# A compilation of questions about the GENOA code

**Prepared for:**
**By**

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# Frequently Asked Questions about the GENOA Code

## General

**Q1 –Describe GENOA Analyses Capabilities**

**A1 – Durability and Damage Tolerance, Reliability, Virtual Testing, of metals, polymer and ceramic matrix composite**

**A2-Virtual manufacturing of Composite lay up, and filament winding process**

**Q1 –Does GENOA performs analysis of full structure**

A1 –Yes GENOA is capable of simulating the very large structure and it's constituents.

**Q1 – What is the capability of GENOA on types of structural- analysis**

A1 – *GENOA can presently perform: static, dynamic, fatigue, creep, impacts, analysis under thermo-mechanical loading conditions. GENOA also can perform Random Vibro-acoustic analysis in time or frequency domain power spectrum density (PSD) analysis.*

*Q2 –what is the capability of GENOA in material analysis*
*A1- GENOA can perform micro-mechanical modeling of material constituents (i.e. fiber, matrix, and interface)*

**Q1-Are any support libraries required for running GENOA on the PC (OpenGL, etc)?**

***A1****-No. The software is self-contained. GENOA-PC utilizes a commercial code called View kit (that integrates all modules for execution on all platforms). View kit is self-contained and utilizes libraries: 1) NUTCracker, 2) Reflection X (X emulator), and 3) Open GL graphics.*

**Q-What kind of user documentation will be provided for modeling, analysis and post processing capabilities?**

***A-****Documentation includes 1) a User's Manual, 2) a Theory Manual, and 3) a Verification Manual.*

**Q-Was the GENOA software developed under NASA funding? What was the agreement of the development, and what rights does NASA have to GENOA?**

***A****-In Part. The GENOA software was developed under NASA/GRC-STTR/SBIR, NASA/ATP, and NASA/LARC-CSB two years contracts, and Alpha STAR internal funding. The software has been verified extensively under Boeing ACT, ABL Honeywell High Temperature combustor, and Boeing X37 programs. Alpha STAR internal funding was the result of General Electric contract, to create the manufacturing module, The software has been enhanced under maintenance and service funding provided by NASA whitesands and the industry.*

**Q2-Has software been verified to a specific Software Integrity Level?**

***A2****- Yes, the software has been verified to all levels of software integrity using the Software Control System (SCS).*

**Q3-Did development and verification conform to IEEE standards?**

***A3****-Yes. The conformance to standard is based on open software foundation (OSF) specifications. Binary files can be read (from one type of workstation to another) according to IEEE standards*

**Q-Is it practical to use NASTRAN as the analysis engine, rather than using the GENOA FEM module? If this is done, are numerous features lost and analysis efficiency reduced? Is the export to NASTRAN simply for static analysis for verification, etc., and not meant for progressive failure analyses?**

***A1****- There is no plan to use NASTRAN in place of the current GENOA FEM solver. GENOA and NASTRAN can be used in a complementary manner for verification purposes.*

***A2****- Yes, capability may be lost: 1) through the thickness integration, 2) Random Crack propagation, and 3) transverse shear computation.*

***A3****- Full translation capability between NASTRAN and GENOA exists. NASTRAN can be used for static analysis of GENOA generated (intermediate mesh and degraded material properties) files and for* *verification purpose only.*

***Q*-Can the model be provided to GENOA in PATRAN or ABAQUS form?**

***A**-The GENOA translator can read PATRAN neutral, NASTRAN bdf, COMET-AR, COSMOS input, and ABAQUS translation files.*

**Q-Does GENOA have pre- and post-processing capabilities?**

***A**- Yes. GENOA utilizes a pre-processor to set up the input data, post processors to: 1) output data, 2) animate output, 3) produce far field stress/strain, and energy release rate plots.*

## Modeling

**Q-What information is needed to set-up the finite element model?**

***A**-A commercial FEM model (i.e. NASTRAN) may be used to get started. A typical FEM (i.e. nodes, elements, boundary conditions, and multi point constraint) is enhanced by the GENOA graphics user interface to include: 1) composite ply schedules, 2) fiber/matrix/interface or lamina properties*

**Q-What are the similarities between GENOA and ICAN?**

***A**- ICAN is part of GENOA. GENOA utilizes composite micro mechanics codes, such as ICAN, as subroutines to distribute loads the FEM level to the micro-mechanics level.. Presently there are available three micro-mechanics subroutines that take into account the complexity of micro-mechanics modeling. Also the ICAN subroutine has been enhanced to include the modeling of 1) three-dimensional fiber architecture, 2) honeycomb structure, 3) stitched and woven fiber architecture, and 4) fiber/matrix interfaces.*

## Finite Element Analysis

**Q-What element (3D elements, shell element) libraries are available in GENOA?**

***A**- GENOA utilizes NESSUS/MHOST/MINUTES FEM codes that have extensive libraries of elements. GENOA progressive failure analysis module only utilizes 3D 8-noded brick and thick shell elements at the moment.*

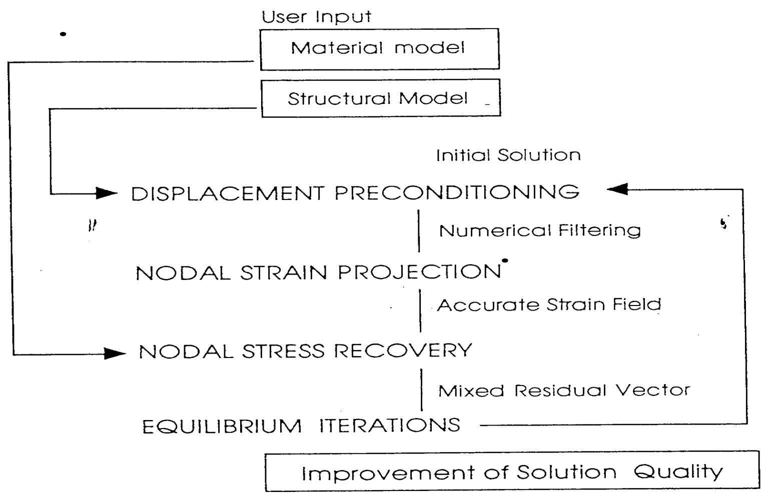
**Q-Can you provide brief explanation or references for a nodal based finite element code? What is the basis of this formulation? Is the basis virtual work, a mixed variational principal or something else?**

**A1 – The reference s for the nodal based FEM is not new. It was developed throughout years as the iterative algorithms to develop continuos stress field such as CANTIN, Loubigang, Touzot (1978) can be identifed as mixed finite element method. Also further development by Zienkiewicz, Violtte, Nakazazawa, Toyoshima (1984).**

*A-2 The global-local analysis procedure referred to as subelement refinement is developed under the frame work of mixed iterative solution*

- *Algorithmic description of the mixed iterative method includes variations for the quasi static, transient dynamic and buckling analysis*
- *The iterative solution algorithm is similar to Newton approach for non-linear finite element calculation:1) initiation, 2) nodal displacement update, 3) strain projection to the nodes, 4) stress recovery at the nodes, 5) form the residual*
- *Reference under contract No. NAS3-23697 Volume I –theoretical manual.*

| | |
|---|---|
| | *1. Create displacement stiffness equations*<br>*2. Nodal strain calculation by* |




*mean square projection (eliminates numerical instability of stress/strain approximations such as spurious oscillations*

3. *The inelastic material models are incorporated in the nodal stress integration*
4. *The improvement is brought back into displacement FE equations through equilibrium iteration loop)*
5. *Iterative quasi Newton update improves solution method*
6. *Local stress due to embedded singularities such as holes, cracks is solved by subelement scheme*

***Figure 1: Fundamentals of the Mixed Iterative Process. From Mixed Variational Principals***

*A-3 The variational formulation and solution algorithms are derived from the mixed three-field HU-Washizu principal. The formulation enables the use of node interpolation for coordinates, displacements, stress, and strain.*

*A-4 mixed variational principle, and defaults to displacement method. The code utilizes a novel concept of computing nodal displacements and stresses simultaneously, based on the mixed iterative solution technique (Figure 1).*

**Q-What is the element topology including number of nodes and number of integration points in-plane and through-the-thickness**

***A1****- A library of simple and efficient iso- parametric elements are included. The GENOA PFA recommended element selections are :1) four noded shell element- isoparametric shell element derived from the Reissner-Mindlin theory for plates and shells, involving six degree of freedom per node. Eighrt generalized strain components are defined at the node with respect to the local cartesian coordinates system. The first three are membrane, the fourth and fifth components are transverse shear strains, and the last three components are curvarture strains. The generalized stress components associated with these entries are:* $N_x, N_y, N_{xy}, Q_{xz}, Q_{yz}, M_x, M_y, M_{xy}$

***A2****- There are five through the thickness integration points available. The thermal gradient input can be represented in the property setup using these five points.*

**Q-How are the transverse stresses computed?**

*A- Out-of-plane normal and shear ply stresses are computed from equilibrium equations.*

**Q-How do you handle step changes in thickness where stresses are discontinuous?**

***A****- Step changes for fillets, drop-offs are presented as duplicate nodes occupying the same or adjacent* *locations in space, depending on the geometry of the discontinuity. Stress discontinuity and changes are utilized in GENOA. Methods to filter certain components of strain and project the element discontinuous quantities to the nodes are developed for a family of linear elements.*

**Q-Explain the constitutive modeling used in GENOA**

*A- GENOA utilizes the micro-mechanics based ICAN code (temperature, moisture, cyclic, constant stress, frequency, and amplitude) constitutive modeling.*

**Q-How are stitches handled in the stitched/RFI material?**

***A**-Stitching is modeled in the GENOA composite micro-mechanics module (enhanced ICAN/CEMCAN). A stitch card is used to represent the angle, and type of stitched material**.** The S/RFI composite is divided into a series of unit cells with both the fiber and stitch segments idealized as linear in the unit cells. A modified PMC3 module computes S/RFI stress limits by adding the oriented contribution of each stitch to each strength (longitudinal or transverse tension, compression or shear) component by tensor transformations in the absolute value.*

**Q-Is GENOA capable of conducting a linear buckling analysis? If so, what approach and what eigen solver is used? Can GENOA be used to predict damage progression in a buckled panel?**

***A1**- Yes,* GENOA capable of conducting a linear buckling analysis

***A2** GENOA utilizes subspace iteration procedure to solve the generalized eigenvalue problem. The subspace iteration method is presented in terms of the eigenvalue problem: 1) initial trial vector, 2) solve for the subspace vector, 3) construct a reduced eigenproblem, 4) solve the reduce eigenproblem, and 5) obtain the improved eigenvectors.*

***A3**- Yes. GENOA can be used to predict damage progression in buckled/postbuckled problems*

**Q-Is failure based on continuum damage mechanics or fracture mechanics? The documentation seems to indicate 'cracks' are damage zones that have equivalent crack fracture parameters. Is this so?**

**A1 Failure is based on continuum damage mechanics. New development also considered fracture mechanism formulation**

*A2. cracks are not damage zones and they do not have equivalent crack fracture parameters. GENOA defines the damage as: 1) matrix, 2) fiber,3) interface, 4) ply failure. Crack is defined as a node failure (a cumulative representation of all the damaged parameters.*

**Q-How does Damage Energy Release Rate or Strain Energy Release Rate play a role in damage propagation? Explain their role in the analysis. Are these post processing quantities only? They don't seem to be used during the analysis. Can you provide a simple example and walk through the steps as to how these parameters are used to indicate fracture initiation, stability, and global failure**? NEED A3 A4

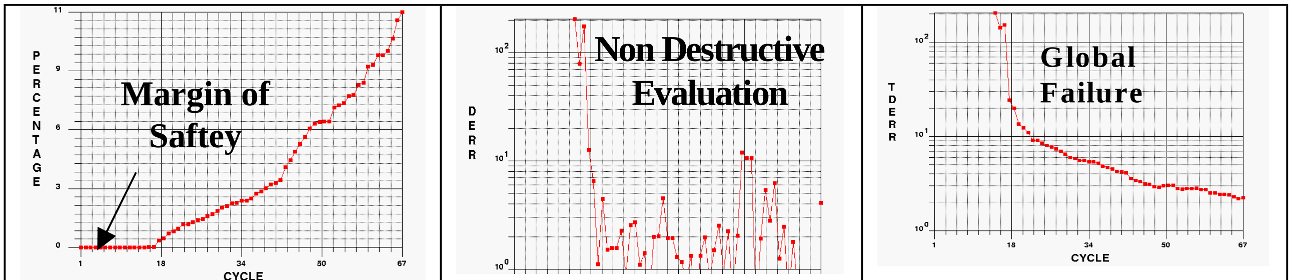
*A1- Damage Energy Release Rates or Strain Energy Release Rates do not play a role in damage propagation.* Assessment of failure with exhaustion of energy is reflected by maximum and minimum values. A local maxima (stick point) represents a build up of energy and initiation of damage in a composite structure. Typically, at the stage of damage initiation, there is a high rate of energy release that dissipates a significant portion of the strain energy stored in the structure. A local minimum (slip point) represents the end of fracture stability in a damaged composite under the applied loading.

*A2- Damage Energy Release Rates or Strain Energy Release Rates are generated by the code and are used to predict critical damage events for monitoring purpose only.*

*A3 – Yes the energy release data are only used as post-processing quantities only*

*A4-* In addition to the 14 failure conditions *Damage evolution metrics* calculates five functions as follows: 1) Percent Damage Volume versus Load – representing margin of safety (Figure 1(a)), 2) Damage Energy Release Rate (DERR) - representing acoustic emission, and inspection, and non destructive evaluation (Figure 1(b)), 3) Total Damage Energy Release Rate (TDERR) - representing global failure (Figure 10(c)), 4) Strain Energy

Damage Rate (SEDR), 5) Equivalent Fracture Toughness (Figure 10(d)). *1*The measure of global fracture toughness is defined in terms of the TDERR, a scalar damage variable that is equal to the amount of damage energy expended for the creation of unit damage volume in the composite structure. The magnitude of TDERR varies during progressive degradation of the composite structure under loading, reflecting the changes in the fracture resistance of the composite. The TDERR function is useful for assessing the overall degradation of a given structure under a prescribed loading condition, and the rate of its increase provides a measure of structural propensity for fracture. Assessment of failure with TDERR is reflected by maximum and minimum values. A local maxima (stick point) represents a build up of energy and initiation of damage in a composite structure. Typically, at the stage of damage initiation, there is a high rate of energy release that dissipates a significant portion of the strain energy stored in the composite structure. A local minimum (slip point) represents the end of fracture stability in a damaged composite under the applied loading (Figure 10 (c)). Computation of the TDERR during progressive fracture allows evaluation of the composite fracture toughness and the degree of imminent failure.




**a) Percent damage Volume Vs. Load Spectrum Spectrum**

**b) DERR Vs. Load Spectrum**

**c) TDERR Vs. Load Spectrum**

**Figure 1. Damage Evolution Metrics as derivatives of Energy Release Rate**

**Q-How are delamination initiation and propagation considered?**

*A- Delamination is considered to be due to transverse tensile failure, out of plane shear failure, relative ply rotation, or normal tensile failure. Normal tensile stresses are computed from the numerical integration of the normal equilibrium equation using ply stresses in adjacent nodes..*

**Q-How do you evaluate da/dN?**

*A- da/dN is determined in a post processing calculation utilizing the multi-factor interaction model (MFIM) and is presented as a post processing plot.*

**B- Q-What is element extinction?**

***A-*** *When two nodes within one element are fractured that element is eliminated.*

**Q-How is equilibrium established after damage growth?**

*A- Equilibrium is established when the structure does not sustain any additional damage under the present applied load. Material properties and geometry* are updated at each establishment of equilibrium.

**Q-What do the terms “element failed” and “nodal fracture” mean in the GENOA results plots?**

*A- “Element failed” means two nodes within an element are fractured. “Nodal fractur” means that all the plies belonging to the node have sustained fiber damage and can not carry any load.*

**Q-The Alpha Star web page feature description of GENOA includes: (1) simulation of crack initiation and growth to failure, (2) progressive fracture analysis to determine durability and damage tolerance. Explain these capabilities?**

*A1-Progressive fracture involves detailed tracking of damaged nodes, detailed representation of a unit cell to track crack initiation, the sequence of growth to failure, and breakage (in matrix, interface, or fiber) within the unit cell.*

*A2-Durability, damage tolerance and life prediction can be a function of several sequential loading* *profiles. As an example, a structure can be first exposed to an impact condition, followed by compression loading, and fatigue loading. In this case the determination of durability and damage tolerance requires three sequential simulations. In each simulation the changed geometry and material properties are the input to the next.*

**Q-Can GENOA be used to analyze sandwich panels? What type of damage can be represented in a sandwich panel? Can damage in a single facesheet be accurately represented with a single shell element? What about delamination, facesheet buckling, and core failure through the thickness?**

***A1****- GENOA's use for analysis of sandwich structure and been verified with the experimental testing of several large scale structures: 1) Boeing/TRW/STI- Airborn Laser Reactor housing, 2) Mini Space Plane Technology (X37 ), Boeing Huntington Sandwich panel.*

***A2-*** GENOA readily represents the failure modes in a sandwich structure. These failure modes were found to be mostly core crushing, delamination, and transverse shear failure.

***A3-*** Yes. Use of the s*hell element, the composite mechanics module with through-the-thickness-integration and a detailed ply schedule (orientation, thickness, and sequence) readily supports accurate representation of the face sheet.*

***A4-*** Facesheet buckling is evaluated on the basis of Euler buckles criteria. Delamination, , and core failure through the thickness are **evaluated based on** *the 14 failure criteria in GENOA.*

**Q-Please explain in detail the failure calculation method and failure criteria being used by Alpha STAR in the Durability and Damage Tolerance (D&DT) study for the compression and tension panels.**

GENOA-PFA code, used for analyses in this program, is an integrated, open-ended, stand-alone computer code utilizing (1) micro and macro composite mechanics analysis, (2) finite element method (FEM) analysis, and (3) a damage evaluation method. The overall evaluation of composite structural durability is carried out in the damage-tracking module that incrementally evaluates composite material degradation in a structure subjected to a specified load spectrum. The composite damage-tracking module evaluates damage initiation/progression in a structure based on the FEM analysis results and failure criteria that guide the synthesis of structural stress redistribution due to material degradation.

The Damage Tracking Process - **Figure 5 shows an example of GENOA-PFA's damage tracking sequence as the load on a structure is increased. A damage equilibrium state is defined as existing when an incremental load increase does not either initiate or exacerbate damage. As the load is increased a point is reached (Location 1 in Figure 5) where there is an assessment of initial composite material damage based on the 14 failure criteria. According to the operative failure criteria, material properties are then degraded for use in FEM iterations to reevaluate the now damaged structure at the damage initiation load. The applied load at a given damage event is maintained and FEM iterations continued as damage accumulates (Locations 2, 3, and 4 in Figure 5) until an equilibrium damage state is again reached or until global structural failure occurs (Location 5 in Figure 5).**

*GEN-PMC is called before and after each FEM analysis to update composite properties based on the fiber and matrix constituent characteristics and the state of damage in the composite lay-up. Through-the-thickness laminate properties computed by GEN-PMC include the elastic moduli of membrane terms, bending terms, membrane-bending coupling terms, bending gradient terms, and shear terms. The finite element analysis module accepts these GEN-PMC generated properties for each node of a structural model under evaluation. The FEM module then performs a structural analysis to determine the effect of a given load increment on the generalized nodal force resultants and deformations. The new values so determined are supplied back to the GEN-PMC module that evaluates the nature and amount of local damage, if any, in the plies of the composite laminate.*

| **Failure Index Process/Description** | |
|---|---|
| 1. Ply failure indicates initial damage | |

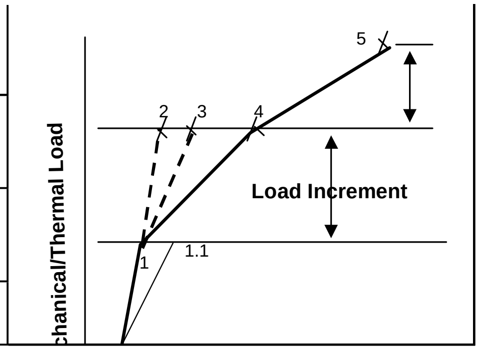
| | |
|---|---|
| • Properties are degraded<br>• Reconstitute a new FEM reanalysis is conducted under the same load |  |
| 2 & 3 Damage accumulation<br>• More degradation, possible composite ply failure | |
| 4 Damage stabilization<br>• No additional damage, with structure in equilibrium | |
| 5 Analysis stops at nodal fracture | |



***Figure 5. Damage Tracking Expressed in Terms of Load vs. Displacement***

**Table 5. Fourteen Damage Modes Considered In GENOA [25, 26]**

| Mode of Failure | Description |
|---|---|
| Longitudinal Tensile | Fiber tensile strength and the fiber volume ratio. |
| Longitudinal Compressive | 1. Rule of mixtures based on fiber compressive strength and fiber volume ratio<br>2. Fiber microbuckling based on matrix shear modulus and fiber volume ratio, and<br>3. Compressive shear failure or kink band formation that is mainly based on ply intralaminar shear strength and matrix tensile strength. |
| Transverse Tensile | Matrix modulus, matrix tensile strength, and fiber volume ratio. |
| Transverse Compressive | Matrix compressive strength, matrix modulus, and fiber volume ratio. |
| Normal Tensile | Plies are separating due to normal tension |
| Normal Compressive | Due to very high surface pressure i.e. crushing of laminate |
| In Plane Shear (+) | Failure due to Positive in plane shear with reference to laminate coordinates |
| In Plane Shear (-) | Failure due to negative in plane shear with reference to laminate coordinates |
| Transverse Normal Shear (+) | Shear Failure due shear stress acting on transverse cross section that is taken on a transverse cross section oriented in a normal direction of the ply |
| Transverse Normal Shear (-) | Shear Failure due shear stress acting on transverse cross section that is taken on a negative transverse cross section oriented in a normal direction of the ply |
| Longitudinal Normal Shear (+) | Shear Failure due shear stress acting on longitudinal cross section that is taken on a positive longitudinal cross section oriented in a normal direction of the ply |
| Longitudinal Normal Shear (-) | Shear Failure due shear stress acting on longitudinal cross section that is taken on a negative longitudinal cross section oriented in a normal direction of the ply |
| Modified Distortion Energy Criterion | Modified from Distortion Energy combined stress failure criteria used for isotropic materials |
| Relative Rotation Criterion | Considers failure if the adjacent plies rotate excessively with respect to one another |

***Q*- Is GENOA's post processing uncoupled from FE driver?**
*A- No, it calls a finite element module many times for the global structural analysis of the composite structure during a progressive damage simulation.*

***Q*- the damage initiation is based on what failure criteria?**
*A-damage initiation and progression are based on the computed ply stress exceeding limits and/or the modified distortion energy (MDE) combined stress failure criterion that is applied at the ply level.*

***Q*- Is GENOA based on classical laminate theory where only in planeloads is permissible?**
*A- Genoa is based on an augmented (Macro-mechanics) classical laminate theory in which the out-of-plane loads are accounted for. Out of plane normal and shear stresses are computed for each ply via* equilibrium equations. These stresses are compared with limiting values computed for each ply by the composite mechanics module.