, we may end up carrying out more than **100 iterations**.
- For the **Stryker A-arm** a typical **deterministic optimization** with **4 iterations** took about **3.55 days**.
- Thus RBDO of Stryker A-arm may very well require **$3.55 \text{ days} \times 25 = 89 \text{ days}$** of computation & I/O time.
- **Parallelization** of the durability calculation (**stress influence coefficients for load cases**), **DSA, RBDO, PBDO, & MVDO** Processes are very much desirable.

HMMWV MULTIBODY DYNAMICS



HMMWV A-ARM FEA MODEL



FE Information		
Nodes		54665
Elements	CBEAM	2
	CBUSH	3
	CQUAD4	13615
	CTRIA3	1997
	RBE2	1481
Parts		10
DOF		328K
CPU ¹ (second)		1min. 16sec.
Memory ² (MB)		86.2
Disk (MB)		1648.4

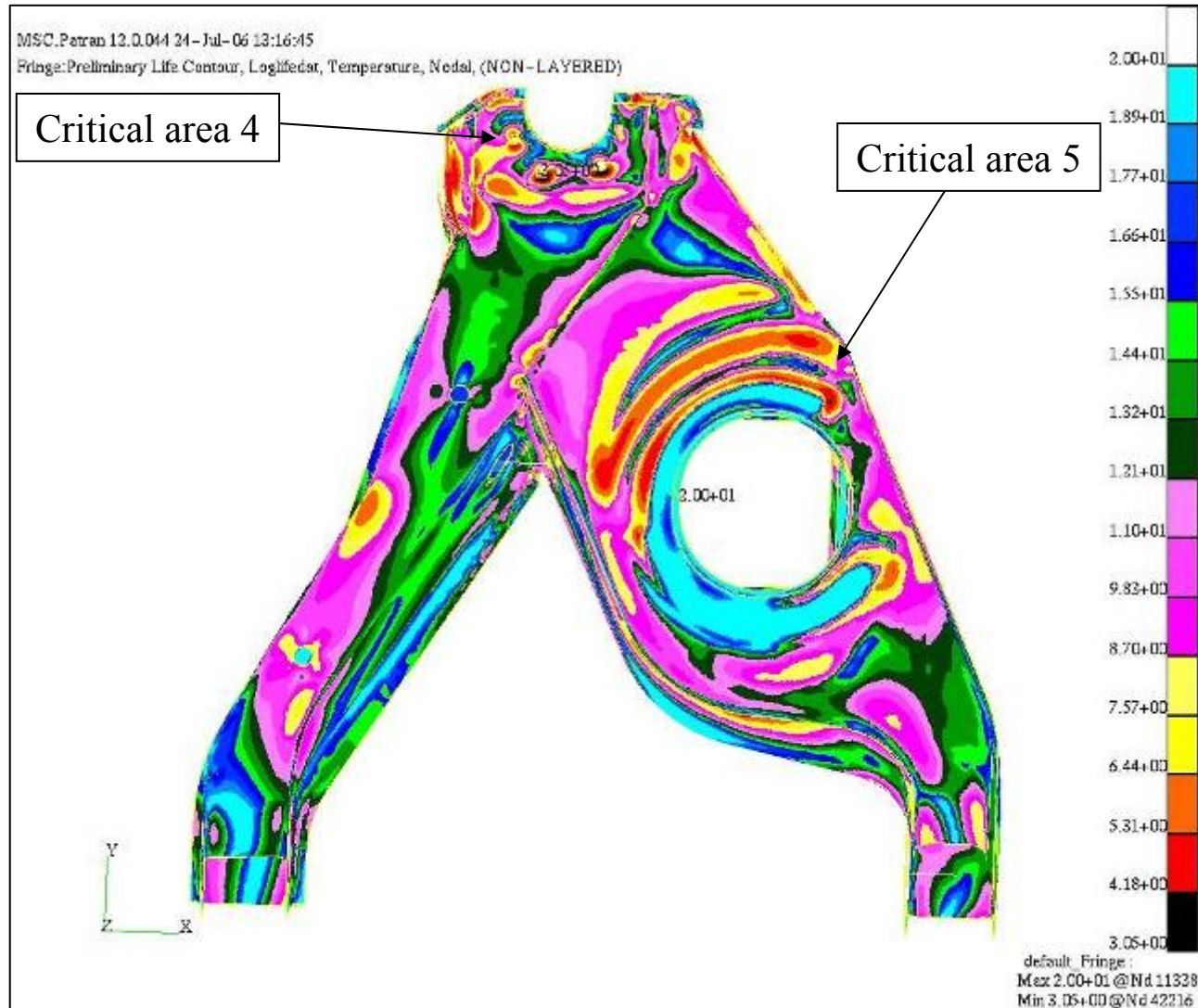
¹3.4 GHz Pentium 4 CPU

²3.2 GB Memory

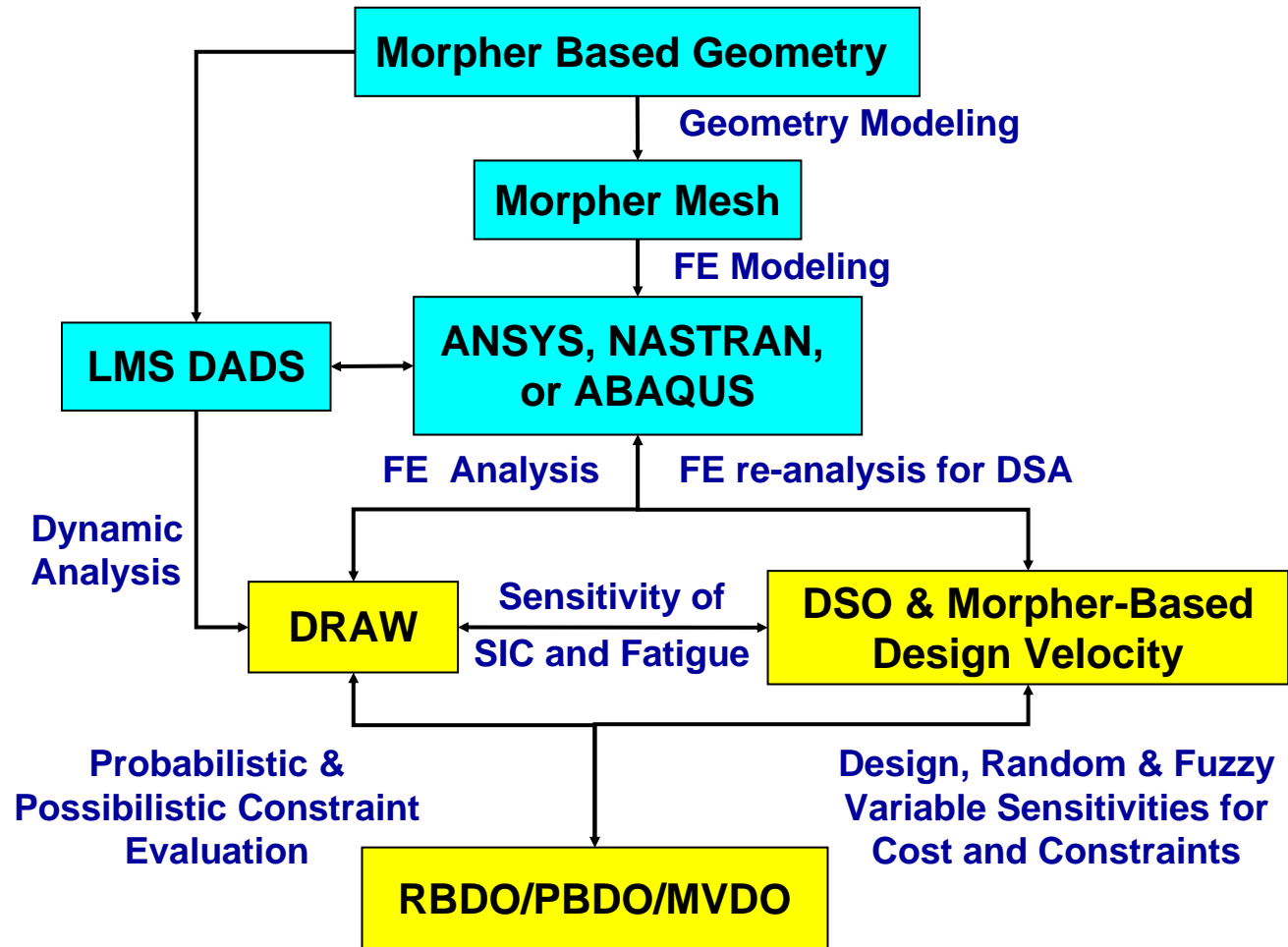
HMMWV A-ARM DRAW RESULTS

- Terrain: 10 in Half-Rounds
- 40 second blocks
- Configuration 1 Boundary Conditions: Constrain 6 degrees of freedom at wheel spindle joint.
- Configuration 2 Boundary Conditions: Constrain 6 degrees of freedom at rear bushing joint.
- Configuration 3 Boundary Conditions: Constrain 3 rotational degrees of freedom at wheel spindle joint, x and y translation degrees of freedom at rear bushing joint, and z translation degree of freedom at front bushing joint.

FATIGUE LIFE CONTOUR, CONFIGURATION 1



DELIVERY OF DURABILITY RBDO/PBDO/MVDO SOFTWARE SYSTEMS

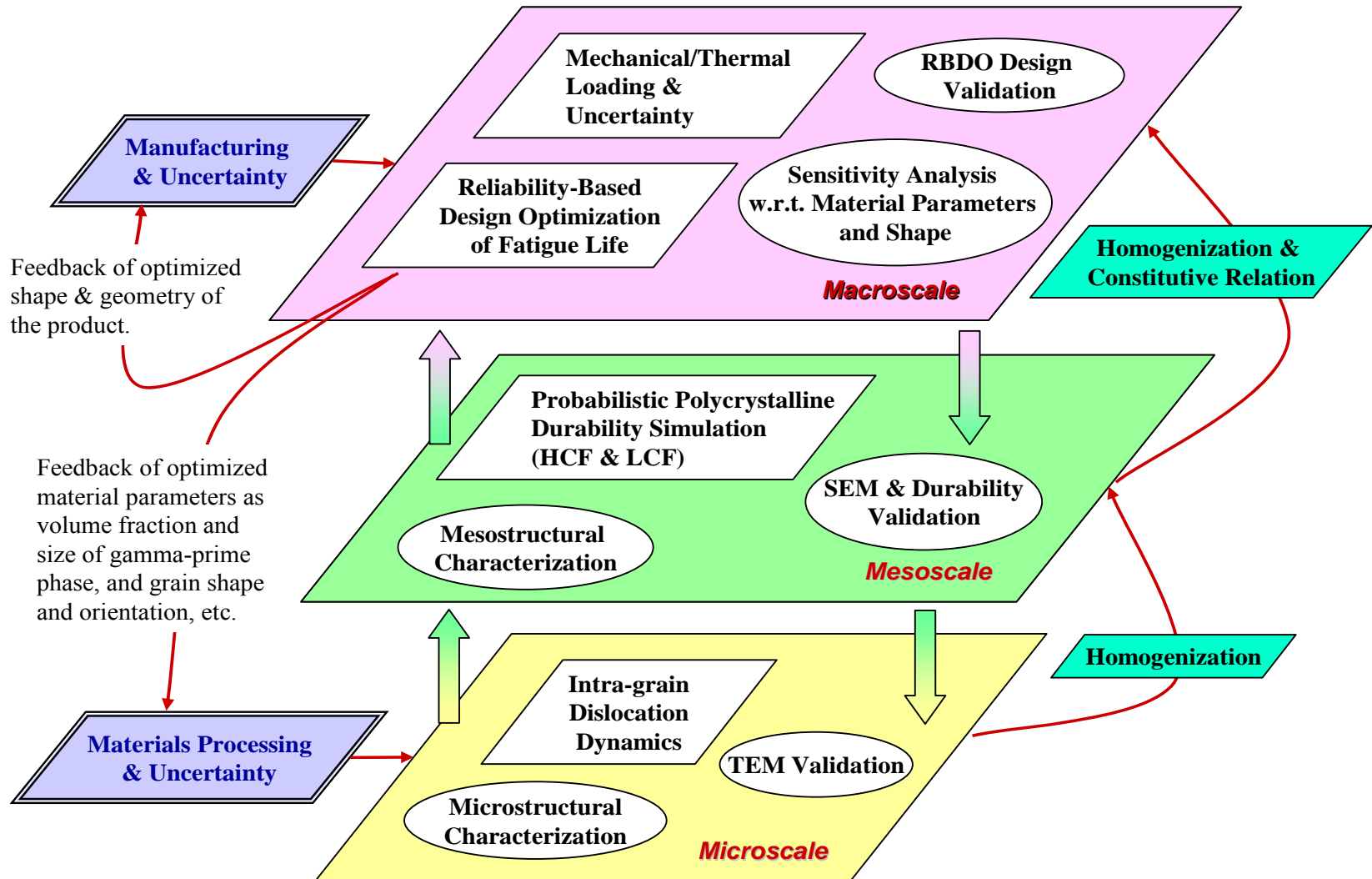


VALIDATION OF RBDO MODELS USING TARDEC'S DURABILITY TESTING SIMULATOR

- Pintle Motion Base Simulator (PMBS)
- N-Post Reconfigurable Simulator
- Vehicle Inertial Properties Evaluation Rig (VIPER)
- Data Collection & Correlation
- Model Validation



RELIABILITY-BASED MULTI-SCALE DESIGN METHODOLOGY FOR SUPERALLOY STRUCTURES



Feedback of optimized shape & geometry of the product.

Feedback of optimized material parameters as volume fraction and size of gamma-prime phase, and grain shape and orientation, etc.