February 2, 2017

NASGRO v8.2 Release Notes

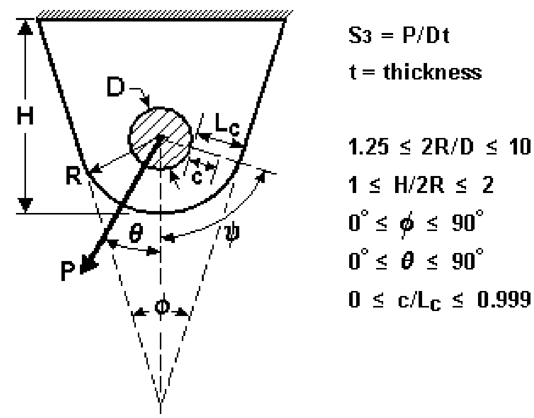
<u>Stress Intensity Factor Models:</u>

- **New Lug Solutions:**
  - **TC30 - Through Crack at Hole in Obliquely Loaded and Tapered Lug**
  - **CC23 - Corner Crack at Hole in Obliquely Loaded and Tapered Lug**

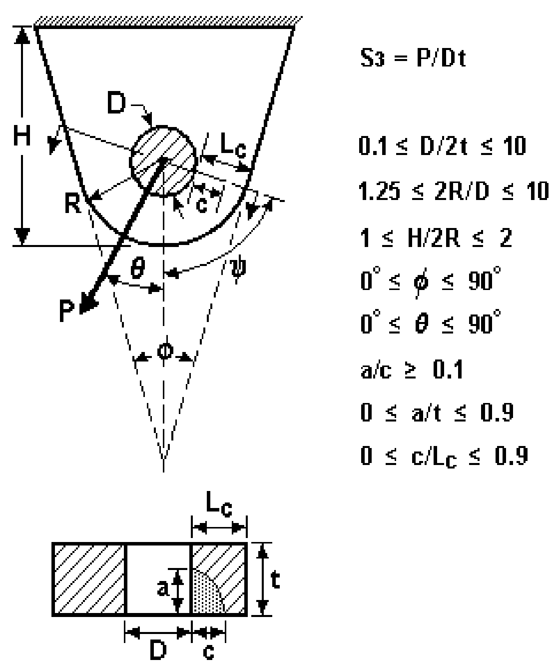
  Two completely new lug solutions are now available that model a through-thickness (TC30) or a corner crack (CC23) at the hole of a symmetric tapered lug under oblique pin loading. These are new univariant weight function (WF) solutions that utilize nonlinear stress distributions obtained from a large matrix of finite element analyses (FEA). They are distinct and separate from earlier lug solutions that assumed straight, short lugs under vertical loading.

  These models consider a neat-fit pin/hole condition, and the FEAs employ state-of-the-art contact algorithms to include the friction and contact between the pin and the lug. Cracks initiate at the location of maximum opening stress that maintains the minimum crack growth ligament. These WF models can also accommodate residual stresses. Additional detail on the development and verification of these new lug models is contained in Appendix C of the User's Manual.

TC30



CC23



- **Revisions to CC16 & CC17 Finite Width Correction Factors for Pin Loading**

The stress intensity factor solution CC16 combines solutions from the Fawaz-Anderson database of wide-plate solutions with finite-width and offset correction factors to compute K-values. These solutions apply to elliptical corner cracks at offset holes in finite-width plates under tension, out-of-plane bend, and pin loading. CC16 was first implemented in NASGRO version 7.1. It was discovered during the v8.0 development cycle that CC16 results for pin-loaded holes (and only pin-loaded holes) in narrow plates could be excessively non-conservative. Therefore, a modified finite-width correction factor for pin-loaded CC16 was developed based on the CC08 solution, which had been modified to accommodate pin-loading and to widen the geometry range significantly. Further study of this revised solution indicated that, while accurate for narrow plates with centered holes, these values could be over-conservative for narrow plates with holes highly offset from the centerline. Therefore, a second CC16 revision focusing on the hole-offset correction factor was developed, verified, and implemented in v8.1a. Once again, the revised CC16 solution only changed K-values under pin-loading – solutions for tension and out-of-plane bending have been unaffected. These solutions were applied to CC17 starting in 8.01 and 8.1f.

Even further study revealed non-physical oscillations – "peaks" and "troughs" – in the solution introduced by the interpolation process. These "peaks" and "troughs" only influenced relatively small cracks ($a/t \leq 0.2$) at small holes ($D/\min(2B, 2 \times (W - B)) \leq 0.5$). The oscillations themselves tend to reduce the overall effect on fatigue lives. Some portions of the fatigue crack growth curve will give crack growth rates that are too low due to low stress intensity factor values. Other portions of the fatigue crack growth curve will give rates that are too high due to high stress intensity factor values. It is unclear exactly how these changes will impact fatigue crack growth lives overall, but the errors may effectively cancel out in some cases.

Several attempts were made to eliminate the non-physical oscillations in the solution. Adding more points to the solution matrix shifted the oscillations to other parts of the solution space, even if the solution matrix tripled in size. NASGRO 8.2b changed the solution space in only the small crack regime and left the remainder of the solution space untouched. Unfortunately, this modification introduced a discontinuity in the stress intensity factor solution at the boundary ($a/t = 0.2$). This discontinuity was triggered by fundamental differences in the two interpolation schemes. This approach has been abandoned.

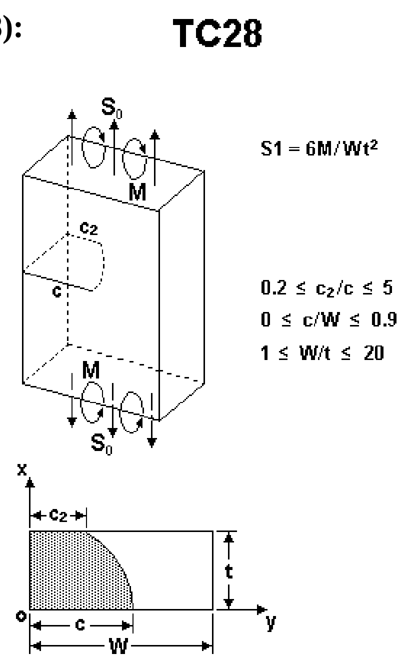
NASGRO 8.2f takes the radical step of changing the entire parameterization for pin-loaded CC16 to eliminate the non-physical oscillations. This approach eliminates the non-physical oscillations and improves the solution quantity. It does not introduce any discontinuities into the solution. The new parameterization scheme interpolates over the relative hole size rather than over the relative crack depth. Consequently, stress intensity factors in NASGRO 8.2f will differ from stress intensity factors in earlier versions of NASGRO. These changes only affect cracks under pin-loading. Again, it is unclear exactly how these changes will impact fatigue crack growth lives overall, but the differences may effectively cancel out in some cases. Preliminary investigations with these new pin-loaded geometry correction factors have revealed lower lives for: 1) cracks on the long ligament side of highly offset holes as $0.5 \times D/(W - B) > 0.5$ and 2) cracks in very thick plates where $D/2t \to 0.1$. In this second case, additional studies suggest that both the old and new geometry correction factors are systematically conservative.

The new correction factor routines are based on a look-up table of nearly 53,000 solutions at various non-dimensional ratios, again based on the current CC08 solution. The look-up table was derived by comparing CC08 solutions for wide plates with CC08 solutions for narrow plates with offset holes. For a given geometry, the routines determine the appropriate correction factor by interpolating over the relevant solution space that includes both finite-width and hole-offset effects. These new correction factors provide improved CC16 solutions for pin-loading that are usually within 10% of benchmark stress intensity factor solutions, as evaluated by a matrix of 162 benchmark K-solutions from 3D finite element models with explicitly meshed crack fronts.

CC17 uses the same pin-loaded geometry correction factors as CC16. Consequently, these modifications to the geometry correction factors propagate to the pin-loaded solutions of CC17 as well. Stress intensity factors computed in NASGRO 8.2f show similar agreement to benchmark values as the stress intensity factors in NASGRO 8.1f.

Additional details on the development and verification of the CC16/CC17 finite width correction factor for pin loading are provided in Appendix C of the User's Manual.

- **New Curved Through Crack at Edge of Plate (TC28):**



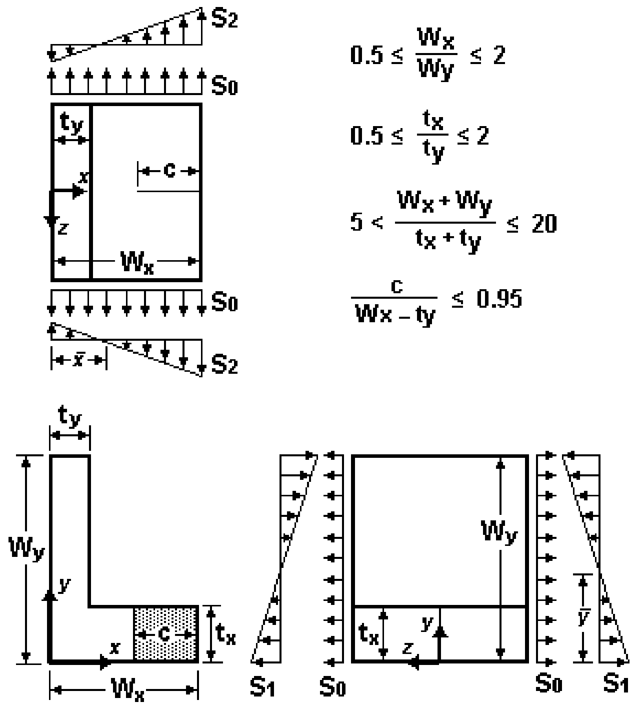
This new univariant weight function (WF) solution models a through crack with a *curved* crack front at the edge of a plate. The two crack tips, respectively denoted by *c*-tip at the front surface and c_2-tip at the back surface, are assumed to be located along a curved crack tip perimeter described by an ellipse centered at the bottom-left corner of the rectangular cross section.

TC28 can accept remote tension and linear out-of-plane bending stress loadings (S0 and S1) or it can accept a univarient stress gradient in the thickness direction S(X). Additional detail on the formulation of this model is contained in Appendix C of the User's Manual.

- **New Through Crack in L-section under Remote Loading (TC31 & TC32):**

The TC31 solution features a through crack in ***one*** leg of an L-section under remote stresses. TC31 places the through crack on the cross-section and normal to the axial length of the structural member. TC31 restricts the through crack to be straight and normal to free surfaces. TC31 contains stress intensity factor (SIF) solutions for cracks under remotely applied uniform stresses and univariant stress gradients. TC31 limits the crack to one leg of the L-section, i.e., it does not turn the corner of the section. At this time, TC31 does not restrain bending.

TC31



$$0.5 \le \frac{W_x}{W_y} \le 2$$

$$0.5 \le \frac{t_x}{t_y} \le 2$$

$$5 < \frac{W_x + W_y}{t_x + t_y} \le 20$$

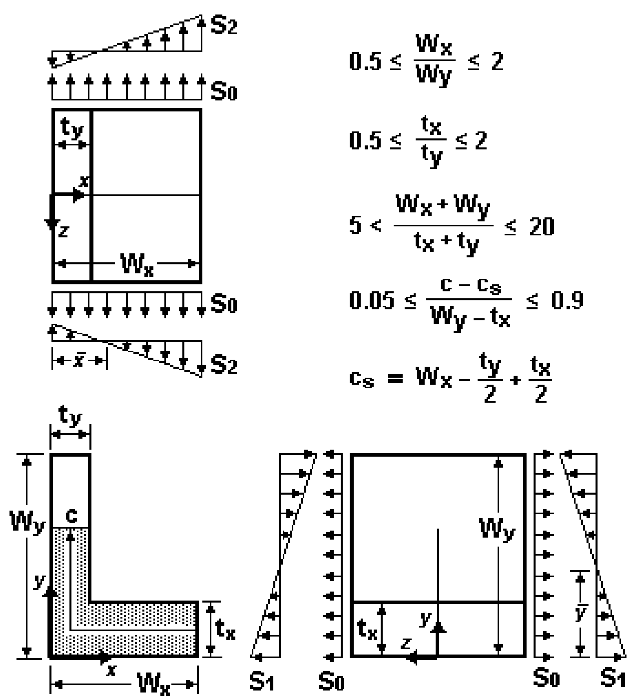
$$\frac{c}{W_x - t_y} \le 0.95$$

The TC32 solution features a through crack in ***two*** legs of an L-section under remote stresses. TC32 places the through crack on the cross-section and normal to the axial length of the structural member. TC32 restricts the through crack to be straight and normal to free surfaces. TC32 contains SIF solutions for cracks under remotely applied uniform stresses and univariant stress gradients. TC32 considers the crack to be in two legs of the L-section, i.e., it has turned the corner of the section. At this time, TC32 does not restrain bending.

TC31 will transition to TC32 with no life (zero cycles) being expended as the crack grows around the corner.   This is a simplifying, but conservative, assumption.

Additional detail on the development and verification of these new models for through cracks in an L-section is contained in Appendix C of the User's Manual.

TC32



$$0.5 \le \frac{W_x}{W_y} \le 2$$

$$0.5 \le \frac{t_x}{t_y} \le 2$$

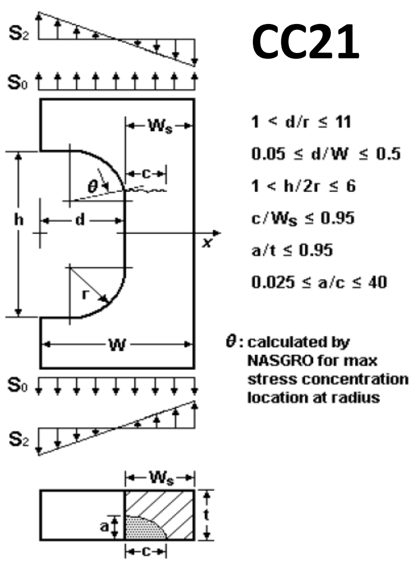
$$5 < \frac{W_x + W_y}{t_x + t_y} \le 20$$

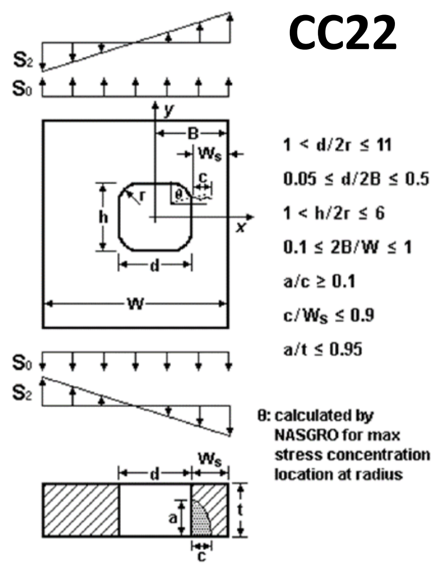
$$0.05 \le \frac{c - c_s}{W_y - t_x} \le 0.9$$

$$c_s = W_x - \frac{t_y}{2} + \frac{t_x}{2}$$

- **New Corner Crack at Rectangular Cutout with Rounded Corners (CC21 & CC22):**

  The crack configurations for CC21 and CC22 are very similar to TC25 and TC26, respectively. Both models represent cracks at the rounded corner of a rectangular cutout in a plate. CC21 models a corner crack at a rectangular cutout at the edge of a plate, whereas CC22 models a corner crack at an internal (offset) rectangular cutout in a plate. The initiation site of the corner crack, the highest stress concentration location, designated by the angle θ, is numerically determined in accordance with the approach used for TC25 and TC26. These corner crack models utilize the crack opening stress extracted along the crack plane and compute the stress intensity factors at both surface tips using the weight function formulation, as described in Appendix C of the User's Manual.





- **Extension of K Solutions for Arbitrary Internal Notches to Thin Sheets**

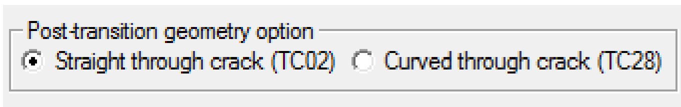
  The geometry limits of the following internal notch (slot or elliptical hole) models were extended to better handle thin sheets: CC14, TC18, and TC26. The new limits are shown in the GUI for each crack case as well as in Appendix C.

- **Tension/Bend Option Added to CC11, TC11, and TC12**

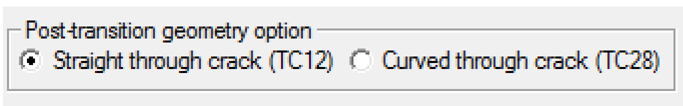
  These three univariant weight function models previously only permitted input of stresses on the crack plane (in tabular or polynomial formats). The capability was added to enable users to now provide tension and bending remote loadings.

- **Optional Transitions from Corner Crack in Plate to Curved Through Crack**

  With the implementation of the new through crack with a *curved* crack front at the edge of a plate model (TC28, discussed above) the user now has the ability to optionally select TC28 as the post-transition geometry for the following corner crack in a plate models: CC01, CC09, and CC11. The default remains a transition to a *straight* crack front model. On the geometry page, the GUI provides radio buttons for the user to optionally select the curved through crack (TC28) as the post-transition option:



CC01



CC09 & CC11

- **Superseded Models:**

  The following crack cases have been moved to the "superseded solutions" group:

  - CC03 – (use CC19 instead)
  - SC12 – (use SC32 instead)
  - EC02 – (use EC05 instead)
  - BE02 – (use TC23 instead)
  - BE03 – (use HC01 instead)

  These models may still be used but are no longer recommended. They are being retained in the "superseded solutions" group for historical and comparative purposes. Note that the "Boundary Element Solutions" category has also been removed from the menu of crack case categories, since both BE solutions have been moved to the "superseded" category.

- **Revised Geometry Limits & Transition Criteria for WF Solutions**

  - A comprehensive review of geometry limits and related transition criteria for "newer" WF solutions led to some minor adjustments for consistency between solutions
  - Newer limits are less restrictive and may lead to slight increases in calculated lifetimes, although differences may be very small in some cases
  - Notable changes:
    - SC30 & SC31: limits on crack center offset removed entirely
    - SC30 & SC31: limits on $c/\min(B, W\text{-}B)$ now consistently 0.95 (some previously 0.9 or 1.0)
    - SC18: limits on crack center offset (T/t) removed entirely
    - CC09 and CC11: a/t and c/W limits now consistently 0.95 (some previously 0.9)

NASGLS Upgrades & Additions:

- The NASGLS computing engine has been upgraded and is now able to handle 3-dof and 4-dof crack cases.

- The following crack cases have been added to the NASGLS module:
    - CC11, SC30, SC31, EC04, EC05

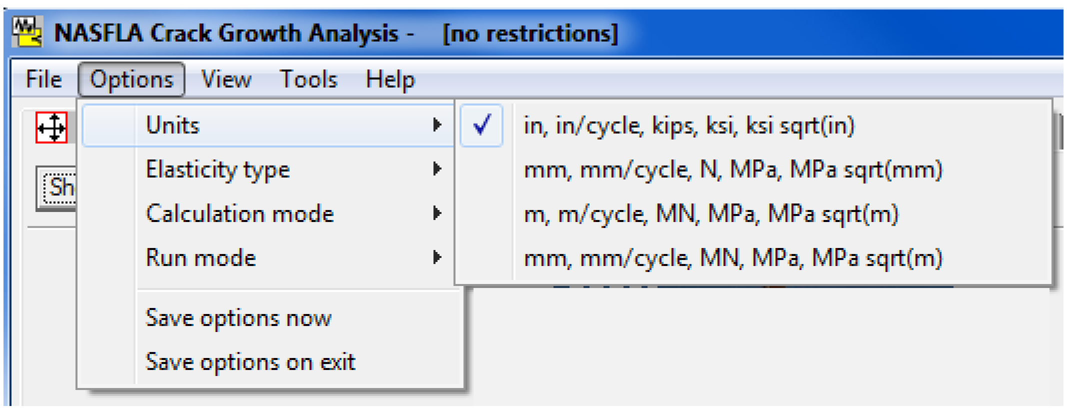
New Sets of Metric Units

Two new sets of Metric units have been added to NASFLA, NASSIF, and NASCCS. These are:

m, m/cycle, MN, MPA, MPA sqrt(m)

mm, mm/cycle, MN, MPA, MPA sqrt(m)

The user can now choose between four sets of units as shown below by clicking on Options/Units from the main menu bar in NASFLA, NASSIF, and NASCCS as shown below.

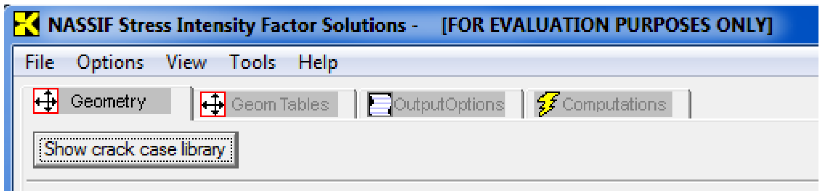


Additional points to note about these two new units systems:

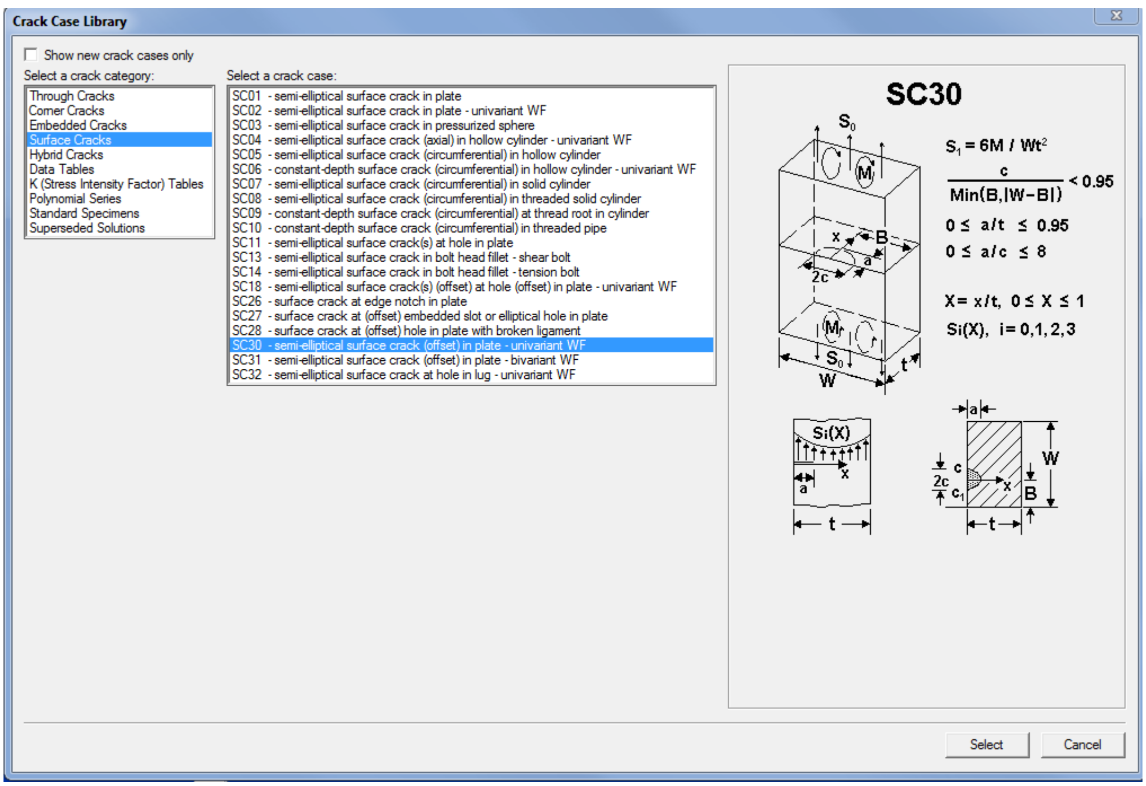
- These two new systems are <u>not</u> available in NASGLS, NASBEM or NASFORM.
- These two new systems are <u>not</u> available for the “Constant Closure” or “Strip Yield” load interaction models.
- The {m, m/cycle, MN, MPA, MPA sqrt(m)} units system previously existed in NASMAT. Now, NASMAT fits performed in this set of units can be saved to the NASFLA materials file.
- The {mm, mm/cycle, MN, MPA, MPA sqrt(mm)} units set is <u>not</u> be supported in NASMAT at this time.

New GUI for Crack Case Selection

The graphical user interface (GUI) used to choose and select the NASGRO crack cases (stress intensity factor solutions) has been re-designed for all modules (NASFLA, NASSIF, NASCCS, and NASGLS). When any of these modules are first opened a button named "Show crack case library" appears as shown below:

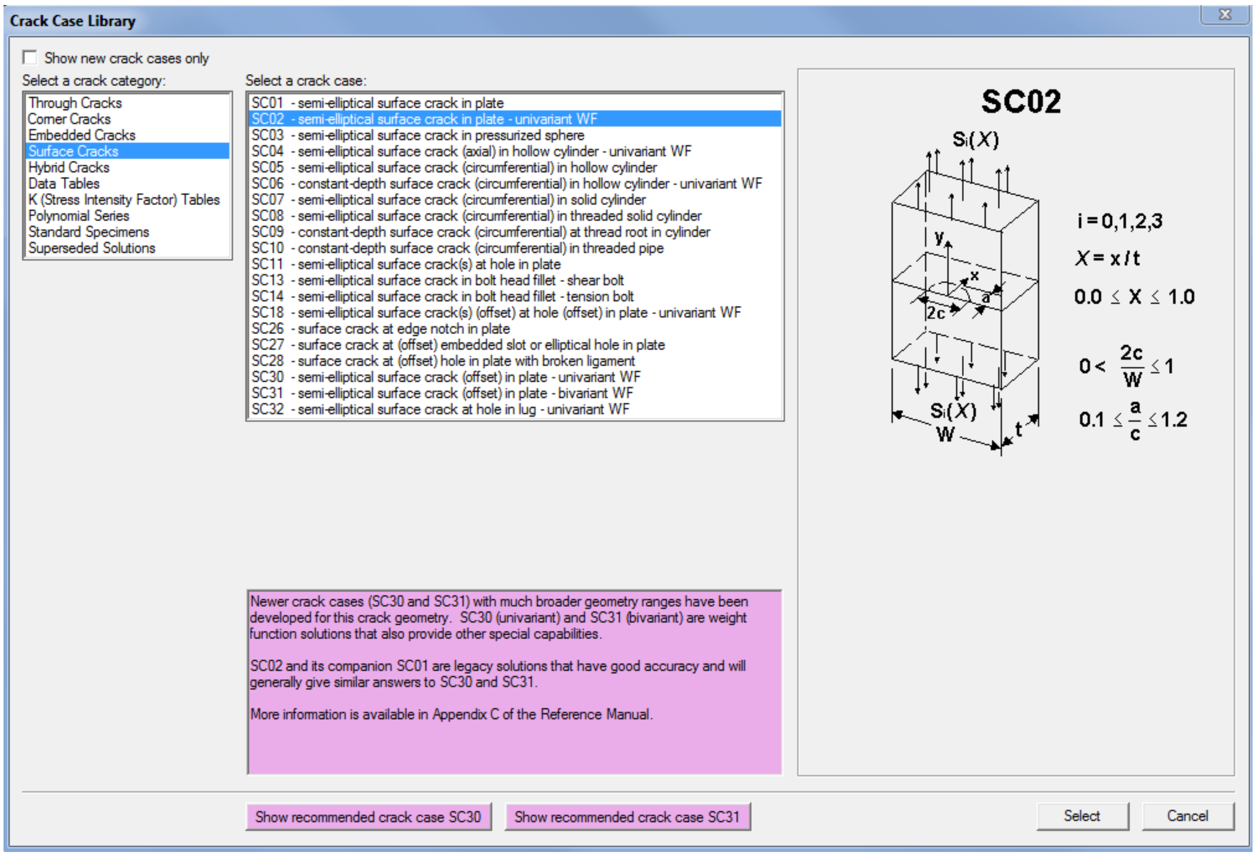


Clicking on the "Show crack case library" opens up the Crack Case Library screen which enables the user to first choose the crack category and then the crack case (and the drawing of the model and limits are automatically displayed). Note that the previously used pull-down menus have been removed. An example is shown below using SC30.

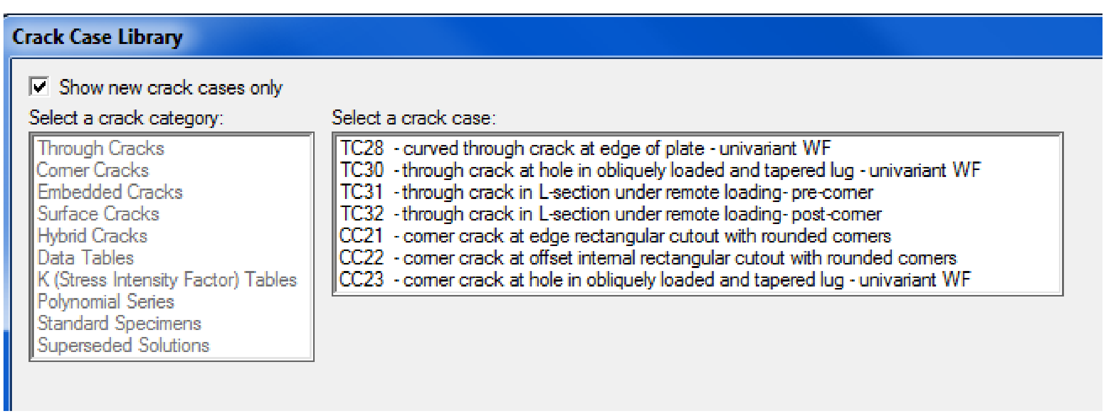


A key feature of this new GUI for displaying and choosing crack cases is that the user can easily view different crack cases (witihin a chosen crack category) and have the drawing displayed automatically for easy review and deciding on which model to use in the analysis. Once that decision is made, then the user would click on the "Select" button to proceed with specifying the geometry details and continue setting up the analysis for that module.

Previous versions of NASGRO displayed pop-up notes or warnings for a number of crack cases that provided guidance to the user regarding the limitaions of some of the legacy models and recommedations for using newer crack cases instead. These pop-ups have now been replaced by text boxes displayed directly in the GUI as shown below using SC02 as an example. Note that below the text box are buttons that allow the user to show the recommended model choices before making the final model selection for use in the analysis.



There is also a checkbox at the top of the Crack Case Library screen that allows the user to display the new crack cases first introduced in this version, as shown below. The user can now easily explore the features of the new crack cases without having to search through the entire lists of different crack categories and cases.



Saving User Changes to 1D and 2D Tabular Material Data to User File

After loading 1D or 2D tabular user material data from file into the NASFLA GUI, any manual changes made to that data on-screen can now be immediately saved to the user file, using the new button “Save Data To User File”. Previously available only for the “NASGRO equation” data format, this feature is now also available for both “1D tabular” and “2D tabular” user data formats. Changes made to existing user tabular data, as well as “New (tabular) Data” that is entered, may be saved to the user tabular material file. The changed data can be saved to file under the same ID, or as an entirely new material ID, to the same user file from which the original data was read. “New Data” entered will always be saved as a new material ID to the tabular material file that is specified by the user. If a new material ID is created from changes to existing file data, that material ID will also be loaded automatically into the NASFLA GUI’s Material tab after it has been added to the file.

Configuration Control Improvements:

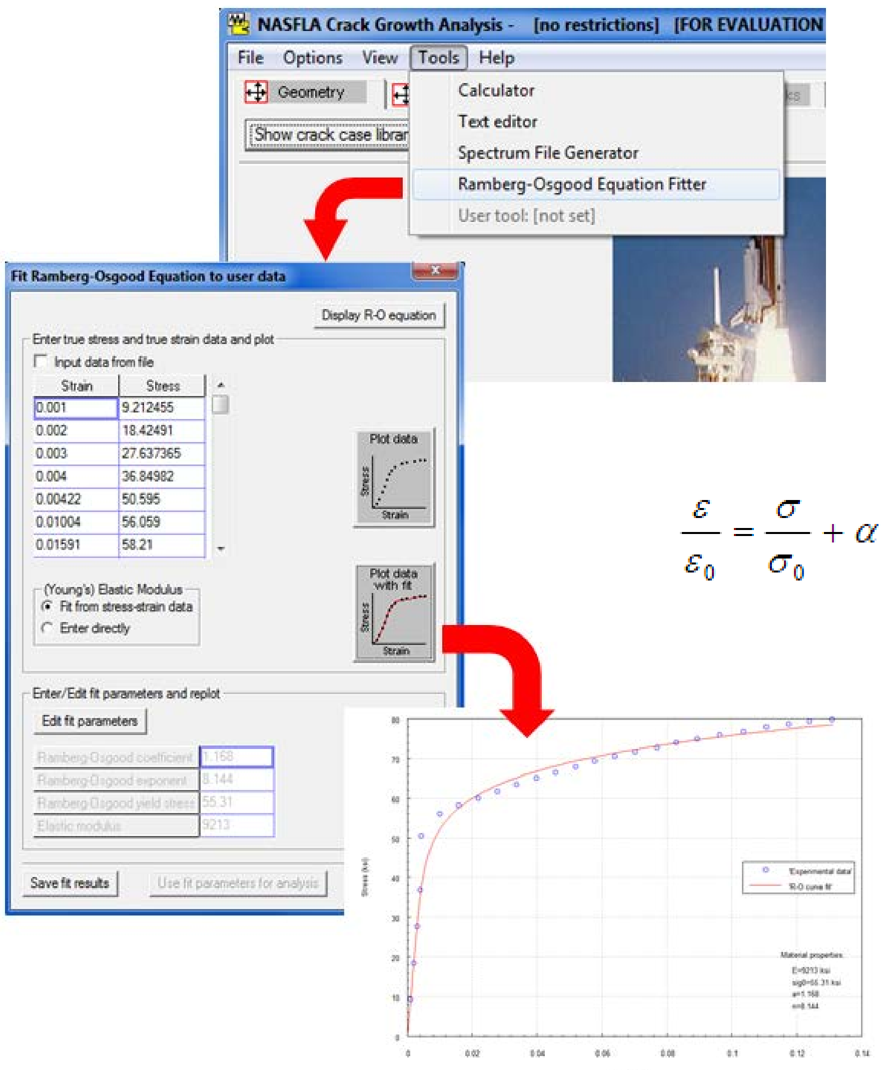
Profile files have been updated to allow compatibility between versions. Any profile generated by version 8.2b or later will now be compatible with future versions of the Configuration Control GUI. Previously, profiles were not designed to be compatible between versions.

Menu items have been added to duplicate the existing functionality of the following buttons: “Add/Edit Manager’s Notes”, “Remove All Restrictions”, and “Create Control File” located at the bottom of the Configuration Control GUI. This is to accommodate some laptop users whose displays and screen resolutions were not capable of displaying the full height of the GUI, preventing the display of those buttons.

Ramberg-Osgood Stress-Strain Curve Fitting Tool:

An analysis tool to curve-fit tabular true stress-strain data to the Ramberg-Osgood equation was developed and is accessible via the "Tools" menu at the top of the NASFLA GUI. The units used will be those in effect by default or as changed using Options/Units.

This tool reads true stress-strain data from a text file (or accepts manual input) and enables users to easily generate the parameters of the Ramberg-Osgood equation for use in the Failure Assessment Diagram (FAD) analysis approaches that require it (FITNET Option 3 and API/ASME Method B) as well as for other NASGRO analysis options such as shakedown). It has the capability to graphically display and output the original data alone as well as a combined plot of the fit and the original data. The figure below shows an example of the GUI displays and resulting fit for the Ramberg-Osgood fitting tool using a "notional" material.

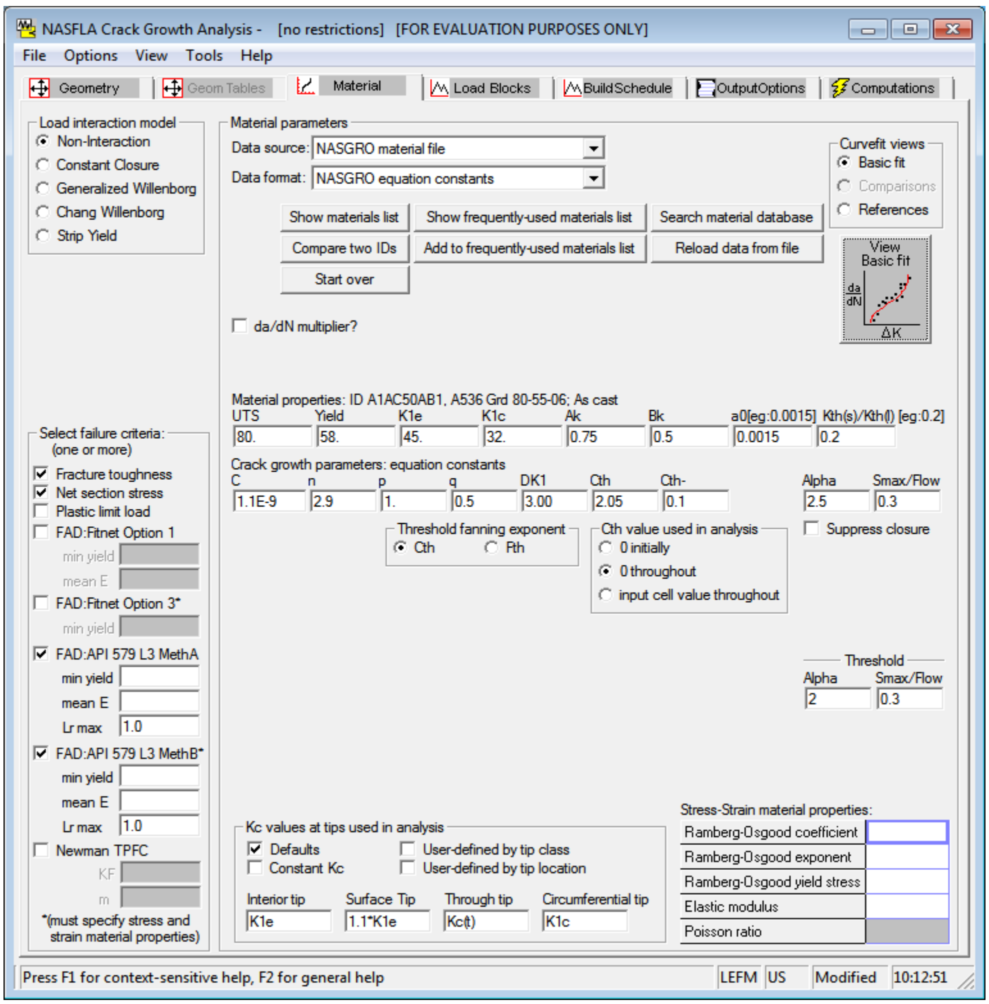


$$\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_0} + \alpha\left(\frac{\sigma}{\sigma_0}\right)^n$$

Example of the Ramberg-Osgood fitting tool GUI and resulting fit for a "notional" material

New ASME FFS/API-579 FAD Approach:

NASGRO has the capability of using a Failure Assessment Diagram (FAD) as one of the "Alternate Failure Criteria" described in Appendix X of the NASGRO User's Manual. Previously, there were two FAD options available in NASGRO as outlined by the FITNET[1] procedures. Now, in NASGRO v8.2, the ASME FFS/API-579[2] failure assessment diagram methods have been incorporated into NASGRO. The "Select failure criteria" box on the material page has been expanded and slightly rearranged to accommodate the new ASME FFS/API-579 FAD options as shown below. The new GUI arrangement will allow the user to select *either* the FITNET FAD approach *or* the API/ASME FAD approach *but not both*. Complete details of the implementation of all the alternative failure criteria in NASGRO are provided in Appendix X of the NASGRO User's Manual.



Example of the NASFLA material screen showing the addition of the ASME API 579 FAD options in the "Select failure criteria" box

---

[1] *FITNET Fitness-For-Service (FFS) Procedure*, M. Koçak, S. Webster, J. J. Janosch, R.A. Ainsworth, and R. Koers, Editors, 2008.

[2] *Fitness-For-Service*, API-579-1/ASME FFS-1, June 5, 2007.

Application of Surface Crack Closure Correction Factor to SIF Models

Updates and fixes have been made regarding the application of the surface crack closure correction factor as shown in the table below. This revised table is also included in Section C14 of Appendix C. Table entries in **bold red font** indicate fixes and changes made in v8.2f.

Surface crack models

Crack case	Crack closure factor (β_R) used: a-tip	c-tip	a1-tip	c1-tip	Crack case	Crack closure factor (β_R) used: a-tip	c-tip	a1-tip	c1-tip
SC01	No	Yes	N.A.		SC13	No	N.A.		
SC02	No	Yes			SC14	No			
SC03	No	Yes			SC17	No	Yes	N.A.	Yes
SC04	No	Yes			SC18	Yes	No	Yes	N.A.
SC05	No	Yes			SC19	No	Yes	N.A.	Yes
SC06	No	N.A.			SC26	Yes	No	Yes	N.A.
SC07	No				SC27	Yes	No	Yes	
SC08	No				SC28	Yes	No	Yes	
SC09	No				SC30	No	Yes	N.A.	Yes
SC10	No				SC31	No	Yes	N.A.	Yes
SC11	Yes	No	N.A.		SC32	Yes	No	Yes	N.A.
SC12	Yes	No							

Corner crack models

Crack case	Crack closure factor (β_R) used: a-tip	c-tip	a1-tip	c1-tip	Crack case	Crack closure factor (β_R) used: a-tip	c-tip	a1-tip	c1-tip
CC01	Yes	Yes	N.A.		CC13	No	No	N.A.	
CC02	Yes	Yes			CC14	Yes	Yes		
CC03	Yes	Yes			CC15	No	No		
CC04	Yes	Yes			CC16	Yes	Yes		
CC07	Yes	Yes			CC17	Yes	Yes	Yes	Yes
CC08	Yes	Yes			CC19	Yes	Yes	N.A.	
CC09	No	No			CC20	**Yes**	**Yes**		
CC10	Yes	Yes			CC21	**Yes**	**Yes**		
CC11	No	No			CC22	Yes	Yes		
CC12	No	No			CC23	Yes	Yes		

Standard specimens

Crack case	Crack closure factor (β_R) used: a-tip	c-tip	a1-tip	c1-tip	Crack case	Crack closure factor (β_R) used: a-tip	c-tip	a1-tip	c1-tip
SS08	Yes	No	N.A.		SS11	Yes	Yes	N.A.	
SS09	Yes	Yes							

Boundary element solutions and Hybrid crack model

Crack case	Crack closure factor (β_R) used: a-tip	c-tip	a1-tip	c1-tip
BE03	Yes	Yes	N.A.	
HC01	Yes	Yes	N.A.	

Color-coded solution type:

- (yellow) Uni-variant weight function solution
- (green) Bi-variant weight function solution
- (blue) Displacement-controlled crack model

Additional Changes, Fixes and New Items by NASGRO Module for v8.2 Final

February 2, 2017

	Applicable NASGRO Module										
Category	NASGRO Main	Config Control	NASFLA	NASSIF	NASCCS	NASGLS	NASMAT	NASBEM	NASFORM	Users Manual	**Description**
Fix			X								For multi-temperature plotting, the values of the plot coordinates saved to text file were incorrect, due to an unnecessary antilog conversion being performed.
Fix				X							CC08 NASSIF analysis using D/B ratios at solution limits caused a run-time error. There were two issues involved. One was the solution limits posted in GUI bitmap for D/B were incorrect. The second was that the error caught by DLL did not terminate the computation right away and thus crashed the GUI.
Fix			X	X	X	X					Crack Case CC08: The geometry limits for D/B have been updated from "0.1 <= D/B <= 1.9" to "0.02 <= D/B <= 1.8"
Fix			X								The beta-correction factors for surface crack tips for CC20 and CC21 crack models were missing. This has been fixed and the surface beta-correction table in Appendix C was also updated.
Fix			X								When changing units, the user-entered values for "Kc values at tips used in analysis" options was not being properly converted.
Fix					X						Disabled the irrelevant check (the NSY check) in calculation of threshold crack size calculation
Fix			X								When reading 2D tabular material data from file, records containing more than nine R-values will not be read (since the table in the GUI that displays this data holds a maximum of nine R-values). An error message will be issued stating the record selected exceeds the maximum number (9) of allowed R-values. The user will then be required to edit that record for it to be read successfully by the GUI.
Fix			X								Some 2D tabular material data could not be loaded into the NASFLA GUI, due to the user data exceeding the current table capacity, which has since been increased.
Fix			X								CC01 NASFLA analysis with HCF threshold check resulting in slightly longer life when compared with the result from v8.1f. The discrepancy was found from incorrect initialization of HCF parameters that overwrote the input value. The update should give the same result as those from v8.1f.
Bug fix			X								On the Build Schedule tab, when choosing to load schedules from file, schedules would not load stress scale factors or file names on the Load Blocks tab.
Known Issue & Workaround			X								When plotting multitemperature material IDs in the NASFLA GUI, saved PNG files are missing text from the plot legends and axes labels. The current workaround for this issue is to copy the plot “to screen” image, which is correct, to the clipboard (make that plot image window active by clicking on the title bar, then press Ctrl+C), from which it can then be pasted (press Ctrl+V) into an MS Word document and saved, or into MS Paint and saved as either a .PNG or .JPG file.