A Simulation Tool for Fatigue Analysis and Lifecycle Prediction

Daniel Kujawski*, Phani C.R. Sree, Deepak Abburi and Joshua T.L. Kuok

Western Michigan University
Mechanical and Aerospace Engineering, Kalamazoo, MI 49008-5343, U.S.A.

Abstract: *This paper presents an interactive web-based simulation tool for a modern fatigue analysis and lifecycle prediction methodology of smooth and notched components. Users around the globe with diverse degree of fatigue familiarity may access it via Internet by means of multiple platforms such as desk- and lap-top computers, tablets and/or smart-phones. In particular, the users with a limited fatigue analysis background would benefit from "on-the-fly" fatigue learning experience. This is accomplished by means of proper guidance through a step-by-step process and providing specific details and explanations without the need of a tutorial handbook. It makes a self-explanatory and frustration free web-based simulation software, which allows users to learn the fatigue fundamentals while expanding their knowledge on modern fatigue analysis methods. For variable amplitude loading a dedicated spectrum analysis tool is provided for a potential clean-up and desire modifications of a raw spectrum data. Subsequently, a rainflow method is used and the corresponding hysteresis loops at the notch-root are determined. Then, the relevant interactive graphs, calculated values and tables are displayed. The web-based learning tool can be accessed at www.fatiguenet.com.*

Keywords: Web-based software, fatigue analysis, notch stresses, Neuber's rule, spectrum loading.

1. Introduction

In general, fatigue damage occurs in materials when subjected to variable amplitude stresses that are below the ultimate tensile strength, or even the yield strength of the material (Dowling, 2013). To avoid fatigue cracking, components are designed by allowing a sufficient safety factor. Too high of a safety factor would result in bulky and expensive components. Hence, R&D departments employ highly trained engineers to perform fatigue analysis on components before and during prototype development. This involves extensive time and resources to create new designs. Due to cut offs in R&D budgets many new designs are based on old and proven designs. In the global and highly competitive market, the R&D departments are mostly afforded by relatively large organizations. Routinely the R&D departments acquire dedicated fatigue software. On the other hand, smaller organizations seldom have R&D departments but they may have a periodic need for fatigue analysis. Therefore, there is an overall demand for a straightforward web-based fatigue analysis tool accessible via Internet, which can be used occasionally. Specifically, in an age of technological advancement, which is growing exponentially, there is an increasing trend that students in colleges shift more towards an 'e-learning' platform to grasp knowledge outside of the classroom environment.

In order to carry out a meaningful fatigue analysis, requires some fundamental fatigue life analysis knowledge, which most students would not have learned during their undergraduate studies. Also, most practices in small companies are limited when it comes to fatigue analysis and life prediction know-how experiences. For more than a decade, fatigue analyses websites are available on-line (e.g. References 4-6). At present, these websites provide material database and elaborated fatigue analyses that also include fatigue crack propagation and multi axial fatigue analyses. Hence, this paper is focused on a simple, self-explanatory and interactive web-based fatigue analyses learning tool dedicated to the first time or unexperienced users.

Nomenclature			
E	modulus of elasticity	ε'_f	fatigue ductility coefficient
b	fatigue strength exponent	$\Delta\gamma/2$	shear strain amplitude on critical plane
c	fatigue ductility exponent	σ_a	normal stress amplitude
FS	Fatemi-Socie parameter	σ_{ar}	fully reversed stress amplitude, applied
k	coefficient in Fatemi-Socie parameter	$\sigma_{ar\,G}$	fully reversed stress amplitude, Goodman
k_t	elastic stress concentration factor	$\sigma_{ar\,M}$	fully reversed stress amplitude, Morrow
k_f	fatigue notch factor	$\sigma_{ar\,SWT}$	fully reversed stress amplitude, SWT
$2N_f$	number of reversals to failure	σ'_f	fatigue strength coefficient
R	stress ratio, $\sigma_{min}/\sigma_{max}$	σ_m	mean normal stress
S	nominal normal stress	σ_{max}	maximum normal stress
SWT	Smith-Watson-Topper parameter	σ_{min}	minimum normal stress
ε_a	normal strain amplitude	$\sigma_{N\,max}$	maximum normal stress on critical plane
$\varepsilon_{a\,e}$	elastic strain amplitude, σ_a/E	σ_u	ultimate tensile strength
$\varepsilon_{a\,p}$	plastic strain amplitude, $\Delta\varepsilon_p/2$	σ_y	yield strength

The aim of this paper is to present an interactive web-based tool for learning a modern fatigue analysis and life prediction methodology of smooth and notched components. The web-based tool may be easily accessed by means of multiple platforms such as desktop and laptop computers, tablets and/or smart-phones, as illustrated in Fig. 1. Users with limited fatigue background would benefit from the proposed interactive "on-the-fly" learning experience. At each step, concise fundamental fatigue information is provided without the need of a tutorial handbook. It constitutes interactive, self-explanatory web-based educational tool, which allows the users to learn the fatigue fundamentals as well as to expand and master their knowledge on modern fatigue analysis methods. It can be used alone or in tandem with commercial FEA software.

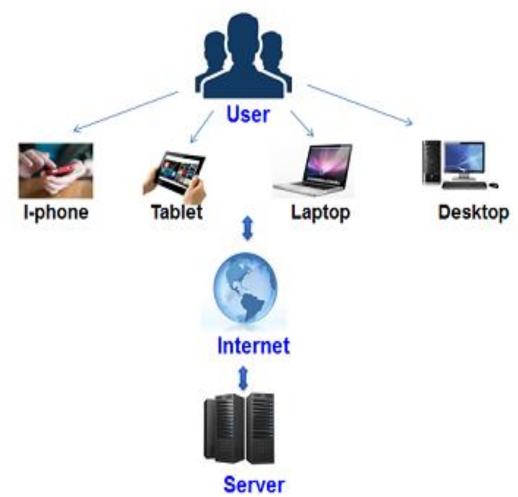


Figure 1 Illustration of the web-based access.

For variable amplitude loading histories a rainflow method is used to count the cycles and to determine the corresponding hysteresis loops at the critical locations. In addition, a dedicated spectrum analysis tool is provided, which enables clean-up and desired modifications of a raw spectrum data such as to eliminate midpoints, truncate or clip a given spectrum. During analysis the relevant interactive graphs and calculated values are displayed. The following sections provide a summary of the proposed web-based interactive fatigue analysis learning tool.

2. Structure/flowchart of the web-based software

The core structure of the proposed web-based software shown in Fig. 2 provides multiple options for users to select. Unexperienced or first time users could be confused given so many options. In order to assist such users, brief explanations and tips for each step are provided as shown in Appendix. The objective of these explanations together with provided equations regarding fatigue life predictions approaches is to map-up common similarities and differences among them.

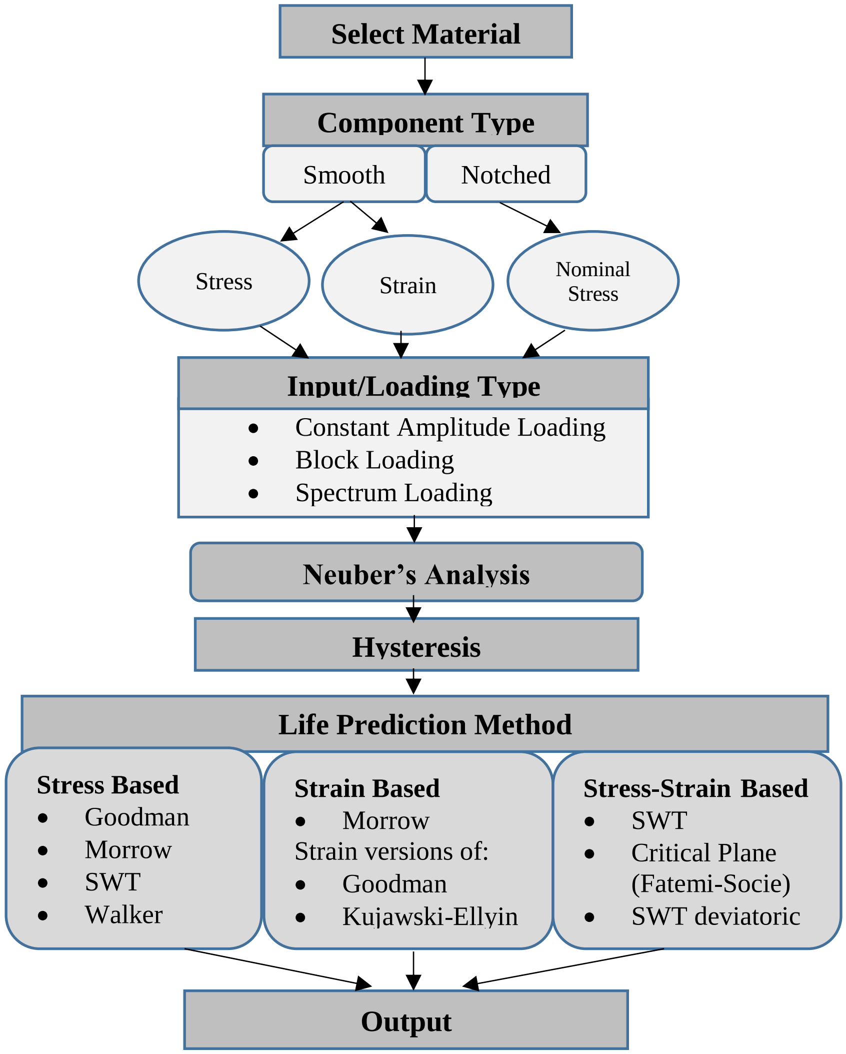


Figure 2 General structure of the educational version of the web-based fatigue analysis tool.

3. Web-based software

The website is structured to be simple and self-explanatory, flowing from Step 1 to Step 7, as shown in Fig. 3. The current website features an educational version of the software along with video examples of using the software. The website also provides additional spectrum analysis software to prime the raw spectrum data before fatigue life prediction analysis can be carried out using the educational version. In this section, the analysis procedure is discussed with different options available on the website. As the user enters the website (www.fatiguenet.com), the home page is presented. Under 'Educational Version', the 'Software' tab is selected, which presents the life predication software. Below are the steps involved with explanation and screenshot of the steps depicted in Fig. 3. In this educational version, the user would be presented with helpful tips and information at each step.

Step 1: Select Material

In this step, the desired material, units (SI or English), and language are selected. The educational version provides five different materials with an additional option to input user defined material properties. Six languages: English, Chinese, French, German, Japanese, Russian, and Spanish are available to select with English being default language.

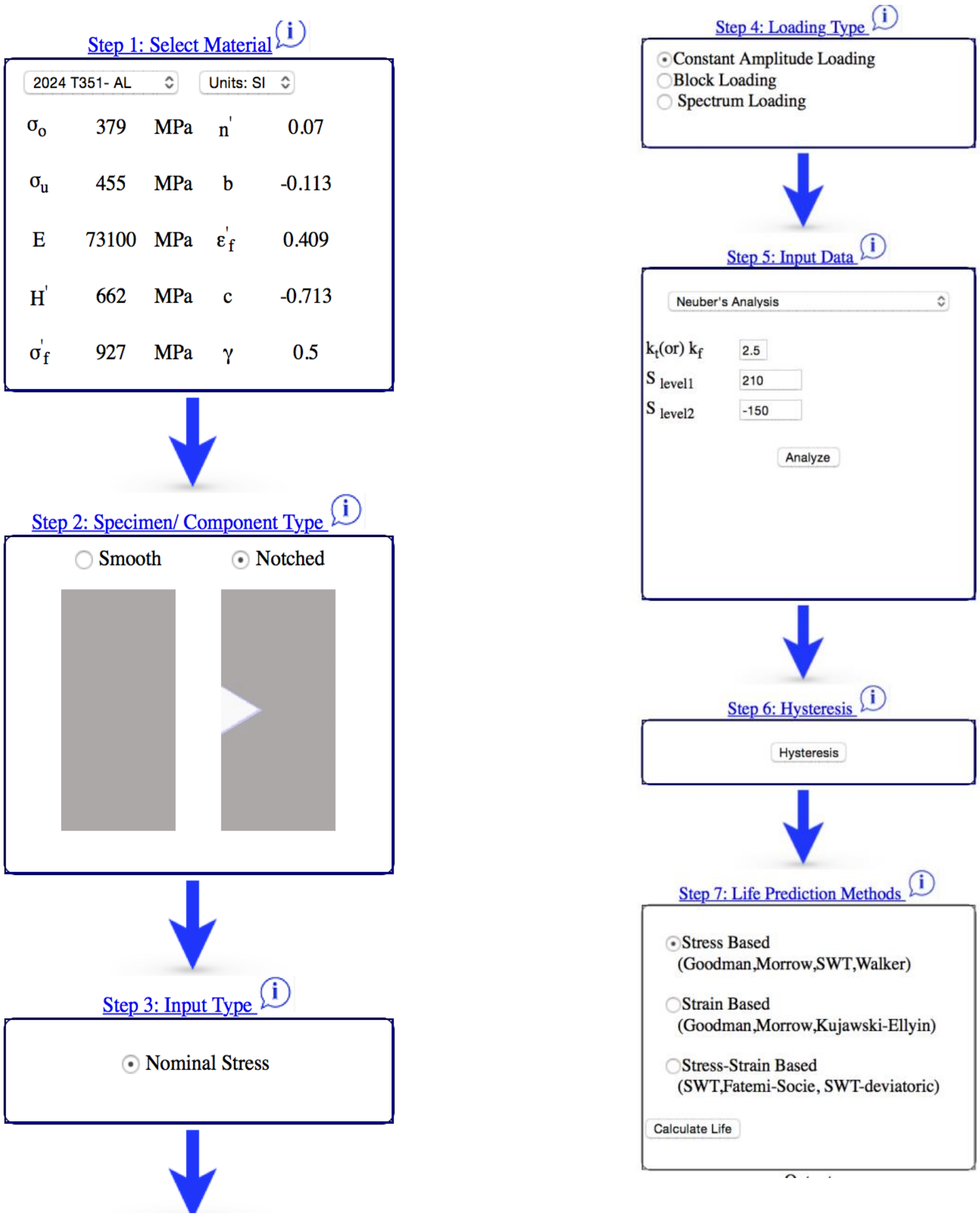


Figure 3 Screenshot of Step-1 to Step-7 from website.

Step 2: Specimen Type

In this step, the users are provided with an option to choose a smooth or a notched specimen/component. The ‘smooth’ is used in generic terms, i.e. it applies to notches when the local elastic/plastic strains and stresses are known, e.g. from FE analysis. Selecting a smooth specimen would result in a k_t value of 1 to be used in the analysis, which the users cannot change. On the other hand, for a notched specimen the users would be able to input the desired k_t (or k_f) value ($k_t = 2$ is default) in the proceeding step. A plasticity corections for notch-root stresses and strains are obtained using Neuber’s rule (Neuber, 1961).

Step 3 : Input type
If smooth specimen is selected in Step 2, users would have the option to select either stress or strain as the input data type. If notched specimen is selected the nominal stress, S_n , is the input data type (where $S_n < \sigma_y$).

Step 4: Loading Type
The user can select three loading types to be analyzed. The software is designed to analyze the following loading types:

1. Constant Amplitude
2. Block Loading
3. Spectrum Loading

.
Step 5 : Input Data
In this step k_t (or k_f) value is specified. If smooth specimen is selected in step 2, the value is displayed as 1 and cannot be altered. In case of a notched specimen, the default value is 2 but may be changed according to the users need. For a constant amplitude loading the user shall specify the loading levels as $S_{level\ 1}$ and $S_{level\ 2}$. Loading always starts from zero and continues towards *Level 1*, which can be the maximum or the minimum stress. Proper information is displayed if the user chooses *Block Loading* or *Spectrum Loading* options.

Step 6 : Neuber's Analysis/Hysteresis Loop(s)
Selecting "*Analyze*" in Step 5 displayes Neuber's curve (the upper curve in Fig. 4a) which is interacting with the Ramberg-Osgood stress-strain curve (the lower curve in Fig. 4a). For a given material the interactive Neuber's curve is valid for any value of the product of S_n and k_t (or k_f). Also, instead of $k_{t*}S_n$ (or $k_{f*}S_n$) value, the elastic notch-root stress can be used and the Neuber's curve will provide the corresponding plasticity correction for estimated elastic-plastic stress and strain. It can be noted that a deviatoric formulation of Neuber's rule (Kujawski, 2014) is not active in this educational version.
Then, selecting the 'Hysteresis' button displays the hysteresis loop shown in Fig. 4b or loops for the *Block Loading* or *Spectrum Loading* options.

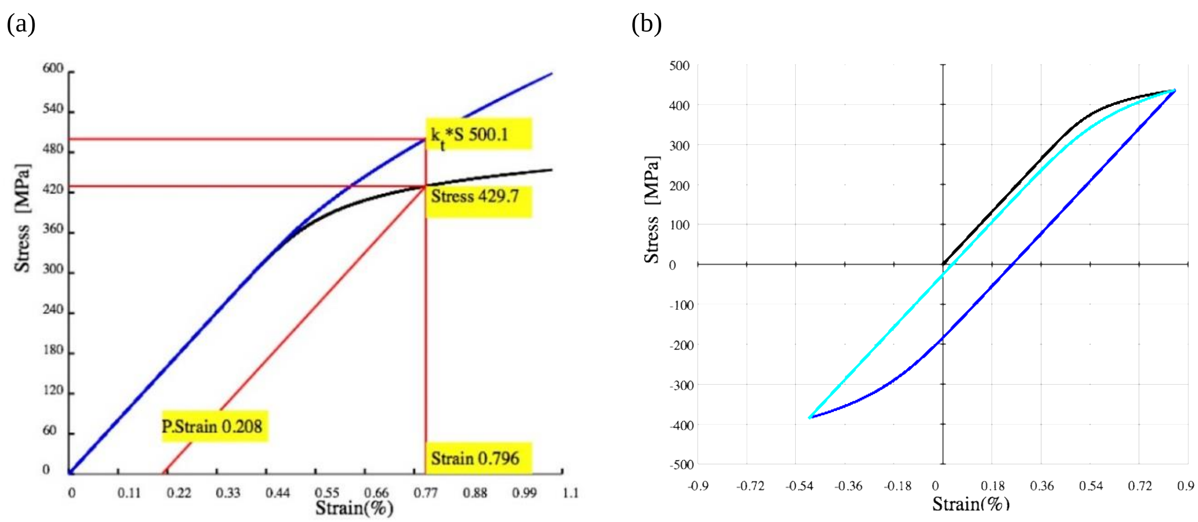


Figure 4 Screenshot of (a) the interactive Neuber's graph and (b) the hysteresis loop.

Step 7 : Life Prediction Methods
In this step the life prediction method based on stress, strain or stress-strain is selected. The stress-based approach includes four well known approaches for mean stress effects, i.e. (Goodman, 1930), (Morrow, 1968), (Smith, 1970) and (Walker, 1970). Strain-based approaches consist of Morrow (Morrow, 1968) and the strain versions of Goodman and Kujawski-Ellyin (Kujawski, 1995) models. The SWT parameter (Smith, 1970) is available as the stress/strain-based method. A critical plane method of Fatemi-Socie (Fatemi, 1988) and the deviatoric formulation of the SWT parameter (Kujawski, 2014) are not actve in this educational version.

The output window provides a consolidated numerical values for maximum, minimum, mean and amplitude of stresses and strains at the notch tip. The life predictions graph is depicted in Fig. 5 and the corresponding fatigue lives are provided in Fig. 6. After completion of the analysis, three printing options are avalilable such as: print this page, print this table, and print explanations (Fig. 6).

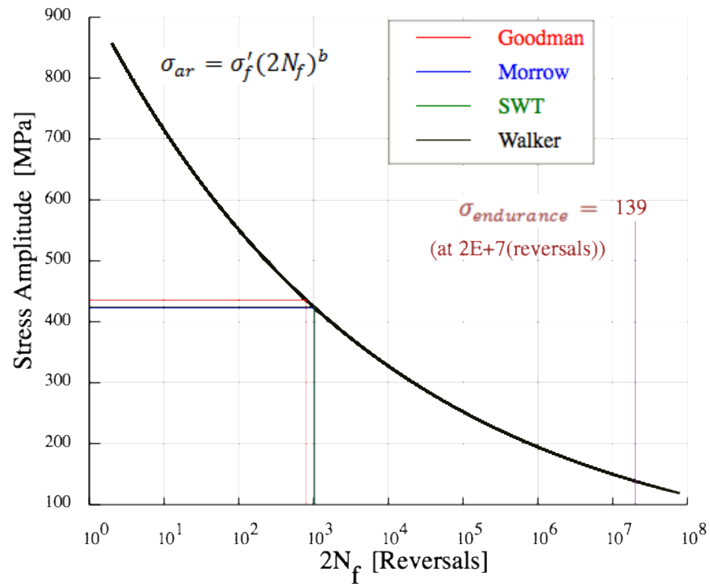


Figure 5 Screenshot of graphical representation of life prediction for various approaches.

Material name:2024 T351- AL	Goodman	Morrow	SWT	Walker
Life(Reversals)	794	1036	1016	1016
σ_{ar}	436	423	424	424
$\sigma_{a,endurance}$	147	143	141	143

Print this page   Print this Table   Print Explanation

Figure 6 Screenshot of comparison table showing numerical values of life prediction.

4. Spectrum Analysis Tool

Besides the life analysis software, the website also provides a spectrum analysis tool to prime/optimize the raw spectrum data before fatigue life analysis can be carried out. The software is divided into 5 main steps:

1. Cleaning
2. Rainflow method
3. Removing small cycles
4. Clipping
5. Truncation

The software also consists of short explanation videos for the 5 steps listed above to assist user in further understanding each process.

4.1 Cleaning

Spectrum analysis should always only contain peaks and valleys in its data. In this step, a raw spectrum data would be cleaned by removing its intermediate points, and thus leaving only peaks and valleys in the spectrum data so that it can be used for spectrum analysis.

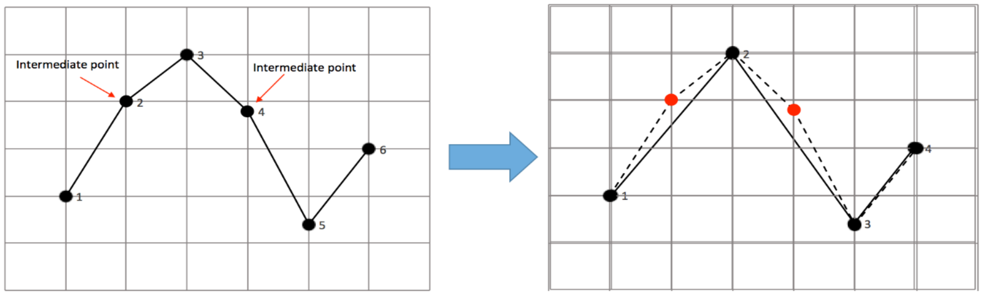


Figure 7 Intermediate points removal - before and after cleaning.

As depicted in Fig. 7, the raw spectrum data had 6 points in total, which consists of 2 intermediate points. Once the cleaning process is done, the 2 intermediate points were removed, the graph on the right in Fig. 7. Hence, now leaving only 4 points when compared to the initial 6 data points.

4.2 Rainflow Method

Rainflow method is used to count the number of cycles for the life prediction of the component as shown in Fig 8. A cycle will not be counted if the previous range, $\Delta\sigma XY$, is larger than the following range, $\Delta\sigma YZ$ (Fig. 8a). But if the opposite occur a cycle X-Y-X' is counted (Fig. 8b).

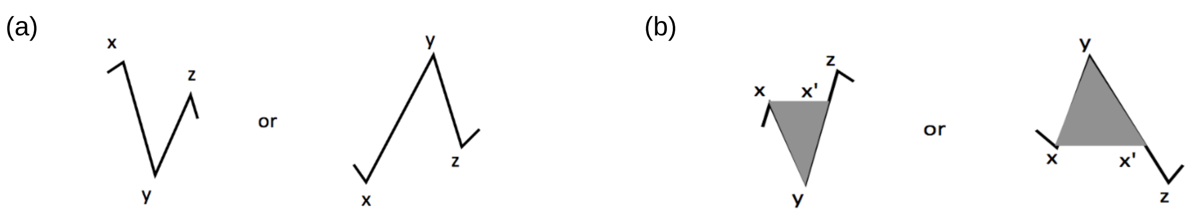


Figure 8 Rainflow method (a) No cycles counted, (b) A cycle of X-Y-X' is counted.

4.3 Removing Small Cycles

If the loading histories containe ranges smaller than the user defined threshold value, Δ_{th}, that does not affect the life, therefore the cycle(s) associated with those ranges could be removed. This shortens the analysis, since the number of loading cycles to be considered is reduced. In this step, a threshold range, Δ_{th}, is specified (e.g. Δ_{th}=15), and any range smaller than Δ_{th} will be removed, and turning points will be updated. This method of removing the small cycles is illustrated in Fig. 9.

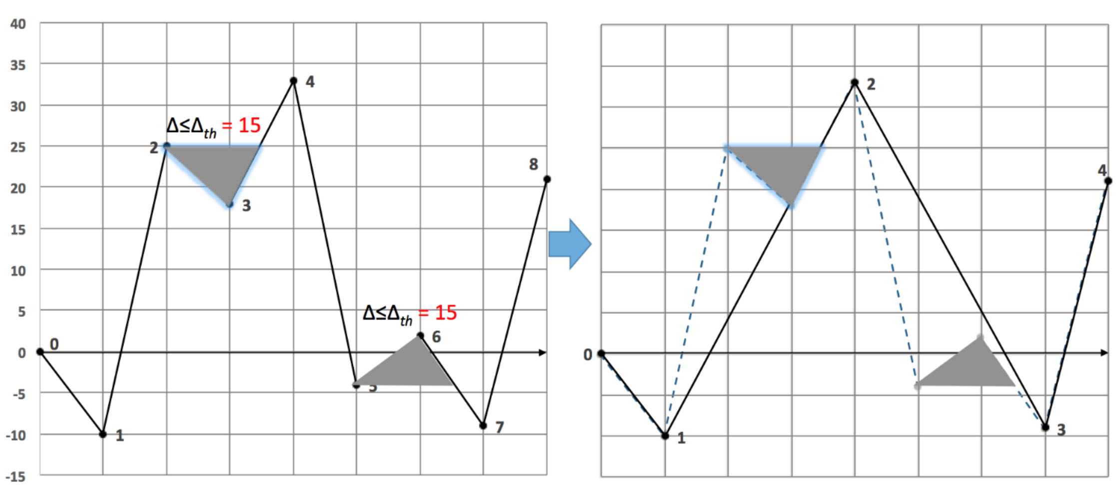


Figure 9 A spectrum before and after removing small cycles with ranges Δ ≤ 15.

4.4 Clipping

Clipping allows users to modify the raw spectrum data of the component, by eliminating some of the highest loading peaks. This is done when the user specifies its $\mathbf{M_{max}}$ value, and any point(s) in the loading histories that is larger than $\mathbf{M_{max}}$ will be clipped down to the $\mathbf{M_{max}}$ value, turning points will be updated subsequently. This method is illustrated in Fig. 10 shown below. Points 2 and 4 from the graph on the left of Fig. 10 are clipped down to the $\mathbf{M_{max}}$ red dotted line. If intermediate points are created it will be removed, the final result is shown on the right graph in Fig. 10.

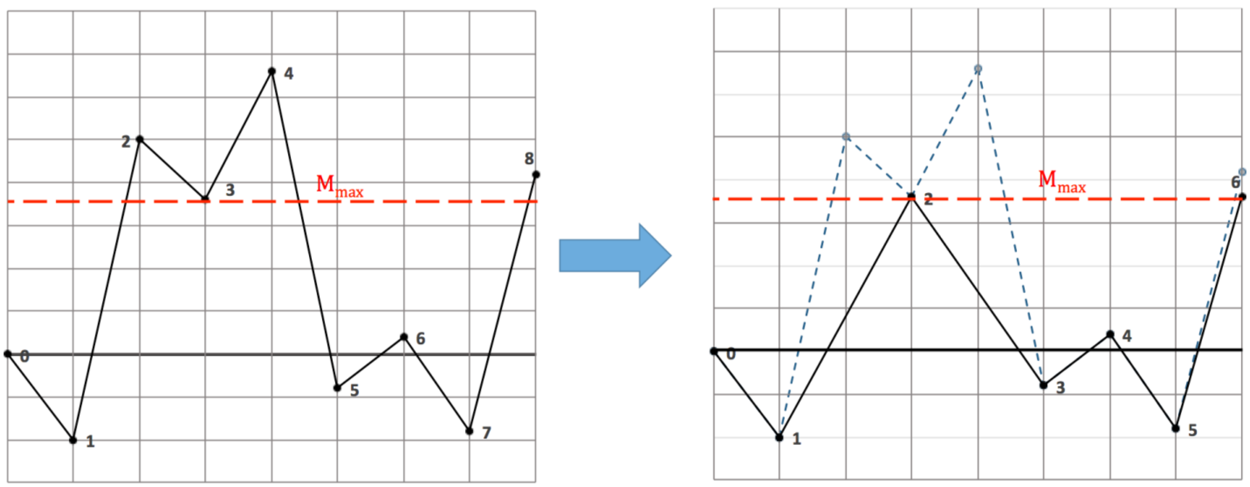


Figure 10 A spectrum before and after clipping.

4.5 Truncation

Truncation is very similar to clipping. Instead of eliminating high overload peaks, truncation eliminates underload peaks in loading histories. This is done in the similar way as clipping, by specifying its $\mathbf{V_{truncation}}$ level, and any points in the loading histories that are below the specified $\mathbf{V_{truncation}}$ level will be removed, and turning points will be updated. This is illustrated in Fig. 11.

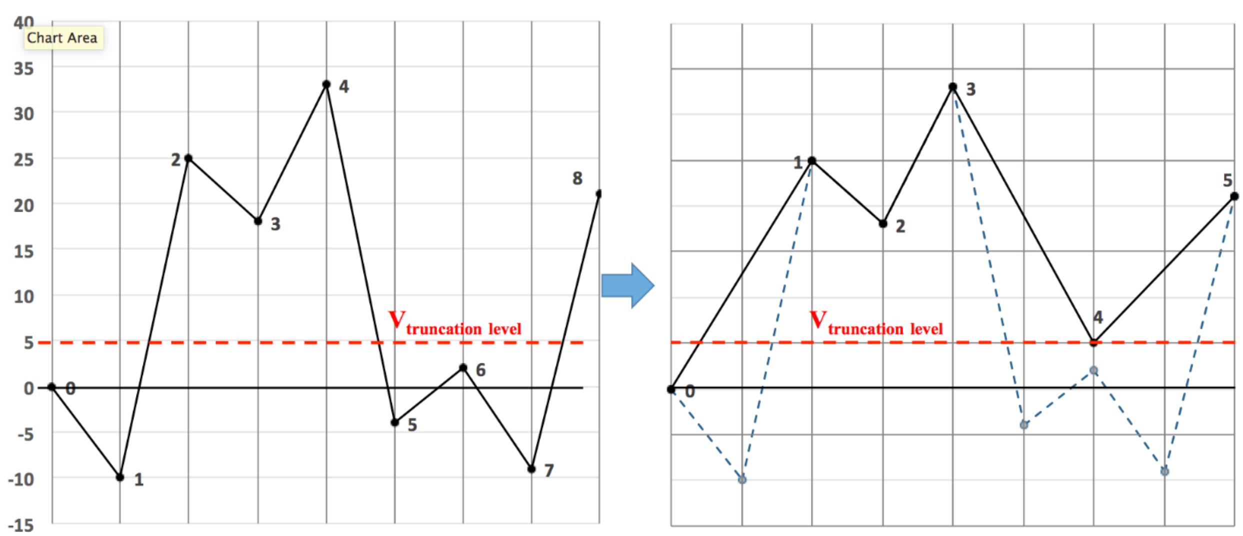


Figure 11 A spectrum before and after truncation.

Points 1,5,6 and 7 on the left side of the graph in Fig. 11 are truncated up to the $\mathbf{V}_{\mathbf{truncation}}$ level , turning points are then subsequently updated.

5. Conclusions

An interactive web-based learning tool for a modern fatigue analysis and life prediction methodology of smooth and notched components has been developed. Users from around the globe may access it via Internet by means of multiple platforms such as desktop and laptop computers, tablets and/or smart-phones. In particular, the users with a limited fatigue background would benefit from possibility to expand their fatigue learning experience. The tool can be used to analyze constant amplitude, block loading and spectrum loading histories. Dedicated spectrum analysis software is also included. Life predictive capabilities include stress-based, strain-based and stress-strain based approaches.

Acknowledgements

This research is supported by Western Michigan University Technology Development Fund.

6. References

1. Dowling, N. E, “Mechanical Behavior of Materials,” fourth ed., Prentice Hall, Upper Saddle River, New Jersey, 2013.
2. Fatemi, A., Socie, D. F, “A Critical Plane Approach to Multiaxial Fatigue Damage Including Out-of-phase Loading,” Fatigue Fract Eng Mater Struct., Vol. 11, 1988, 149–165.
3. Goodman, J., “Mechanics Applied to Engineering,” London, Longmans Green, 1899 [see also, vol. 1, 9th ed., 1930].
4. https://www.efatigue.com
5. http://fde.uwaterloo.ca
6. http://fadoff.cz/page
7. Kujawski, D, and Ellyin, F, “A Unified Approach to Mean Stress Effect on Fatigue Threshold Conditions, International Journal of Fatigue, Vol.17, 1995, 101-106.
8. Kujawski, D, “On Energy Interpretations of the Neuber’s Rule,” Theoretical and Applied Fracture Mechanics, Vol. 73, 2014, 91-96.
9. Kujawski, D, “A Deviatoric Version of the SWT Parameter,” International Journal of Fatigue, Vol.67, 2014, 95-102.
10. Morrow, J. D, “Fatigue Properties of Metals,” In: Fatigue Design Handbook Sec. 3.2. SAE Advances in Engineering, 1968, 21–30.
11. Neuber, H, “Theory of Stress Concentration for Shear Strained Prismatic Bodies with Arbitrary Non Linear Stress Strain Law,” Trans. ASME, Journal of Applied Mechanics, 1961, 544–555.
12. H. Smith, K. N., Watson, P., Topper, T. H, “A Stress–Strain Functions for the Fatigue of Metals,” Journal of Materials, Vol. 5, 1970, 767–778.
13. Walker,K, “The Effect of Stress Ratio During Crack Propagation and fatigue for 2024-T3 and 7075-T6 Aluminum,” *Effects of Environment and Complex Load History on Fatigue Life*, ASTM STP462,West Conshohocken, PA, 1970, 1-14.

Appendix: Explanations provided in each step

Life Analysis Tool Educational version supports up to 100 points in spectrum/block loading (uniaxial only). Other loading conditions such as torsion, bending and multiaxial are supported in the full version.

Step1: Select Material

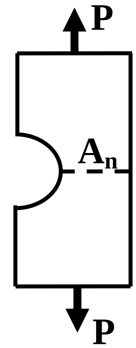
Selection from five different materials with custom material option is available in the educational version (more materials are available in the full version)

Select SI unit or English unit

Note: *More detail explanations and descriptions for each step are available under* (i) *icon.*

	Stress	Strain
SI units	MPa	m/m or mm/mm
English units	ksi	in/in

Step 2: Specimen/Component
Smooth
Select input
Notched



Step 3: Input Type
Nominal Stress $S_n = P/A_n$
($S_n < \sigma_0$ where σ_0 is the yield strength)

Step 4: Loading Type
Three loading types are available for selection:
1. Constant Amplitude Loading
2. Block Loading
3. Spectrum Loading

Step 5: Input Data
<u>For smooth specimen/component</u>
k_t (or k_f) = 1, is set as default and cannot be changed
<u>For notched specimen/component</u>
k_t (or k_f) = 2, is set as default and can be changed accordingly
<u>Constant Amplitude Loading</u>
Input stress S_{level1} and S_{level2} or strain ε_{level1} and ε_{level2}
Loading starts from zero and proceeds to S_{level1} (or ε_{level1}) then is cycling between S_{level1} (or ε_{level1}) and S_{level2} (or ε_{level2}).
S_{level1} (or □$_{level1}$) can be positive or negative.
<u>Block & Spectrum Loadings</u>
User have the option to download sample file or choose their own data file for analysis. Users can select a normalized factor if desired.
Analyze *(by clicking on)*
An Interactive Neuber's chart is displayed corresponding to S_{level1} or ε_{level1}, respectively.

Step 6: Hysteresis
An initial loading and hysteresis loop (s) curves are displayed.

Step 7: Life Prediction
Three live prediction approaches are available for selection:
1. Stress based (Goodman, Morrow, SWT, Walker),
2. Strain based (Morrow and strain versions of Goodman & Kujawski-Ellyin),
3. Stress-Strain based (SWT, Fatemi-Socie, SWT-deviatoric)

Life predictions are determined for all models within the selected approach (stress, strain or stress-strain based).
Note*: For $\sigma_m < 0$ Goodman's relation is typically set to $\sigma_{arG} = \sigma_a$.*
<u>Output</u>
Relevant local and nominal stresses and strains, endurance limits, calculated lives and fatigue graph(s) are displayed. An entire screen or table only can be printed by selecting a suitable printing button.