DARWIN® 10.2 Release Notes

October 2025
Southwest Research Institute®

Summary of New Capabilities

Stress intensity factor solutions and enhancements:
- New SIF Solutions for Cracks at Holes
- Bivariant SIF Solutions Available in All Auto-Modeling Analysis Modes

New capabilities for fatigue crack growth life and fracture risk assessments:
- Bilinear Paris Small Crack Growth Model
- Fatigue Crack Growth (FCG) Rate Scatter
- GP Monte Carlo Support for FCG Rate Scatter
- FCG Threshold Filtering
- El Haddad Small Crack Model Enhancement
- Support for NASGRO Load Spectrum Data Files
- Crack Path Temperature Gradient Effects
- Support for Time-Dependent Properties in Vacuum & Air

New capabilities for low-cycle fatigue (LCF) life assessments:
- LCF Life Screening
- Total Life (LCF+FCG) Assessment
- Min LCF Life Screening
- Min LCF Life Feature Assessment

New capabilities for residual stress:
- User Definition of Residual Stress Along Curved Surfaces in 2D FE Models
- Residual Stress Profiles in 2D FE Models Extended to Bivariant Crack Types
- Bulk Residual Stress Enhancement

General enhancements:
- Element Refinement Tool Enhancement
- Hot Corrosion Enhancements
- Formation Module Programming Guidelines for Improved Execution Speed

Computational speed and visualization enhancements:
- Autoplate Speed Enhancement for Large 3D FE Models
- Autozoning Random Access Memory Improvement
- Critical Initial Crack Size (CICS) Speed Improvements
- GUI Speed Enhancements for Large 3D FE Models
- Enhanced GUI Visualization of 2D Axisymmetric FE Models via VTK

New pre/post processing capabilities:

- New Capabilities for Viewing Legacy Results Files
- Fracture Model Export
- New Capabilities for Assigning Elements via Imported ANSYS CDB Files
- Focused Text-Based Results Files
- SIO File Converter Tool

New SIF Solutions for Cracks at Holes

DARWIN includes several legacy SIF solutions for assessing damage associated with cracks that are located at holes: SC18, SC29, CC08, CC10, and TC13. SC18 and SC29 are surface cracks in univariant and bivariant stress fields. CC08 and CC10 are corner cracks in univariant and bivariant stress fields. TC13 is a through crack in a univariant stress field.

The legacy DARWIN crack-at-hole SIF solutions were created a number of years ago using reference solutions that were based on relatively sparse solution matrices. DARWIN 10.2 provides new crack-at-hole SIF solutions that use the same weight function formulations that were used in previous versions. However, the new reference solutions were developed based on denser solution matrices, providing results that are more accurate than previous versions of DARWIN.

The new crack-at-hole SIF solutions were renamed as follows:

- SC37 – surface cracks in univariant stress fields
- SC38 – surface cracks in bivariant stress fields
- CC26 – corner cracks in bivariant stress fields
- TC43 – through cracks in univariant stress fields
- CC08 – corner cracks with enhanced transition criteria (i.e., CC08 now transitions to TC43)

The relationship among legacy and enhanced crack models is shown in Table 1. The CC08 and CC08_LEGACY crack models utilize the same CC08 SIF solution to compute SIF values. They are differentiated by their associated crack transition models. CC08 cracks transition to the enhanced TC43 crack model, whereas CC08_LEGACY cracks transition to the legacy TC13 crack model.

The new crack-at-hole SIF solutions are available in the DARWIN crack editor (Figure 1) and zone editor menus. Users may continue to use the legacy crack-at-hole SIF solutions. The GUI Preferences menu provides a new preprocessing option entitled "Deprecated Crack at Hole SIF Solutions" (Figure 2). When applied, it enables users to select legacy crack-at-hole SIF solutions in the crack editor (Figure 3) and zone editor menus.

TC13 and TC43 are transition crack types that are not available in the crack and zone editor menus. These two crack types are only available to the DARWIN computational engine and in the GUI postprocessing screens.

Table 1: Relationship among DARWIN legacy and enhanced crack models.

Legacy Crack Model	Enhanced Crack Model
SC18	SC37
SC29	SC38
CC10	CC26
TC13	TC43
CC08_LEGACY	CC08

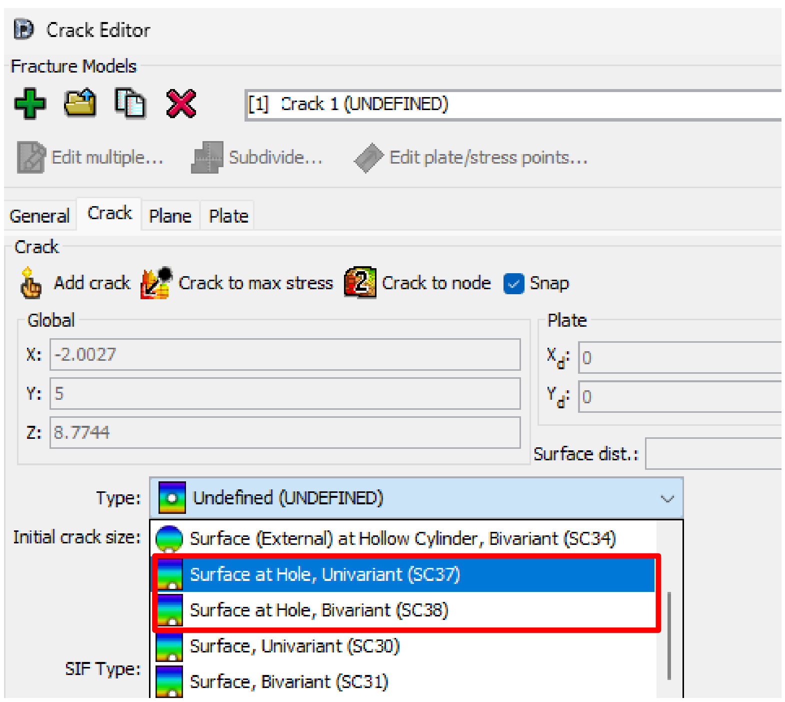


Figure 1: New crack-at-hole SIF solutions as they appear in the DARWIN crack editor menu.

Note that during project conversions from pre-DARWIN 10.2 to DARWIN 10.2, the GUI by default will convert the CC08 crack type to CC08_LEGACY. However, the GUI enables users to change the crack type from CC08_LEGACY to the new CC08 crack type after the project file has been converted to DARWIN 10.2 if desired.

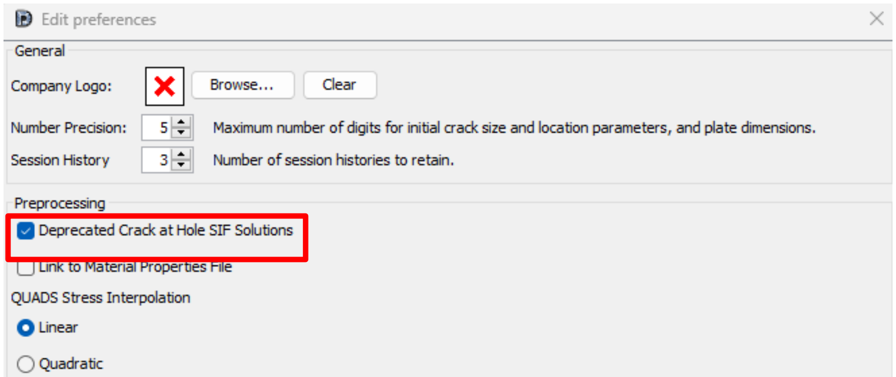


Figure 2: The GUI Preferences menu provides a new preprocessing option entitled "Deprecated Crack at Hole SIF Solutions" to enable the use of legacy crack-at-hole solutions.

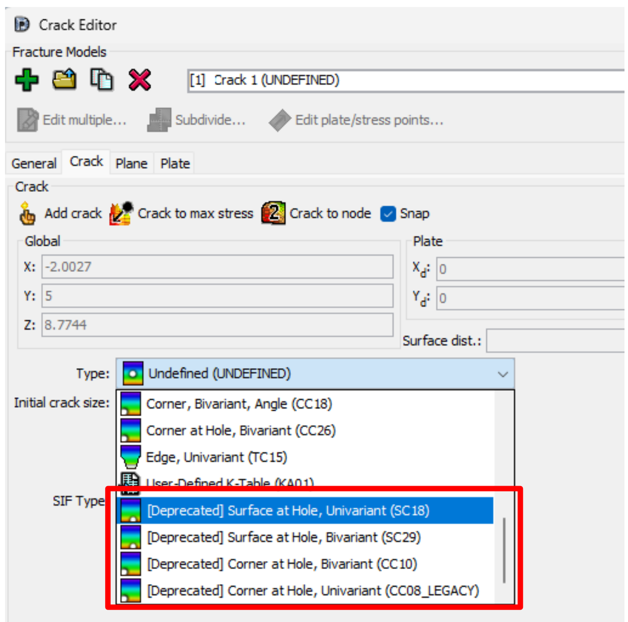


Figure 3: Users may continue to select the DARWIN legacy crack-at-hole SIF solutions via the crack editor menu (when enabled).

Bivariant SIF Solutions Available in All Auto-Modeling Analysis Modes

In previous versions of DARWIN, bivariant plates were restricted from use on convex crack surfaces. This restriction was due to the missing material on the surface face of the plate (region indicated with red dots in Figure 4). The fracture plates associated with bivariant cracks were required to be fully contained within the component geometry, effectively restricting Auto-Modeling to univariant crack models.

In DARWIN 10.2, the bivariant SIF solutions were enhanced to support convex crack surfaces. This has enabled fracture plates associated with bivariant crack types to fall outside the component geometry. This enhancement provides the option for bivariant plates to be applied to all DARWIN Auto-Modeling capabilities including life contours (Figure 5), autozoning (Figure 6), CICS contours, and manual zoning.

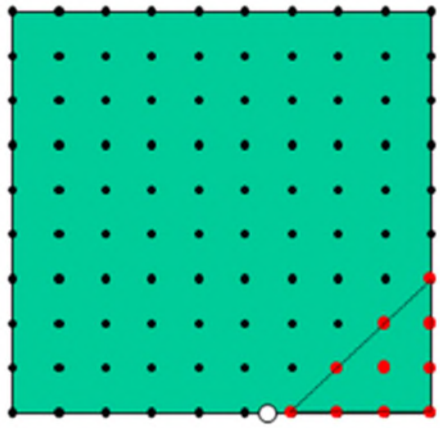


Figure 4: Previous versions of DARWIN did not support bivariant plates in finite element models with convex crack surfaces due to missing material on the surface face of the plate (region indicated with red dots).

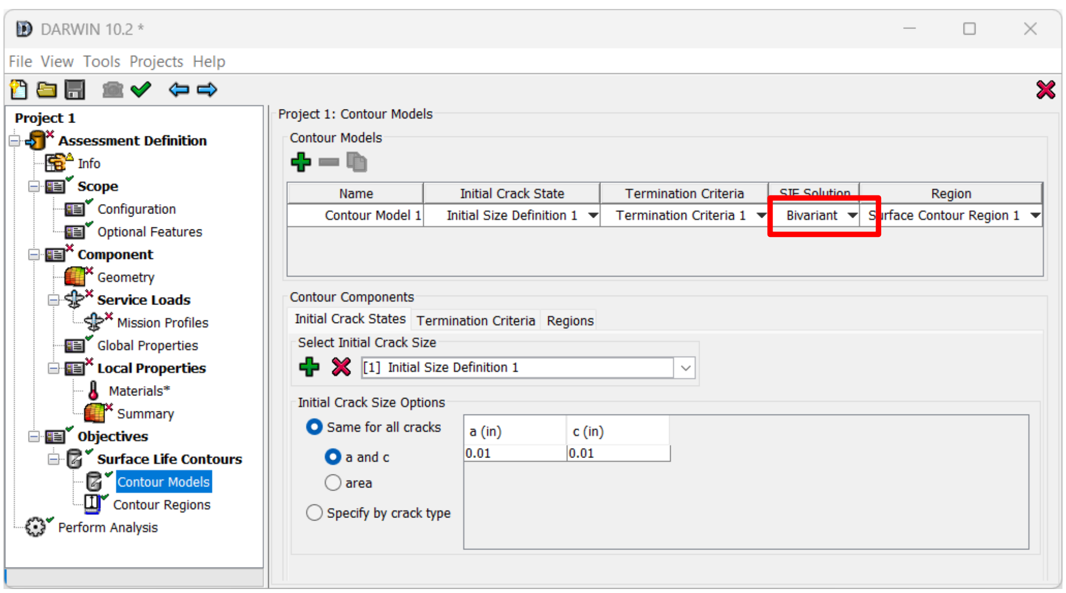


Figure 5: DARWIN 10.2 provides the option for users to apply bivariant crack models to life contour analyses.

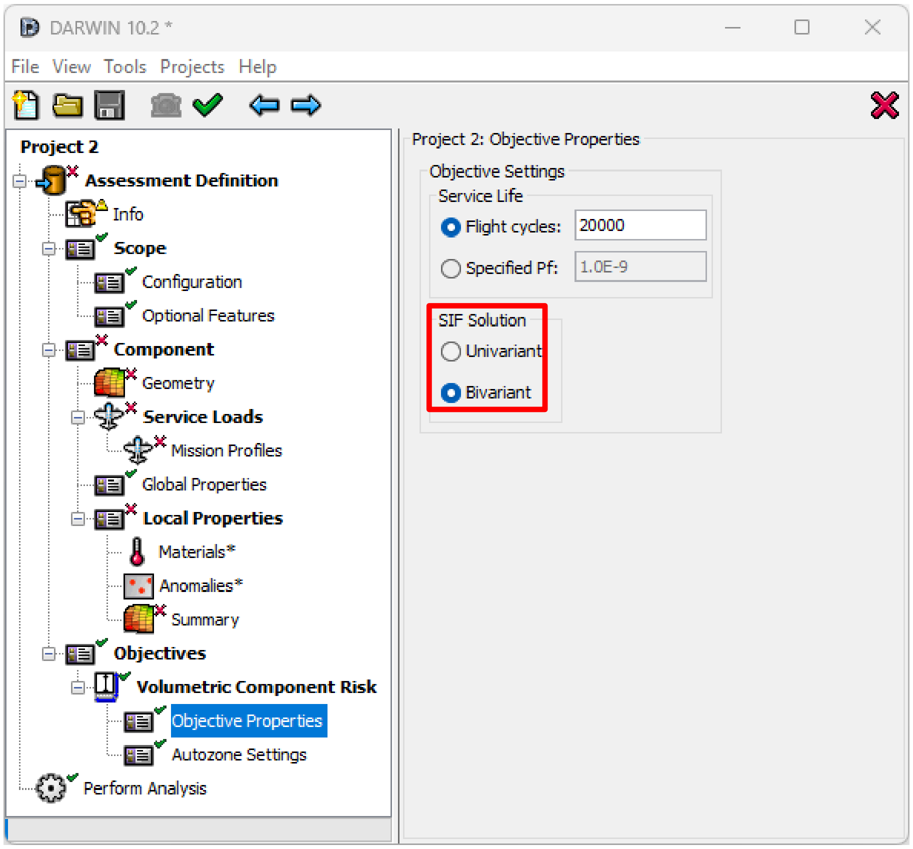


Figure 6: DARWIN 10.2 provides the option for users to apply bivariant crack models to autozoning analyses.

Bilinear Paris Small Crack Growth Model

Small fatigue cracks may grow at rates that are faster than anticipated from large-crack data trends. Small cracks may grow at stress intensity factor (SIF) ranges that are below the large-crack threshold. Previous versions of DARWIN include two options for modeling accelerated small-crack behavior that are based on the a_0 parameter that is associated with the Kitagawa diagram: (1) El Haddad, and (2) SIF threshold. The El Haddad model increases the crack driving force by adding a_0 to the physical crack size in the computation of the SIF. The SIF threshold model decreases the SIF threshold value (ΔK_{th}) in the NASGRO® FCG equation as a function of a_0. The small-crack effect expressed by both of these models diminishes quickly as the physical crack size becomes large compared to a_0.

DARWIN 10.2 provides a new approach for modeling small-crack behavior in which crack growth equations are fitted exclusively to small-crack data, and different equation parameters are used for small versus large fatigue cracks. Paris equation curves are used to develop separate models for the small-crack and large-crack regimes. The resulting bilinear Paris model is used to determine crack growth rates over an entire range of ΔK values and crack sizes.

The DARWIN material properties file (*.mat). has been enhanced to support the new Bilinear Paris small crack model. It enables users to input small crack growth (SCG) model parameters in a new section of the file entitled “SCG DADN DATA”. Large crack growth model parameters are input in a separate section of the file entitled “DADN DATA”. An example of the enhanced *.mat file illustrating the new section for defining small crack growth parameters is shown in Figure 7.

The Bivariant small crack growth model provides support for stress-ratio effects using existing DARWIN models including the Newman crack closure equations, the Walker equation, and the Walker equation with interpolation. Model parameters can be specified for both air and vacuum environments.

```
SCG DADN DATA

AIR
FCG_FORMAT                          PARIS
C_FORMAT                            EXPONENT
STRESS_RATIO_FORMAT                 WALKER_EQN
TEMPERATURE_INTERPOLATION_FORMAT    CLOSEST
!C_Coeff       n_Exp     dKth       Kc         m-       m+      Temp
-11.939        5.262     5.0        61.7       0.20     0.759   75.0
-11.890        5.132     4.8        60.2       0.18     0.702   400.0

VACUUM
FCG_FORMAT                          PARIS
C_FORMAT                            EXPONENT
STRESS_RATIO_FORMAT                 WALKER_EQN
TEMPERATURE_INTERPOLATION_FORMAT    CLOSEST
!C_Coeff       n_Exp     dKth       Kc         m-       m+      Temp
-11.939        5.262     5.0        61.7       0.20     0.759   75.0
-11.890        5.132     4.8        60.2       0.18     0.702   400.0
```

Figure 7: The DARWIN *.mat file includes a new section that enables users to provide small crack growth (SCG) model parameters for the Bilinear Paris small crack growth model.

Fatigue Crack Growth (FCG) Rate Scatter

It is well known that fatigue crack growth (FCG) lifetimes exhibit variability even for nominally identical components or coupons due to uncertainty in factors such as initial crack size, material properties, and applied stress. Predictions of FCG lifetimes introduce additional uncertainty due to imperfections in the life prediction models. In previous versions of DARWIN, material property variability and life model uncertainty has been modeled via an optional life scatter factor that is applied directly to the calculated FCG lifetime.

DARWIN 10.2 provides a new FCG rate scatter model entitled “Paris Random” that provides direct treatment for measured variability in FCG rate parameters associated with the Paris equation. Scatter is treated separately for small-crack growth (SCG) and large-crack growth (LCG) rates. The Paris equation (in $da/dN = 10^c (\Delta K)^n$ format) is used to describe FCG rates. FCG scatter is modeled as a multivariate normal distribution based on statistical fits of Paris equation *c* and *n* parameters. Two correlated normally distributed FCG rate scatter factor variables were introduced (XC = scatter in the Paris *c* parameter, and XN = scatter in the Paris *n* parameter). These variables are applied to deterministic *c* and *n* values to form new random variables *c*' and *n'*. A correlation coefficient variable RHO is also introduced to model the correlation among the XC and XN variables.

The DARWIN material properties file (*.mat). has been enhanced to support the crack growth rate scatter model. It enables users to input FCG rate scatter factor variables that are associated with the Paris Random model. An example of the enhanced *.mat file illustrating the new FCG rate scatter factor variables is provided in Figure 8.

A single set of scatter factors is used to model the scatter in parameters at all temperatures and stress ratios within a *.mat file. One set of scatter factors is used for SCG, and another set of scatter factors is used for LCG. DARWIN does not require use of FCG rate scatter for both large and small crack growth models.

Fatigue crack growth rate scatter values that are used for each Monte Carlo sample are reported in the results section of the DHF file. Both LCG and SCG rate scatter data are supported.

```
TITLE
Random Paris model

DESCRIPTION
Paris model with crack growth rate scatter

UNITS   US

DADN DATA

AIR

FCG_FORMAT                        PARIS_RANDOM

C_FORMAT                          EXPONENT

XC_MEAN                           0.95

XC_STDEV                          0.001

XN_MEAN                           0.97

XN_STDEV                          0.002

RHO                               0.5

STRESS_RATIO_FORMAT               NONE

TEMPERATURE_INTERPOLATION_FORMAT  NEXT_HIGHEST

! C Coef          n Exp       dkth        Kc     Temp

-11.939           5.262       5.0         58.7   75.0

-11.890           5.132       5.0         55.2   400.0
```

Figure 8: The DARWIN *.mat file has been enhanced to enable users to input the variables that are associated with the new Paris Random FCG rate scatter model.

GP Monte Carlo Support for FCG Rate Scatter

DARWIN includes an efficient probabilistic computational method entitled "GP Monte Carlo" that is significantly faster than standard Monte Carlo simulation. During run time, this method creates Gaussian Process response surface models for application to Monte Carlo simulation. In DARWIN 10.2, the GPM Monte Carlo method was enhanced to provide treatment for the random variables that are associated with FCG rate scatter. It provides support for both SCG and LCG crack growth rate scatter.

FCG Threshold Filtering

DARWIN execution time is strongly dependent on the size of the imported FE model. FE model sizes and complexity have increased significantly in recent years, which has created a need for more efficient computational methods in DARWIN.

The new Crack Growth Threshold Filtering feature in DARWIN 10.2 provides the potential for improved computational efficiency for large FE models. It identifies interior nodes with driving forces that are below the threshold for fatigue crack propagation. These nodes are excluded from further analysis for improved computational efficiency.

The Crack Growth Threshold Filtering optional feature is available when using the Volumetric Component Risk objective. This feature is enabled by selecting the **Crack Growth Threshold Filtering** checkbox in the **Optional Features** preprocessing screen (Figure 9).

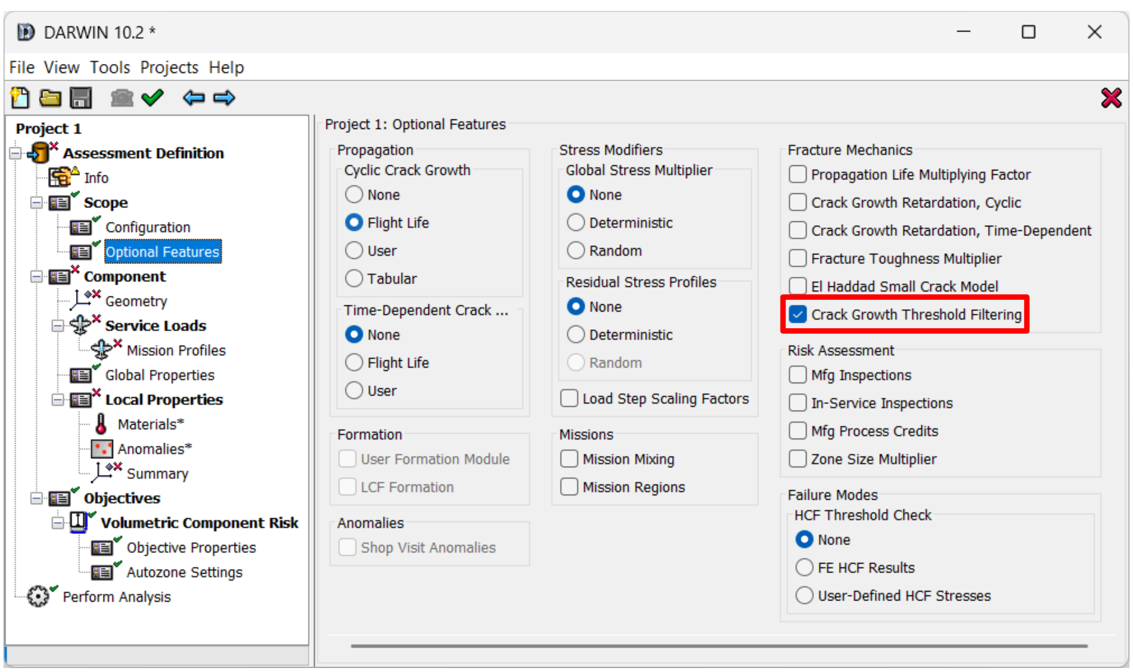


Figure 9: The new Crack Growth Threshold Filtering feature provides the potential for improved computational efficiency for large FE models.

El Haddad Small Crack Model Enhancement

In previous versions of DARWIN, the El Haddad small crack correction parameter was limited to a single value that was applied in both air and vacuum environments. DARWIN 10.2 was enhanced to enable the user to specify different small crack correction parameter values for air and vacuum environments.

Support for NASGRO Load Spectrum Data Files

In addition to DARWIN, Southwest Research Institute also supports a deterministic damage tolerance software program called NASGRO® that is used primarily by the aircraft and spacecraft structures communities. Load spectrum information is defined in NASGRO via external files called "NASGRO Long Block" (*.lb) files. Some users have expressed interest in defining load spectrums in DARWIN via NASGRO *.lb files. Previous versions of DARWIN did not provide this capability.

DARWIN 10.2 includes a new **NASGRO Long Block** feature that provides support for NASGRO *.lb files. This feature is enabled via the Project Setup menu shown in Figure 10. When enabled, the user can create missions that are based on imported NASGRO Long Block files. DARWIN provides the capability for users to specify unique stress gradients for both the maximum and minimum load case (T1 and T2) for each stress quantity (S0, S1, S2, and S3) that is associated with a NASGRO *.lb file (see Figure 11). Users may specify scaling factors and activate or deactivate each stress quantity. DARWIN Mission Mixing and Mission Regions optional features are compatible with this new feature.

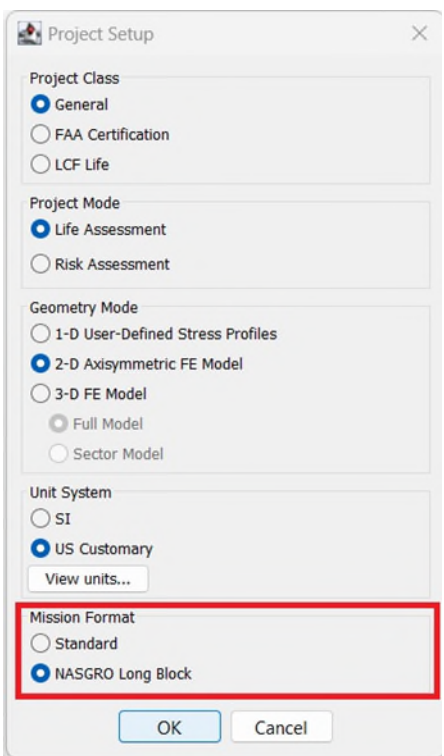


Figure 10: DARWIN 10.2 includes a new feature for support of NASGRO Long Block load spectrum data files.

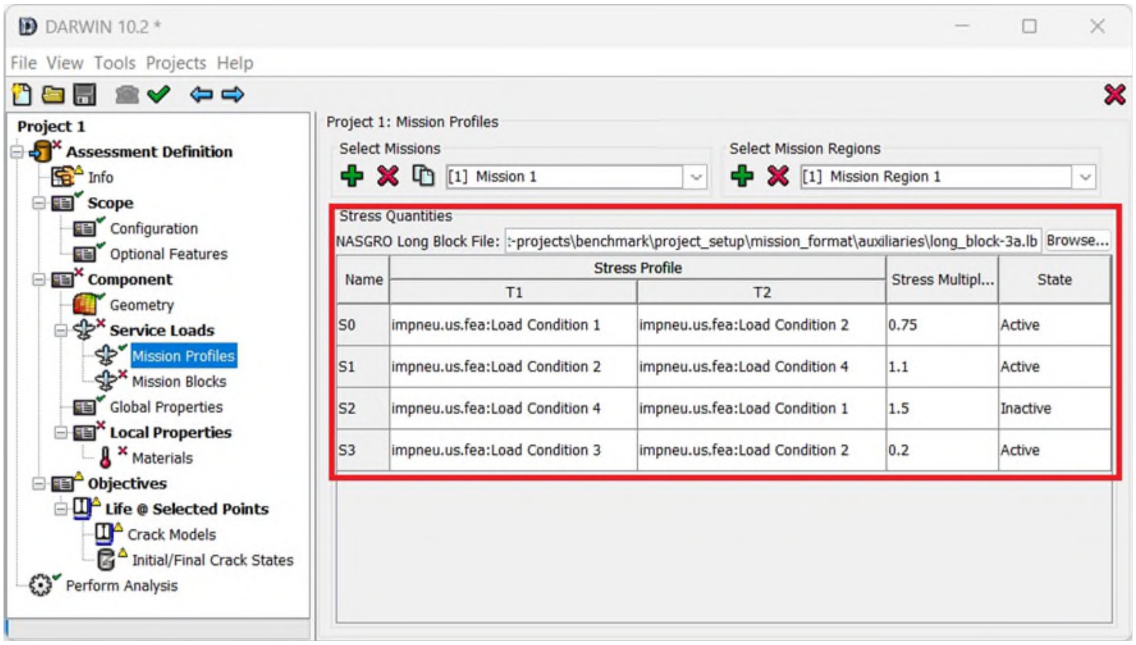


Figure 11: Defining missions in DARWIN using NASGRO Long Block files.

Crack Path Temperature Gradient Effects

In previous versions of DARWIN, FCG rates along the crack path were based on the temperature at the crack center. These previous versions did not have the capability to adjust fatigue crack growth rates to account for changes in temperature along the crack path.

DARWIN 10.2 has been enhanced to compute cyclic and time-dependent FCG rates at crack tips based on the temperatures along the evolving crack front. This enables users to assess the influence of temperature gradient effects on FCG lives. This new feature is enabled via a new checkbox entitled **Crack Path Temperature Gradient Effects** that is located in the Material Properties section of the Global Properties preprocessing screen (see Figure 12). This feature supports both univariant and bivariant temperature gradients and enables the capability for more accurate FCG life prediction.

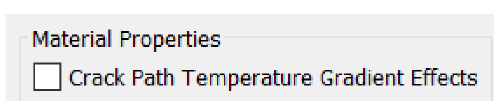


Figure 12: Enabling crack path temperature gradient effects in DARWIN 10.2.

Support for Time-Dependent Properties in Vacuum & Air

In previous versions of DARWIN, the material properties file was limited to one set of properties for time-dependent fatigue crack growth. DARWIN 10.2 was enhanced to enable the user to specify different time-dependent fatigue crack growth properties for air and vacuum environments.

LCF Life Screening

The DARWIN software was originally developed as a probabilistic damage tolerance analysis tool. Crack formation life was assumed to be zero, and the initial crack size was based on a distribution of anomaly sizes. Previous versions of DARWIN include an interface that enables users to link their own algorithms for crack formation. However, these versions did not provide any native crack formation methods.

DARWIN 10.2 provides new capabilities for computing crack formation life, also known as conventional LCF life assessment. These capabilities include direct support for four different LCF life equations as well as supporting technology for cyclic shakedown and rainflow.

The four supported LCF life equations are as follows:

1. Coffin-Manson-Morrow

$$\sqrt{(\sigma_{amp} + k \cdot \sigma_{mean})\, E\, \epsilon_{amp}} = A(N_i)^b + C(N_i)^d \qquad (1)$$

2. Smith-Watson-Topper

$$\sqrt{(\sigma_{amp} + k \cdot \sigma_{mean})\, E\, \epsilon_{amp}} = A(N_i)^b + C(N_i)^d \qquad (2)$$

where

$$P_{SWT} = \sqrt{(\sigma_{amp} + k \cdot \sigma_{mean})\, E\, \epsilon_{amp}}$$
$$\sigma_{amp} = \Delta\sigma/2 \qquad (3)$$
$$\varepsilon_{amp} = \Delta\varepsilon/2$$

3. Walker Strain

$$\left({}^{\sigma_{max}}/_{E}\right)^{(1-w)} \cdot (\Delta\varepsilon)^w = A(N_i)^b + C(N_i)^d \qquad (4)$$

4. Tensile Hysteretic Energy

$$\frac{2(P_{SWT})^2}{E} = A(N_i)^b + C(N_i)^d \qquad (5)$$

where

$$P_{SWT} = \sqrt{(\sigma_{amp} + k \cdot \sigma_{mean})\, E\, \epsilon_{amp}} \qquad (6)$$

Note that some of these equations use the common symbols A, b, C, and d, but those parameters have different values (and different meanings) in the different life models.

Material properties for each of these equations are provided by the user at multiple discrete temperatures, in the same manner that DARWIN currently provides different FCG or stress-strain properties at multiple discrete temperatures. DARWIN supports three interpolation options for temperature effects on FCG and stress-strain properties: actual interpolation, or use the nearest temperature, or use the next highest temperature. However, DARWIN only supports actual interpolation (not nearest or next-highest temperature) for the LCF life equations.

Component finite element analysis is often performed assuming elastic material responses, but actual stresses at some locations (especially significant stress concentrations) may exceed the yield strength. The resulting local plastic deformation will impact both the actual cyclic strain values and the mean stresses that are applied to the LCF life equations. These effects can be addressed approximately with shakedown algorithms that estimate the local elastic-plastic response.

Previous versions of DARWIN include optional shakedown algorithms to support FCG analyses. Those shakedown algorithms admit only monotonic plastic deformation but also address the local redistribution of stress along the crack line in the vicinity of the peak stress. In DARWIN 10.2, a new set of crack formation shakedown algorithms was introduced to support conventional LCF analysis. These new algorithms admit both monotonic and cyclic plasticity at the initial crack location where the crack formation life is computed. The user can choose between traditional Neuber or Glinka algorithms to perform the local shakedown calculation.

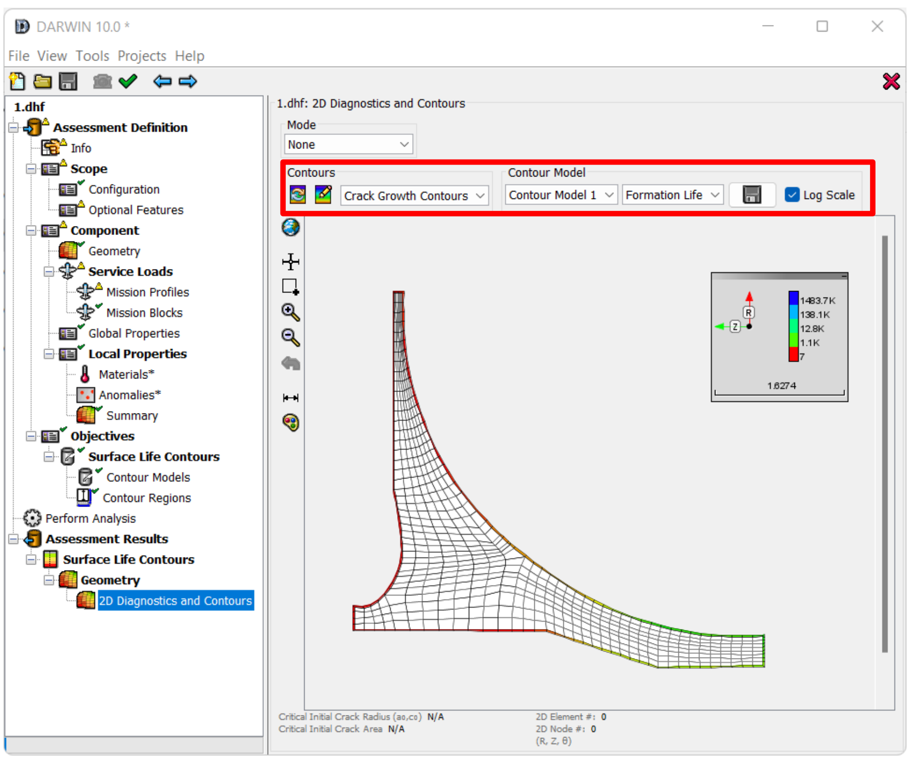
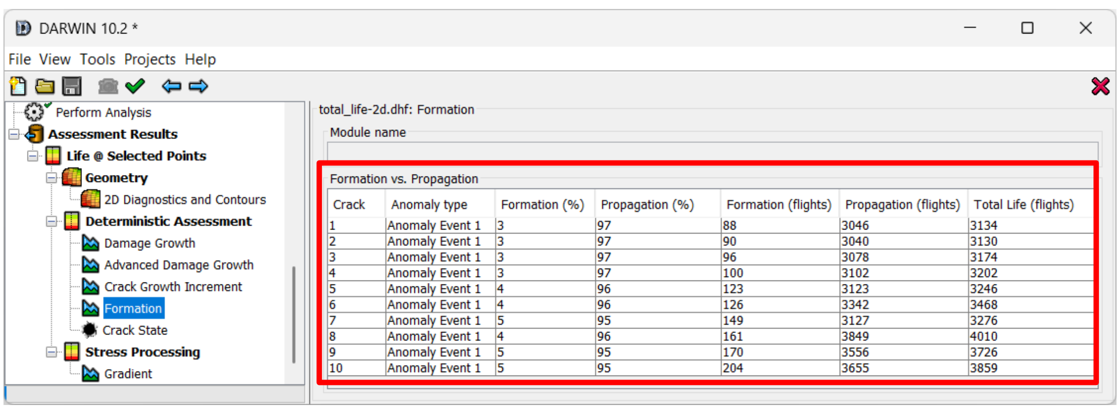


Figure 13: Viewing LCF life contour results in DARWIN 10.2.

These equations are exercised in a new **LCF Screening** analysis mode that performs life calculations at all nodes in a user-selected region and identifies the locations exhibiting the lowest LCF lives. In this mode, DARWIN calculates the conventional LCF life based on one selected LCF life equation at every node on the surface of a component in a selected region. The results are visualized as deterministic surface life contours (see example in Figure 13). DARWIN also generates a text file with a rank ordering of the nodes that exhibit the minimum LCF lifetimes (the user defines how many nodes will be listed). The LCF screening mode is a convenient way for users to identify the LCF hotspots in a component.

Total Life (LCF + FCG) Assessment

The conventional LCF life models and their related algorithms can also be applied in DARWIN in another new project mode entitled **Total Life** that supports total life (i.e., LCF + FCG) analysis. In this project mode, the total life is based on the sum of a crack formation calculation (using one of the conventional LCF life equations) and a crack growth calculation (using the legacy DARWIN capability for FCG analysis). Users provide a list of specific nodal locations on the surface of the component where this total life calculation is to be performed. The user would typically first perform an LCF Screening Analysis to identify the individual nodes with the shortest crack formation lifetimes, and then use this list to determine where corresponding FCG calculations will be performed, starting from a user-defined initial crack size. The results of an example total life analysis are shown in Figure 14.



Crack	Anomaly type	Formation (%)	Propagation (%)	Formation (flights)	Propagation (flights)	Total Life (flights)
1	Anomaly Event 1	3	97	88	3046	3134
2	Anomaly Event 1	3	97	90	3040	3130
3	Anomaly Event 1	3	97	96	3078	3174
4	Anomaly Event 1	3	97	100	3102	3202
5	Anomaly Event 1	4	96	123	3123	3246
6	Anomaly Event 1	4	96	126	3342	3468
7	Anomaly Event 1	5	95	149	3127	3276
8	Anomaly Event 1	4	96	161	3849	4010
9	Anomaly Event 1	5	95	170	3556	3726
10	Anomaly Event 1	5	95	204	3655	3859

Figure 14: Example Total Life analysis results in DARWIN 10.2.

Min LCF Life Screening

LCF lives for some materials can be partitioned into two separate groups that have distinctly different failure mechanisms: (1) min-life, and (2) mean-life. The min-life group is dominated by FCG and can be modeled using probabilistic damage tolerance (PDT) concepts. DARWIN 10.2 includes a new min LCF life PDT model that predicts lifetimes associated with the min-life group. It considers random anomalies at the grain size scale, random FCG rates, and small crack effects. Unlike the conventional LCF approach that requires calibration to smooth specimen fatigue tests, the min LCF life PDT model predicts lower bound lifetimes using a probabilistic approach that is informed by the scatter in the sizes of microstructural anomalies/features and variability in FCG rates.

In a DARWIN min LCF life screening analysis, an LCF risk versus cycles curve is computed at all of the nodes on selected surfaces of an FE model. The LCF life associated with a specified (conditional) fracture risk is computed directly from the fracture risk versus LCF life curve at each node. This value is called the minimum LCF life because it represents the lowest number of cycles at which the component can safely remain in service without exceeding a specified conditional risk value. Min LCF life contours are constructed based on these minimum LCF life values.

The new **Surface Min Life Contours** analysis mode in DARWIN 10.2 can be used to compute min LCF life contours. This analysis mode enables the user to identify the regions on the surface of the component at which an accurate minimum LCF life assessment is needed. It also provides a conservative estimate of the minimum LCF life for the component. In this analysis mode, SCG and LCG rate *c* and *n* parameters are modeled as deterministic quantities to improve the computational efficiency of conditional minimum LCF life computations. Scatter factors for the SCG and LCG rate *n* parameters are set at their mean values. Scatter factors for the SCG and LCG rate *c* parameters are set at fixed values. In this analysis mode, the anomaly size is the only random variable. Conditional fracture risk versus cycles are computed analytically rather than via numerical (i.e., Monte Carlo) simulation. This enables conditional minimum LCF lives to be computed at each node in a FE model via a deterministic FCG life analysis, substantially reducing the overall computation time.

The resulting min LCF lives are displayed as color contours on the FE model surfaces. A text file containing the lowest-life nodes is generated that is similar to the text file that is generated in the LCF Screening analysis mode.

Min LCF Life Feature Assessment

DARWIN 10.2 includes a new **Volumetric Min Life** analysis mode that performs a traditional PDT risk assessment and computes the min LCF life for a specific feature that has been identified via the Min LCF Life Screening mode. During analysis execution, a zone-based risk assessment is performed on the surface of the selected region of the component. The minimum LCF life is computed based on the risk target (conditional or unconditional) that is specified by the user. The resulting min LCF life value is displayed as a single color on the surface of the feature. The zone with the smallest min LCF life is also highlighted as a single color.

In contrast with the screening mode, several random variables are available in the Volumetric Min Life (i.e., feature) mode including initial anomaly size (modeled as an anomaly distribution), scatter in small and large crack growth rate *c* and *n* parameters, and inspection variables (inspection time and probability of detection). A few random variables are restricted from the analysis including stress scatter, crack initiation life scatter, and crack propagation life scatter.

User Definition of Residual Stress Along Curved Surfaces in 2D FE Models

DARWIN includes an algorithm that provides treatment for residual stresses (RS) in 2D FE models arising from surface enhancement techniques such as peening or cold expansion of holes. This algorithm enables users to apply RS gradients at selected locations along the surfaces of a component.

In previous versions of DARWIN, RS gradients were applied at two points on the surface of a component to define a quadrilateral univariant stress field. The residual stress field was superimposed on the FE model for application to FCG life computations. This approach was limited to surfaces that appeared as straight lines in the cross section of a 2D FE model.

In DARWIN 10.2, the algorithm was enhanced for application to surfaces that appear as curves in 2D FE models. In the revised scheme, RS gradients are assigned to nodes along the surfaces of a component to define RS gradient vectors that are normal to the surface. The resulting RS gradient vectors appear as red dots on the surfaces of the FE model (Figure 15). When a surface or near-surface crack is placed near a surface node associated with a RS gradient vector, the residual stress gradient associated with the RS gradient vector is projected onto the crack plane and superimposed with service stresses for application to fatigue crack growth life computations.

RS gradient vectors are defined via the Residual Stress Gradients editor shown in Figure 16. The editor enables users to define RS gradients and select FE surface nodes associated with each RS gradient vector. The RS gradient vector can be assigned to Multiple FE nodes.

This enhancement is available in all Auto-Modeling modes (FCG life, CICS, and autozoning).

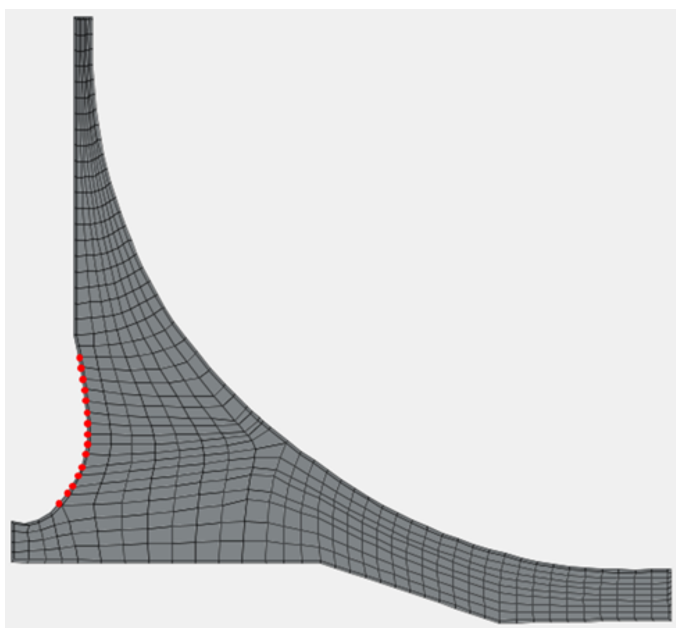


Figure 15: DARWIN 10.2 enhances the Residual Stress Profiles capability for application to surfaces that appear as curves in 2D FE models.

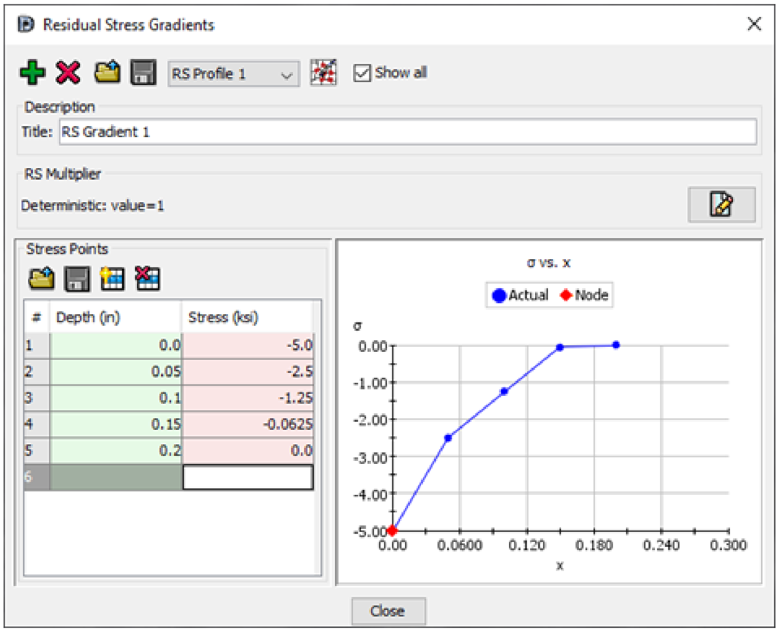


Figure 16: The enhanced Residual Stress Gradients editor enables users to define RS gradients and select FE surface nodes associated with RS gradient vectors.

Residual Stress Profiles in 2D FE Models Extended to Bivariant Crack Types

The DARWIN **Residual Stress Profiles** capability enables users to define a univariant residual stress field that is superimposed directly on 2D FE model geometries for use in fatigue crack growth life and fracture risk assessments. In previous versions of DARWIN, this capability was limited to univariant crack types. In DARWIN 10.2, this capability has been extended for application to bivariant surface cracks (SC31), as shown in Figure 17.

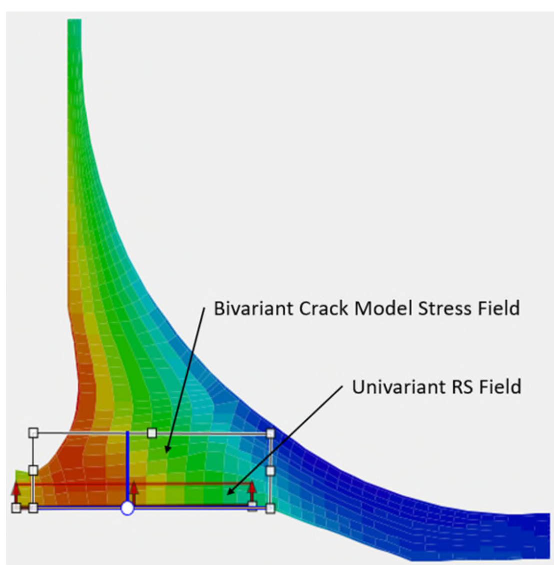


Figure 17: DARWIN 10.2 extends the residual stress profiles capability to enable application of residual stress fields to bivariant crack models.

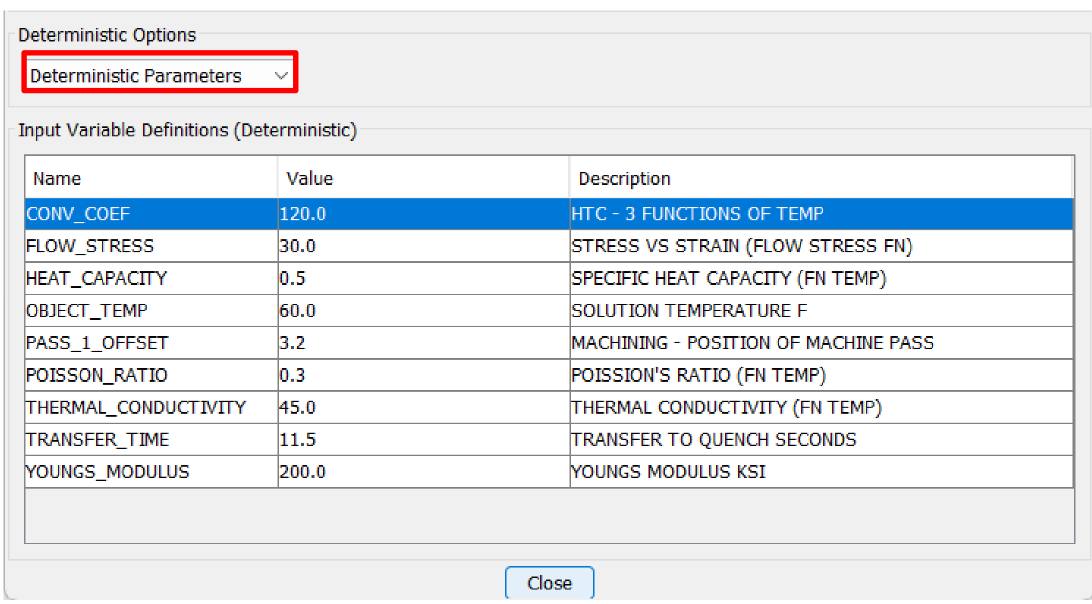
Bulk Residual Stress Enhancement

Previous versions of DARWIN include the capability for users to import bulk residual stress data that are generated from manufacturing process simulations for application to FCG life and fracture risk assessments. For FCG life assessment, this capability was limited to a single residual stress sample case.

DARWIN 10.2 was enhanced to provide two new capabilities for specifying bulk residual stress for application to FCG life assessments: (1) Deterministic Parameters, and (2) Stress Percentile.

The **Deterministic Parameters** option enables users to specify deterministic values for manufacturing process input variables that are related to bulk residual stress (Figure 18). The residual stress data editor displays a table of input variables that are contained in user-imported SIO or HIO files. Users can then define specific deterministic parameter values for each of these variables. At run time, a Gaussian Process (GP) response surface is constructed at each node along the crack path based on the imported residual stress sample cases. The user-specified deterministic parameter values are then applied to the GP response surface to determine the residual stress at the nodes along the crack path.

The **Stress Percentile** option enables users to define deterministic bulk residual stress based on a specified probability value. To enable this feature, users select the Stress Percentile (%) option in the Residual Stress Data editor as shown in Figure 19. At run time, a GP response surface is constructed at each node along the crack path based on imported residual stress sample cases. Monte Carlo simulation is applied to the response surface based on user-provided input random variable parameter values to compute a cumulative probability distribution of bulk residual stress at each node. The deterministic residual stress is then computed at each node (along the crack path) based on the cumulative probability (percentile) value that is provided by the user.



Name	Value	Description
CONV_COEF	120.0	HTC - 3 FUNCTIONS OF TEMP
FLOW_STRESS	30.0	STRESS VS STRAIN (FLOW STRESS FN)
HEAT_CAPACITY	0.5	SPECIFIC HEAT CAPACITY (FN TEMP)
OBJECT_TEMP	60.0	SOLUTION TEMPERATURE F
PASS_1_OFFSET	3.2	MACHINING - POSITION OF MACHINE PASS
POISSON_RATIO	0.3	POISSION'S RATIO (FN TEMP)
THERMAL_CONDUCTIVITY	45.0	THERMAL CONDUCTIVITY (FN TEMP)
TRANSFER_TIME	11.5	TRANSFER TO QUENCH SECONDS
YOUNGS_MODULUS	200.0	YOUNGS MODULUS KSI

Figure 18: The Deterministic Parameters option in DARWIN 10.2 enables users to specify deterministic values for manufacturing process input variables.

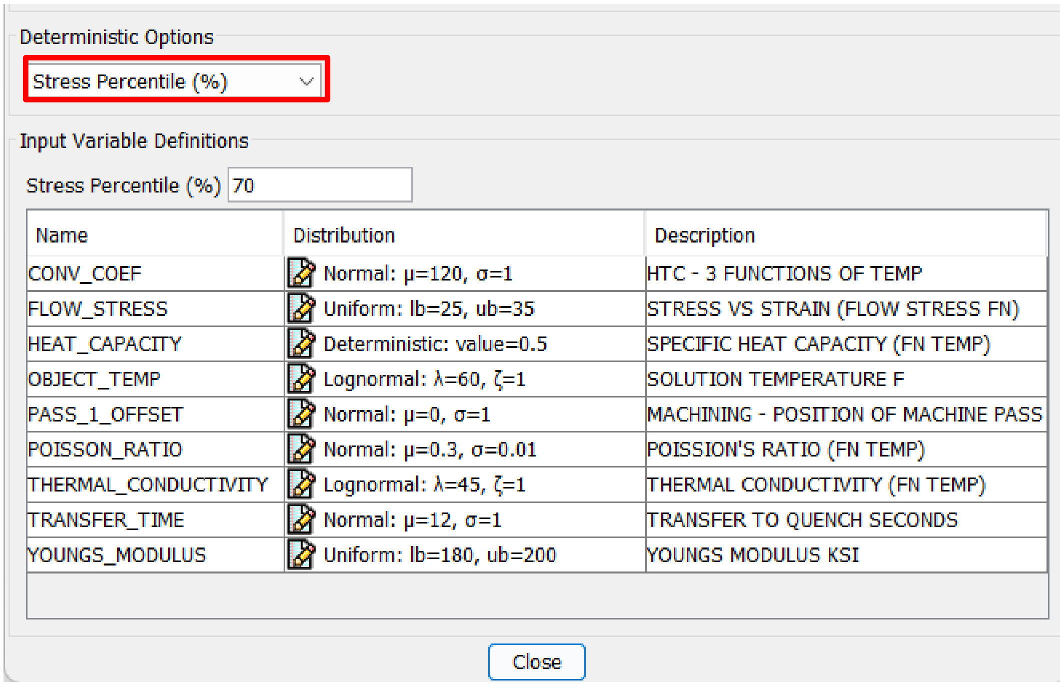


Figure 19: The Stress Percentile option in DARWIN 10.2 enables users to define deterministic bulk residual stress values based on a specified probability value.

Element Refinement Tool Enhancement

DARWIN provides an element refinement tool that enables users to refine the mesh associated with 2D finite element models. The tool makes adjustments to the FE nodes, elements, and associated stresses and temperatures. This enables the creation of zones that are based on the refined mesh. For example, the tool can be used to create onion skin zones along the surfaces of 2D FE models that can be used for certification assessment of Titanium hard alpha anomalies.

In previous versions of DARWIN, the tool was accessible in the Geometry preprocessing screen where zones are created by the user. Users were required to refine the mesh via the tools that are accessible via this screen before proceeding with the zoning process. The refined mesh was associated with a specific DARWIN project. This created confusion for some users.

In DARWIN 10.2, the element refinement tool has been relocated to the Tools menu. Rather than being associated with a specific DARWIN project, the element refinement process is performed via a dedicated GUI instance. This enables users to import a 2D FE model, perform element refinement, and save an updated mesh that is independent of a DARWIN project, as shown in Figure 20.

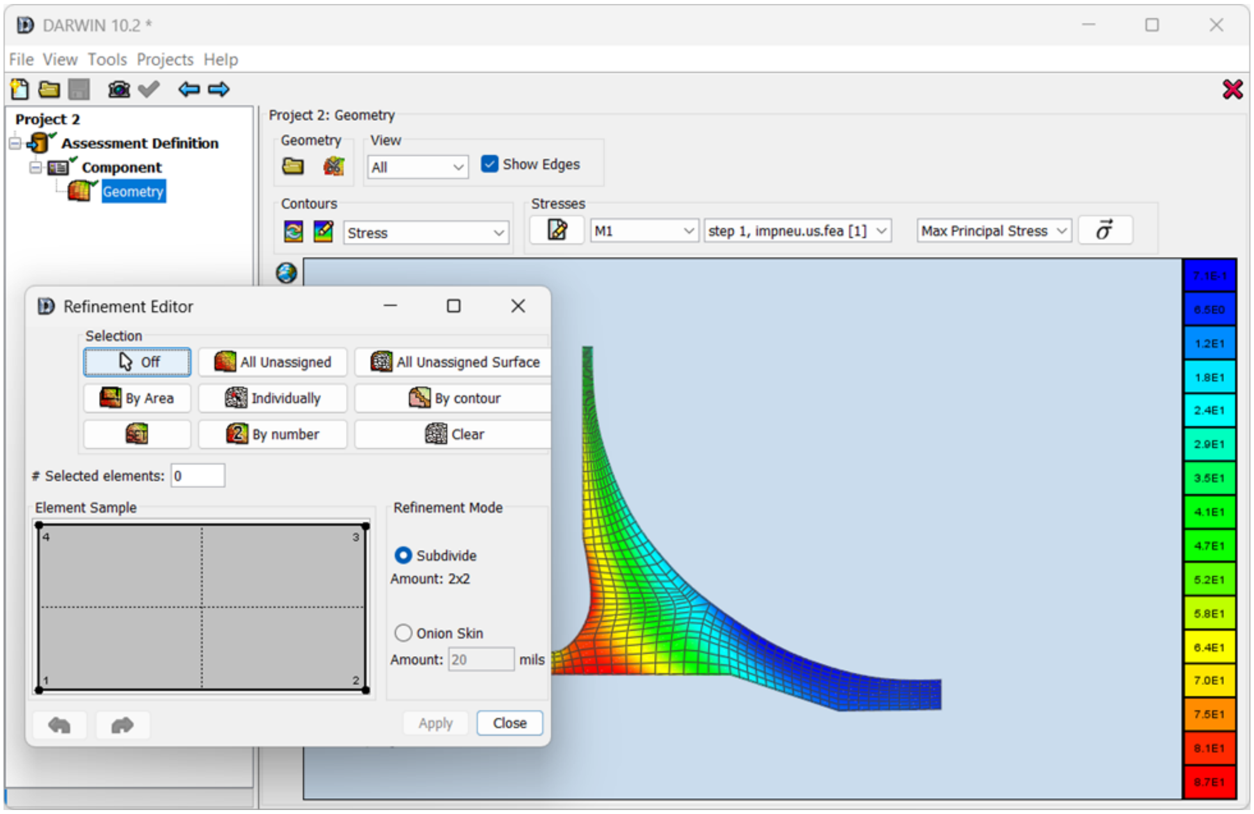


Figure 20: DARWIN 10.2 enables the element refinement process to be performed via a dedicated GUI instance that is independent of a DARWIN project.

Hot Corrosion Enhancements

Recent advances in gas turbine engine design have enabled higher service temperatures, which may increase the susceptibility for hot corrosion (HC) damage in some components. Coatings can sometimes be applied to prolong FCG lifetimes by delaying the formation of cracks at HC pits. However, coatings may also decrease FCG lifetimes due to cracks that may form prematurely in the coatings and propagate into the parent component material.

DARWIN 10.2 provides a new optional feature entitled **Ductile Coatings** for FCG life and risk assessment of components with protective coatings that are subjected to hot corrosion environments. It enables users to specify the locations of coatings by selecting element faces on the surfaces of FE models. Users specify parameters that are associated with ductile coating materials via a new **Ductile Coatings Components** menu (Figure 21).

In addition, DARWIN 10.2 includes several new enhancements for hot corrosion damage assessments:

- Hot Corrosion User Module. This new standalone module enables users to implement their own proprietary hot corrosion algorithms and link them directly with DARWIN.

- User Definition of Engine Parameters. The Mission Profiles screen has been enhanced to enable users to specify engine condition parameters for each mission that are associated with a hot corrosion analysis (Figure 22).
- GUI Visualization of Hot Corrosion Processes. A new post-processing screen entitled "Load vs Time" is now provided that enables users to visualize the timing and duration of active corrosion states for each zone (Figure 23). Several GUI post-processing screens have also been enhanced to display FCG life and fracture risk associated with cracks that form at both corrosion pits and ductile coatings.

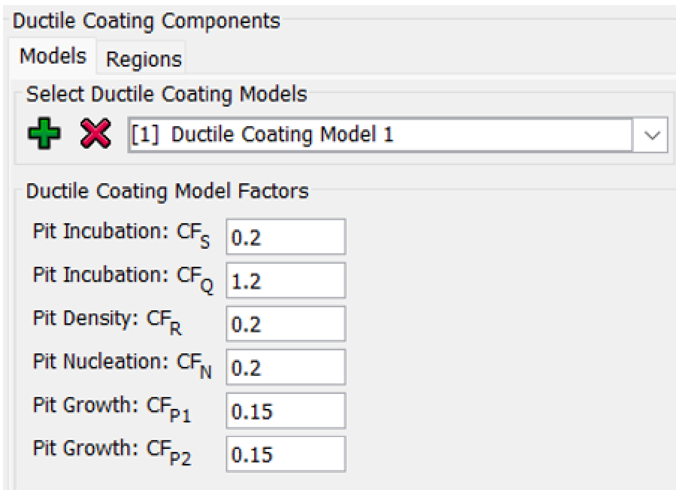


Figure 21: DARWIN 10.2 includes a new "Ductile Coatings Components" menu that enables users to specify parameters that are associated with ductile coating materials.

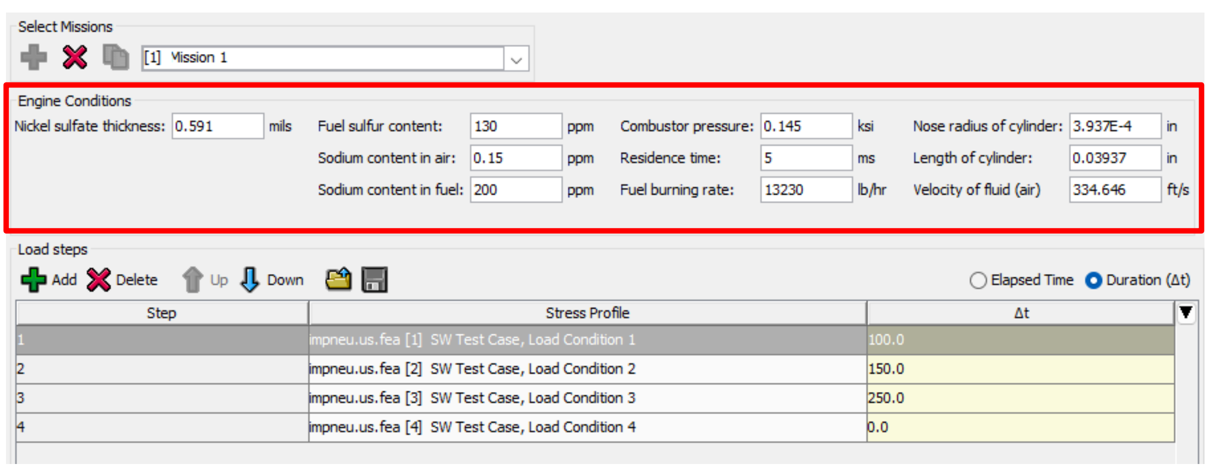


Figure 22: The Mission Profiles screen has been enhanced to enable users to specify engine condition parameters for each mission that are associated with a hot corrosion analysis.

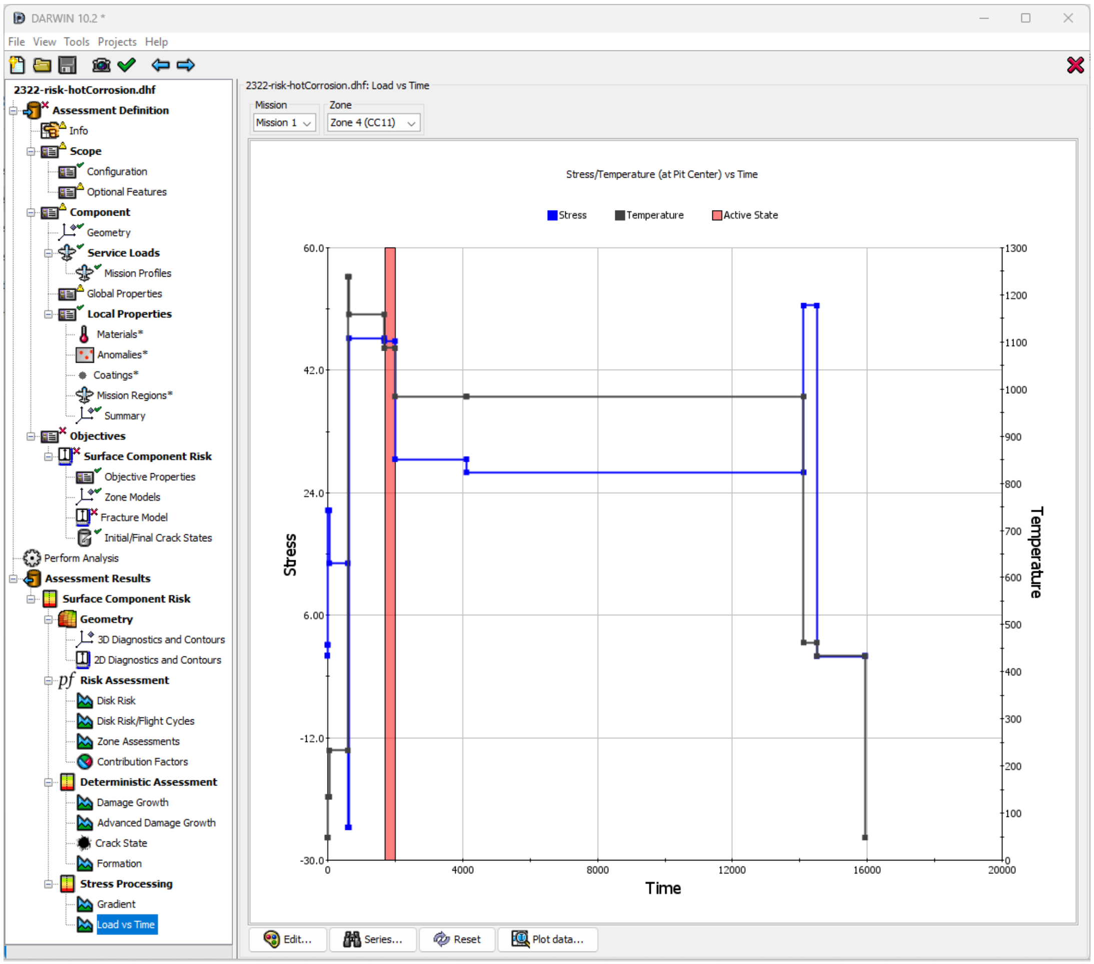


Figure 23: A new post-processing screen is provided that enables users to visualize the timing and duration of active corrosion states for each zone.

- <u>Import Hot Corrosion Parameters from an External File</u>. The DARWIN Anomalies Editor menu has been enhanced to enable users to define hot corrosion parameters in an ASCII formatted text file (*.hc) and import the file directly into DARWIN.

The hot corrosion enhancements and ductile coatings features are now available in the DARWIN "Life at Selected Points" and "Surface Component Risk" objectives. They can be applied to both 2D axisymmetric and 3D FE models.

Formation Module Programming Guidelines for Improved Execution Speed

The User Formation Module capability in DARWIN enables users to incorporate their own crack formation life algorithms for application to fatigue crack growth life and fracture risk assessments. The user is responsible for writing and compiling a formation module library using a set of source files that are distributed with DARWIN. An application programming interface (API) is included that enables the User Formation Module to exchange data with DARWIN during run time.

Some users have reported computational efficiency limitations when implementing and using their own crack formation life algorithms in the User Formation Module (UFM). A review of user-provided UFM libraries has revealed that the use of allocated arrays within the UFM may significantly increase the execution time associated with the use of this module.

In DARWIN 10.2, the programmer's documentation for the UFM has been enhanced to provide guidelines regarding the storage and retrieval of data within the module. Users are advised to retrieve project data from DARWIN's in-memory database (accessed via available API functions) on an as-needed basis rather than storing this information in local memory. The use of allocated arrays should also be avoided whenever possible.

The guidelines were recently applied to a UFM that was provided by a DARWIN customer. A review of the UFM identified several allocated arrays within the UFM. When the allocated arrays were removed, UFM computation time was reduced by a factor of 25.

Additional information, including specific programming examples, is provided in the User Formation Manual programmer's documentation.

Autoplate Speed Enhancement for Large 3D FE Models

The computation time of all DARWIN Auto-Modeling features is dependent on the speed of the Autoplate algorithm. When performing Auto-Modeling analysis of 3D FE models in previous versions of DARWIN, the Autoplate algorithm constructed a 2D FE model of the model geometry at the initial crack location. The resulting 2D FE model geometry and associated stress/temperature values were used for all Autoplate computations at that location. This process was repeated at each initial crack location, which was time-consuming for computation of FCG life and fracture risk contours in large 3D FE models.

In DARWIN 10.2, the FE2NEU finite element results file translator was enhanced to identify the finite elements that are located on the exterior surfaces of 3D finite element models. This information is provided to the Autoplate algorithm during run time, enabling it to quickly identify the boundaries of the 3D geometry that are coincident with the crack growth plane at each initial crack location. This enables Autoplate to extract geometry and stress/temperature information directly from the 3D FE model. This new capability reduces the computation time for Autoplate and associated Auto-Modeling operations for large 3D FE models. The impact of this enhancement on Auto-Modeling speed will vary depending on FE model size and desired project objectives.

Autozoning Random Access Memory Improvement

In previous versions of DARWIN, the random-access memory that was allocated for storage of zone information was based on the number of elements in the associated FE model. A substantial amount of memory (i.e., greater than available memory) was required to support large FE models with 500,000 or more elements. However, risk convergence is often achieved with fewer than 200 zones. DARWIN 10.2 was enhanced to allocate memory for storage of zone information based on a maximum of 1000 zones rather than on the number of elements in the FE model. This has significantly reduced the memory requirements for risk assessment of large FE models.

Critical Initial Crack Size (CICS) Speed Improvements

The DARWIN critical initial crack size (CICS) feature estimates the size of an initial crack that will grow to failure within a specified service life. CICS values can be computed at individual nodes or at all nodes in selected regions of a FE model (also known as CICS contours).

CICS generation is computationally intensive. It relies on an iterative (root-finding) operation to determine the initial crack size that is associated with a specified service life. This involves performing FCG life calculations from a candidate initial crack size multiple times. The iterative search can sometimes require ten or fifteen FCG life calculations at each node. The computational effort required to develop CICS contours for a large FE model may be significant.

The DARWIN CICS algorithm uses a combined approach of bisection and regula falsi methods in sequence to identify CICS values. In previous versions of DARWIN, the two bounding values at which the initial bisection search was initiated (i.e., bracket defined by lower limit a_{min} and upper limit a_{max}) were estimated internally by DARWIN based on the crack location and its associated fracture plate dimensions.

DARWIN 10.2 was enhanced to enable the user to specify initial values for a_{min} and a_{max} (i.e., CICS bounds, Figure 24). The limits provided by the user may be narrower or wider than the limits that are supplied by DARWIN. If the user-provided limits are wider than those supplied internally by DARWIN, the user-provided values of a_{min} and a_{max} are used as the initial values for the bisection search. If they are narrower, the DARWIN internal default values are used as the initial values for the bisection search.

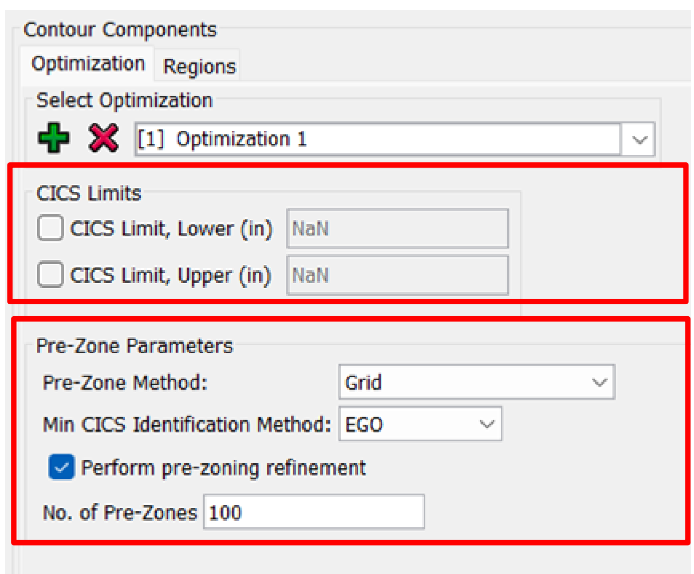


Figure 24: DARWIN 10.2 provides two new options (CICS bounds, CICS response surface) for improving the computation speed associated with CICS assessments.

DARWIN includes a pre-zoning method that has the potential to improve the computational efficiency of volumetric risk assessments. In DARWIN 10.2, the pre-zoning method was adapted for application to computation of CICS values. During execution, the pre-zoning method creates a response surface model of CICS values in each pre-zone based on CICS calculations at a pre-defined number of nodes within the pre-zone. CICS values are then estimated at all nodes in the pre-zone based on the value of the response surface at each node.

The speed improvement associated with the two approaches was evaluated via CICS analysis for four FE models with different numbers of elements. These models were based on a standard turbine engine disk with different mesh densities. The CICS bounds and response surface enhancements reduced computation time by 10%-75% and 80%-98%, respectively, for the FE models that were considered in the study. The generality of these results has not yet been established. Different choices for the CICS bounds would likely have different speed implications for different FE models.

DARWIN 10.2 also includes a new **Surface CICS Contour** objective. This objective allows users to assign a region to element faces rather than element bodies. This enables users to exclude embedded nodes from the project, which may substantially improve computation speed.

GUI Speed Enhancements for Large 3D FE Models

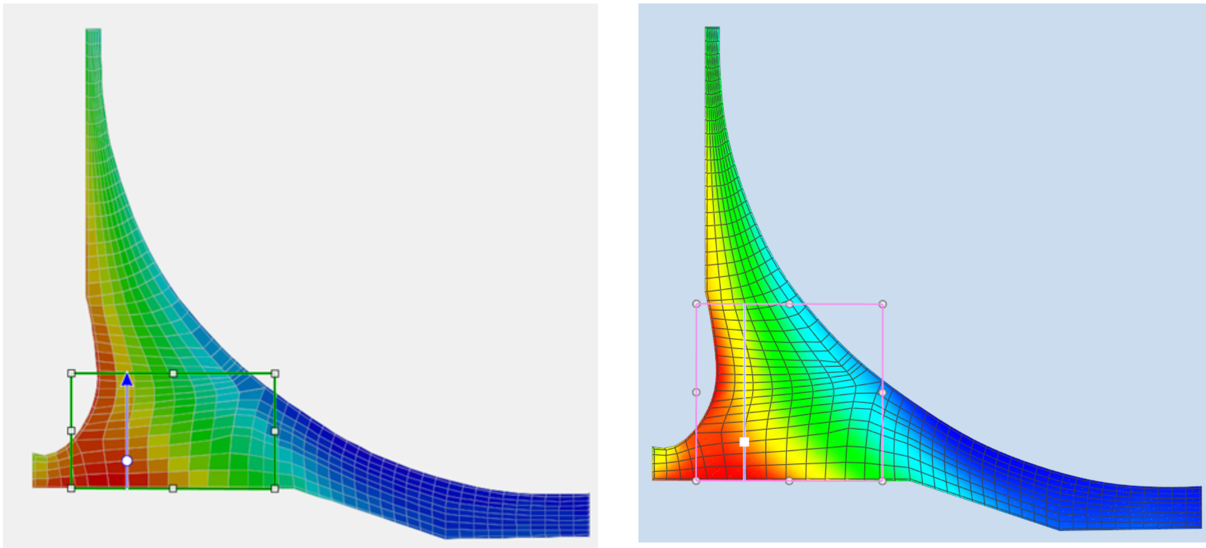
DARWIN 10.2 includes speed enhancements that may significantly reduce GUI response times when working with large 3D FE models. These enhancements involved streamlining the GUI source code to initialize data only for algorithms that are currently in use, refreshing only currently displayed contour values (rather than all contour values), and eliminating redundant display events. These speed enhancements have the most impact on geometry-related preprocessing operations such as assigning elements, selecting crack locations, and viewing stress/temperature contours for specific load cases.

The speed improvement associated with these enhancements was evaluated for GUI preprocessing tasks associated with fatigue crack growth life assessment at user-specified locations for an example 3D FE model with 1 million elements (Windows 10, dual 2.3 GHz processors, 16 GB allocated RAM). The GUI speed improvements reduced GUI response times by approximately 75%. Note that GUI response times for other FE models may vary depending on FE model size, number of project objectives, computer operating system, CPU power, and available RAM (among other factors).

Enhanced GUI Visualization of 2D Axisymmetric FE Models via VTK

The Visualization Toolkit (VTK) is an open-source rendering library implemented in C++ that is widely used for manipulating and displaying scientific finite element data. The DARWIN GUI uses VTK for efficient rendering and interaction of 3D geometries.

In previous versions of DARWIN, the GUI used a Java-based renderer for displaying 2D geometries. The renderer was developed many years ago and was relatively efficient for 2D FE models containing a few thousand elements. However, as FE model sizes have increased, the renderer has become less effective.



(a) **(b)**

Figure 25: GUI visualization of 2D FE contours via (a) previous Java-based renderer, and (b) DARWIN 10.2 VTK enhancement.

In DARWIN 10.2, the Java-based renderer that was previously used for manipulating and displaying 2D FE geometries has been replaced with VTK. In addition to providing improved computation speed, this enhancement also improves the display of color contours as shown in Figure 25.

New Capabilities for Viewing Legacy Results Files

DARWIN users desire and are encouraged to use the most recent DARWIN production release that is available on the DARWIN website. Users may occasionally need to review DARWIN files from previous DARWIN releases. These legacy DARWIN versions are available for download via the DARWIN website. Users also have the option to convert legacy files to a more recent DARWIN version. However, installing a legacy DARWIN version or converting legacy files may sometimes create delays in the review of critical legacy results files.

DARWIN 10.2 was enhanced to provide a new **Legacy Results Viewer** tool. It enables users to view results files from legacy DARWIN versions via the newest version of DARWIN (currently Version 10.2). Users may view both the input and results sections of results files without converting them to the newest DARWIN version.

The Legacy Results Viewer uses a new DARWIN version-specific DARWIN GUI Module (DGM) file to open a new GUI window that is associated with the selected DGM file (Figure 26). The Legacy Results Viewer window is marked with a red border and the word "READ ONLY" in the title bar. Within the Legacy Results Viewer window, users can open and view legacy projects created with the corresponding DARWIN version.

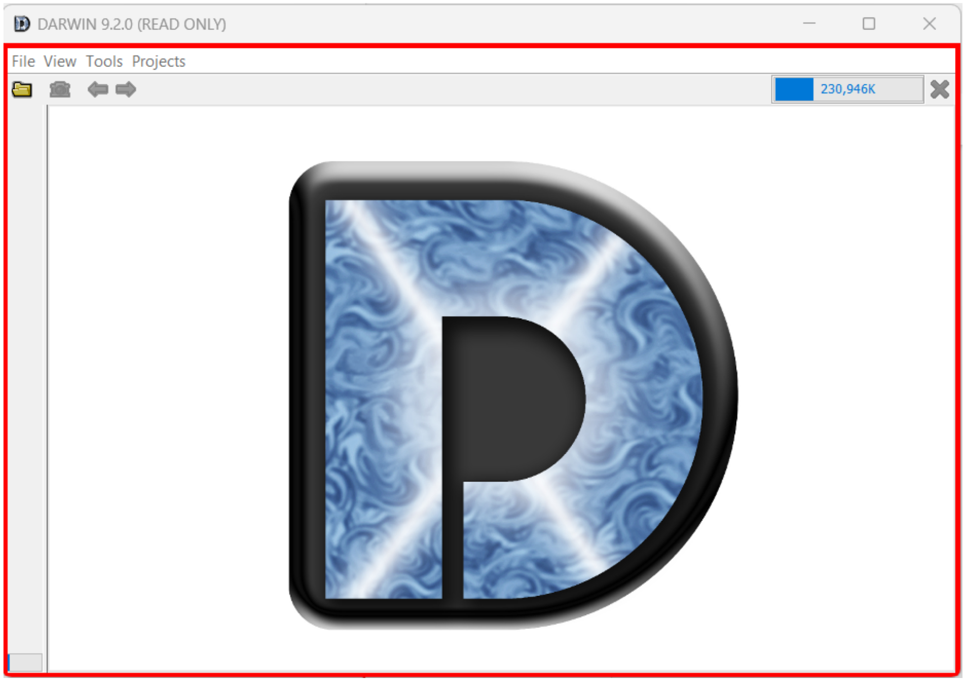


Figure 26: DARWIN 10.2 includes a new Legacy Results Viewer tool that enables users to view results files from legacy DARWIN versions. Note the red border indicating the "read only" status of legacy files that are viewed via this tool.

The new Legacy Results Viewer tool serves as a replacement for the file conversion tool that was provided in previous versions of DARWIN. Version-specific DGM files are available for download from the DARWIN website. DARWIN versions 9.0, 9.1, 9.2, and 10.0 are currently supported.

Fracture Model Export

DARWIN 10.2 includes a new capability to export fracture model parameters to an external file. The following data are provided in the file: crack type and location (in global XYZ coordinates), fracture plate dimensions, crack position relative to the fracture plate, stress magnitude/duration and temperature at the initial crack location, and the magnitude of stress along the crack path. This capability enables users to efficiently review the input values that are used for DARWIN analyses for external verification purposes. An example file is presented in Figure 27.

```
!DARWIN Exported Fracture Model

PROJECT_NAME
2D-Life-LifeAtSelectedPoints.dhf

UNITS                   US

LOCATION_NAME
Crack 1 (CC11)

CRACK_TYPE              CC11

MISSION_NAME
Mission 1

!Global Crack Location
CRACK_LOCATION          0.0          0.0          0.0

FRACTURE_PLATE
!xd yd Hx Hy Hx2 Radius
0.0 0.0 1.0 1.0 nan nan

LOAD_AT_CRACK_CENTER
!Duration Stress Temperature Load_ID
 0.0           100.0         100.0         1

STRESS
LOAD_ID                 1
!X_Local Stress
 0.0          100.0
 0.010101010101010102 100.0
 0.020202020202020204 100.0
 0.030303030303030304 100.0
 0.04040404040404041 100.0
 0.05050505050505051 100.0
```

Figure 27: Example output file illustrating the new Fracture Model Export capability available in DARWIN 10.2.

New Capabilities for Assigning Elements via Imported ANSYS CDB Files

Users routinely assign parameters (e.g., material properties, anomaly distributions, NDE inspections) to finite elements in various DARWIN analysis modes. ANSYS provides the capability for users to assign names to groups of elements and to export these relationships to external (*.cdb) files. This information may be useful for DARWIN users.

DARWIN 10.2 provides a new capability that enables users to assign properties to groups of elements via names that are defined in imported ANSYS *.cdb files. DARWIN 10.2 includes a new 8.0 release of the FE2NEU FEM converter tool that has been enhanced to enable users to import named finite element set definitions from ANSYS *.cdb files during conversion of ANSYS FE files, as shown in Figure 28. When setting up DARWIN project files, users have the option to assign parameters via the imported named element sets.

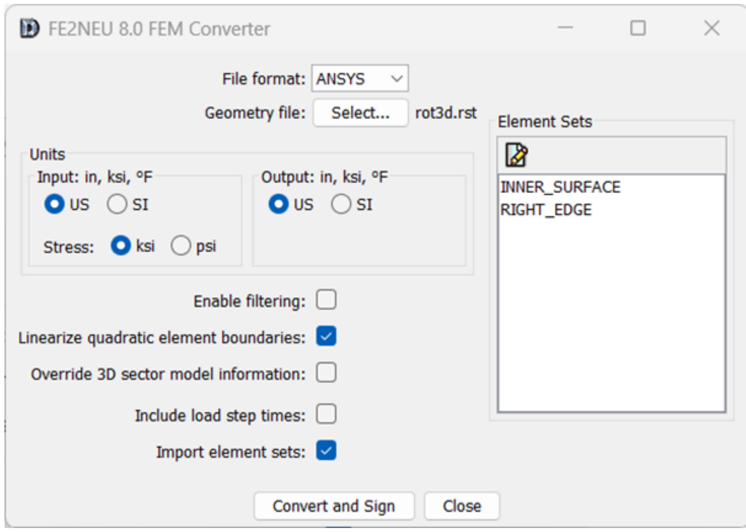


Figure 28: DARWIN 10.2 includes an enhancement to the FE2NEU FEM converter tool that enables users to import named finite element set definitions from ANSYS *.cdb files.

Focused Text-Based Results Files

DARWIN generates two results files upon completion of an analysis. One of the files is a binary-formatted file (*.dhf) that users can import into the GUI to view results. The other file is an ASCII-based text file called the DARWIN Output File (*.out). This file has increased in size substantially as new features have been added to DARWIN. The larger file size makes it more difficult for users to locate and review specific results. The *.dhf and *.out files are written independently, which can introduce the possibility of differences in the results among the two files.

DARWIN 10.2 includes an enhancement for ASCII-based output text files. Rather than outputting a single large file, it now provides a number of smaller text-based output files (called *.dex files) that are organized into folders that are searchable by users. This enables users to identify a smaller output file containing the desired data and to locate the specific output data in the file more quickly compared to the larger *.out file that was provided in previous versions of DARWIN. In addition, the data in the new *.dex files are obtained directly from the *.dhf file, which may help to reduce the possibility of differences in the results among the *.dhf and *.dex files.

In previous versions of DARWIN, *.out files were generated automatically after an analysis was completed. However, since users sometimes prefer to review results in the GUI and do not need to view the ASCII text files, DARWIN 10.2 no longer generates *.dex files automatically. A new capability was added to enable users to generate ASCII text files (via the GUI or command line) after a DARWIN run has been completed. When using the GUI, the files are generated by selecting the “DEX File Export” option in the File menu. When using the command line, the files are generated by adding the optional argument “EXPORT = True” to the standard DARWIN execution command:

```
{path to darwin.exe} {path to DARWIN project file} EXPORT=True
```

When this command is executed for a project that contains DARWIN analysis results, the *.dex results files are generated and stored in the same location as the DARWIN project file. Note that *.dex files are deleted during each project analysis to ensure consistency among the data in the *.dhf and *.dex files.

SIO File Converter Tool

Previous versions of DARWIN include the capability to import bulk residual stress data from manufacturing process simulations. The interface consisted of an ASCII-formatted FE results file that was created by the DEFORM manufacturing process simulation tool and imported into DARWIN. Substantial random-access memory was required to retrieve information from the ASCII-formatted file, so the interface was practically limited to relatively small FE models.

DARWIN 10.2 provides a new capability to import bulk residual stress data from manufacturing process simulations via a new binary-formatted (HDF5) file with subscript “HIO”. Rather than loading the entire contents of the file into memory, the HIO file format enables data to be retrieved on an as-needed basis, significantly reducing the random-access memory that was previously required for accessing data from these files.

DARWIN 10.2 includes a new **SIO File Converter Tool** that enables users to convert ASCII-formatted bulk residual stress data files (*.SIO) into the new binary-based (*.HIO) file format. The new tool is accessed via the Tools > SIO File Converter menu.