

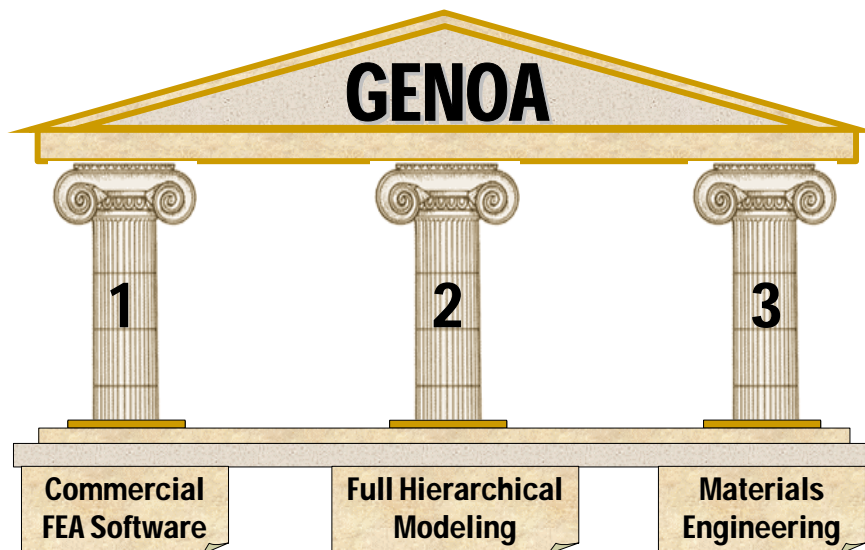
OVERVIEW OF GENOA ANALYSIS PROCESS

GENOA is an engineering software suite that augments commercial finite element analysis (FEA) packages by providing progressive failure analysis (PFA) capability. It can investigate structural responses to material degradation from damage induced by static, cyclic (low and high cycle fatigue), impact, power spectrum density (PSD) and thermal loading. GENOA-PFA also accounts for the effects of manufacturing flaws, residual stresses and the effects of moisture and temperature

A wide range of material systems can be handled, including metals, ceramics, and advanced composites. The latter include polymer matrix composites (PMC) and ceramic matrix composites (CMC). GENOA is unique in that it can analyze not only traditional 2-D tape and fabric laminate layups, but also 3-D weaves and braids. Different weave and braid architecture can be considered.

GENOA-PFA is based on damage tracking and material property degradation at the fiber matrix and fiber/matrix interface micro-scale levels, where damage and delamination have their source. Durability and damage tolerance (D&DT) determination, in the framework of structural fracture damage, is characterized by five sequential stages of damage/crack development: 1) initiation, 2) growth, 3) accumulation (i.e. coalescence of propagating flaws), 4) stable propagation (to a critical amount), and 5) unstable or very rapid propagation (beyond the critical amount) to collapse. GENOA's approach for structural fracture prediction in monolithic or composite materials formally quantifies all active fracture modes, the type(s) of flaws initiating active fracture modes, and the coalescing and propagation of fractures to critical dimensions for imminent structural fracture (failure).

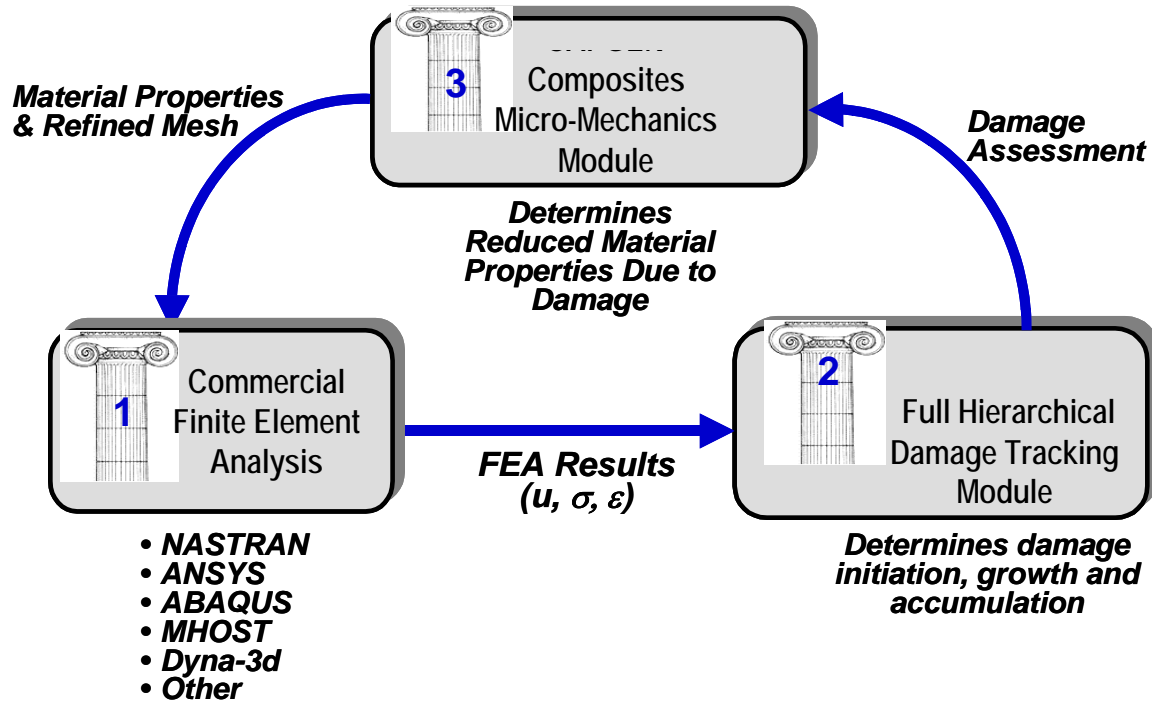
GENOA's architecture is founded on three primary pillars: 1) Commercial FEA software, 2) Full-hierarchical damage tracking and 3) Micro-mechanics material engineering theory.



The three pillars of GENOA

These pillars or modules are not isolated or static. They interact dynamically and continuously to characterize the progressive failure response of a structure. GENOA-PFA enables the user to

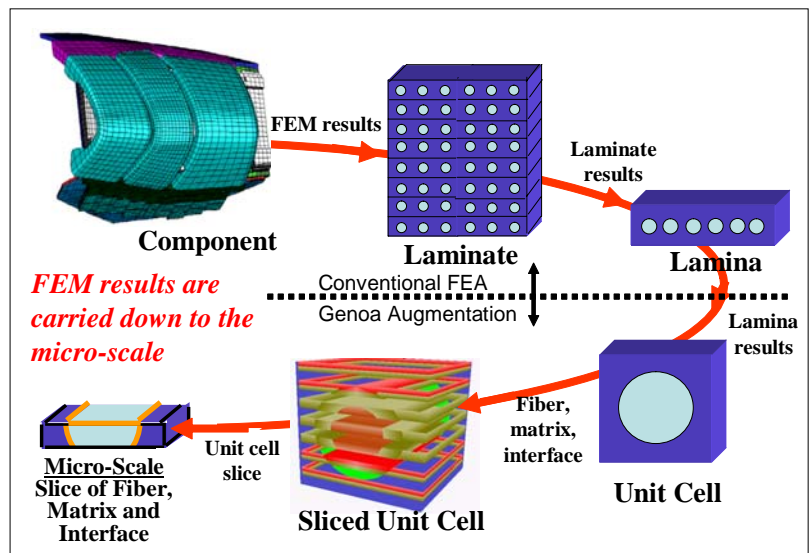
determine the location and load level of damage/fracture initiation, the damage/fracture propagation load history and geometry, and finally, the collapse or max load the structure can sustain and its service life expectancy.



GENOA's pillars continuously interact to track damage

GENOA has two other complementary pillars, namely optimization and probabilistic analysis. A GENOA user can utilize them perform structural life extension and uncertainty analyses.

Displacements, stress and strains, calculated at the macro-structural level by an FEA solution at each FEM node, are passed down to the laminate /lamina level using lamination theory. FEA analyses, not augmented with GENOA, traditionally terminate at this level, that is, they evaluate failure at the lamina or laminate scale. Failure, however, originates at much lower levels. GENOA goes down to the micro-level where failure starts. It augments FEA



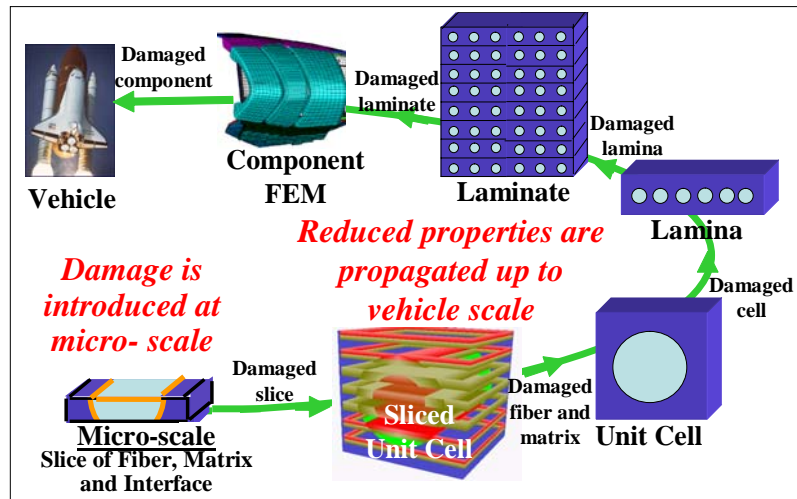
Full hierarchical modeling from vehicle-scale to micro-scale enables stresses and strains to be propagated down

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analysis with a full-hierarchical modeling that goes down to the micro-scale of sub-divided unit cells composed of fiber bundles and their surrounding matrix.

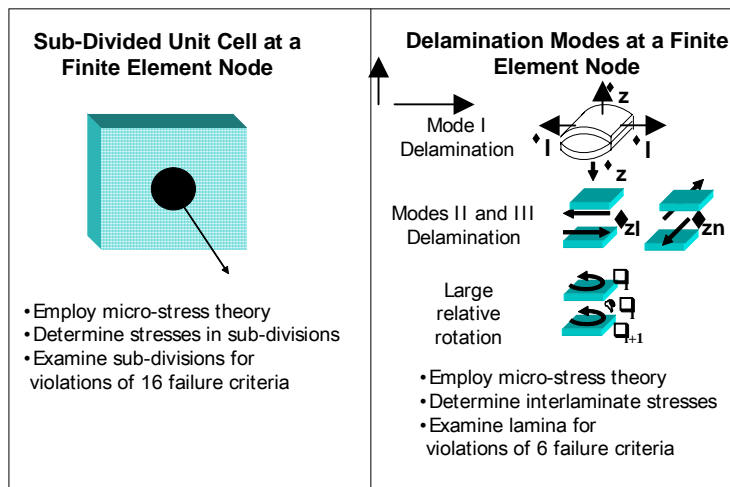
Stresses and strains at this level are derived from the lamina-scale using micro-stress theory. Unit cell subdivisions (small pieces of fiber, matrix, and fiber/matrix interface) are interrogated for damage using an extensive of failure criteria unique for fiber, matrix and interface failure/delamination.

When damage or delamination is found, a set of rules, based on materials engineering and experience, is applied to determine which fiber and matrix material properties to degrade. For composites two local damage tracking options are available: 1) ply level damage tracking and 2) fiber and matrix level damage tracking.



Reduced fiber and matrix properties, at the micro-scale, are propagated back up to the vehicle-scale

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Damage and delamination in sub-divided unit cell tracked at the micro-scale level

Micro-Mechanics Failure Criteria

1. Longitudinal tension	9. Strain invariant failure theory
2. Longitudinal compression	10. Normal compression
3. Transverse tension	11. Custom criteria
4. Transverse compression	12. Normal tension
5. In-plane shear (+)	13. Transverse Normal Shear (+)
6. In-plane shear (-)	14. Transverse Normal Shear (-)
7. Fiber strain limit	15. Longitudinal normal shear (+)
8. Modified distortion energy	16. Longitudinal normal shear (-)
	17. Relative rotation criteria

The diagram shows a list of 17 failure criteria. A red dashed box encloses criteria 1 through 8. A blue solid box encloses criteria 12 through 17. A red bracket on the right groups criteria 1-8 as 'Unit Cell Damage Criteria'. A blue bracket on the right groups criteria 12-17 as 'Delamination Criteria'. Criteria 9, 10, 11, and 16 are not grouped by either bracket.

GENOA has an extensive library of material failure criteria

As damage builds up in a unit cell, it may finally fracture. This means that a lamina, containing that unit cell, has failed at a particular node of the finite element model. When all the laminae at that node fail (i.e., laminate failure), the node is then said to have “fractured”.

Because damage is tracked at the micro-scale, it is quite possible that at a node different types of damage may occur. For example, there may be matrix cracking and fiber breaking in the same lamina and, in fact, in the same unit cell. It is important to keep this in mind when examining the details of damage initiation, accumulation and growth.

The damage tracking process is iterated, increasing the load incrementally, until, the macro-structure can no longer sustain any load increase. At that point the structure has reached “final failure”.

It is this detailed level of analysis, provided by the GENOA augmented FEA, that enables remarkable accuracy at local and global levels. GENOA can thus answer the critical questions,

- **When** failure occurs?
- **Where** failure occurs?
- **Why** failure occurs?
- **What** can be done to avoid premature failure?