NISTIR 8302

NIST Instrumented Charpy Analysis Software (NICAS) – User's Manual

Damian Lauria
Enrico Lucon

This publication is available free of charge from:
https://doi.org/10.6028/NIST.IR.8302

National Institute of
Standards and Technology
U.S. Department of Commerce

NISTIR 8302

NIST Instrumented Charpy Analysis Software (NICAS) – User's Manual

Damian Lauria
Enrico Lucon
Applied Chemicals and Materials Division
Material Measurement Laboratory

This publication is available free of charge from:
https://doi.org/10.6028/NIST.IR.8302

April 2020

U.S. Department of Commerce
Wilbur L. Ross, Jr., Secretary

National Institute of Standards and Technology
Walter Copan, NIST Director and Undersecretary of Commerce for Standards and Technology

National Institute of Standards and Technology Interagency or Internal Report 8302
Natl. Inst. Stand. Technol. Interag. Intern. Rep. 8302, 10 p + 4 Appendices (April 2020)

This publication is available free of charge from:
https://doi.org/10.6028/NIST.IR.8302

Abstract

The *NIST Instrumented Charpy Analysis Software* (NICAS) is a standalone LabVIEW[1] program that can be used to analyze instrumented impact tests in accordance with the following international test standards: ASTM E2298-18 [1] and ISO 14556:2015 [2]. It is also possible to perform some operations manually, *i.e.*, not in strict accordance with the above cited standards. The software is provided free of charge in both raw LabVIEW code and executable (*.EXE) formats with an installer for PC platforms running Windows 7 or later.

Key words

Analysis software; ASTM E2298; instrumented Charpy test; ISO 14556; LabVIEW code; user's manual.

Disclaimer

This software was developed at the National Institute of Standards and Technology (NIST), Materials Measurement Laboratory (MML), in Boulder, Colorado, by employees of the Federal Government in the course of their official duties. Pursuant to title 17 section 105[2] of the United States Code, this software is not subject to copyright protection and is in the public domain. NICAS is an analysis software package. NIST assumes no responsibility whatsoever for its use, and makes no guarantees, expressed or implied, about its quality, reliability, or any other characteristic. The use of certain trade names or commercial products does not imply any endorsement of a particular product, nor does it imply that the named product is necessarily the best product for the stated purpose. We would appreciate acknowledgment if the software is used, and we always welcome feedback from users about possible errors or improvements[3].

[1] Certain commercial equipment, instruments, or materials are identified in this document in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.
[2] Copyright protection under this title is not available for any work of the United States Government, but the United States Government is not precluded from receiving and holding copyrights transferred to it by assignment, bequest, or otherwise.
[3] Contact damian.lauria@nist.gov and/or enrico.lucon@nist.gov.

Table of Contents

List of Figures

List of Appendices

Glossary

A	Striker calibration coefficient for the linear term (kN/V)
B	Striker calibration coefficient for the quadratic term (kN/V^2)
C_{el}	Experimental elastic compliance (mm/kN)
CF	Correction Factor
DFA	Dynamic Force Adjustment
F_a	Crack arrest force (kN)
F_{gy}	Force at general yield (kN)
F_{iu}	Force at unstable crack propagation (kN) [NOTE: this is called F_{bf} in ASTM E2298]
F_m	Maximum force (kN)
F_t	Force at test end (kN)
KV	Dial energy (J)
s_a	Displacement at crack arrest (mm)
SFA	Shear Fracture Appearance (%)
s_{gy}	Displacement at general yield (mm)
s_{iu}	Force at unstable crack propagation (mm) [NOTE: this is called s_{bf} in ASTM E2298]
s_m	Displacement at maximum force (mm)
s_t	Displacement at test end (mm)
W_a	Energy at crack arrest (J)
W_{gy}	Energy at general yield (J)
W_{iu}	Energy at unstable crack propagation (J) [NOTE: this is called W_{bf} in ASTM E2298]
W_m	Energy at maximum force (J)
W_t	Total instrumented energy (J)

1. Introduction

The Charpy impact test has been used worldwide since the late 1800s/early 1900s [3,4] for characterizing the notch toughness of metals, and thereby their suitability for applications ranging from ship hulls and railroad tracks to nuclear reactor pressure vessels. A standard Charpy test consists of a swinging mass (pendulum) dropping from a known height and striking a notched specimen located in its path. As the specimen fractures, the difference between the height to which the pendulum rises and its original height provides a measurement of the energy absorbed in breaking the specimen. The Charpy verification program at the National Institute of Standards and Technology (NIST) supplies thousands of customers worldwide with verification steel specimens that have been certified on the three NIST reference Charpy machines. This program achieves the tightest consistency of any population of Charpy machines in the world [5]. A schematic drawing of a Charpy machine, which identifies its different parts and shows a specimen being impacted, is provided in Fig 1.

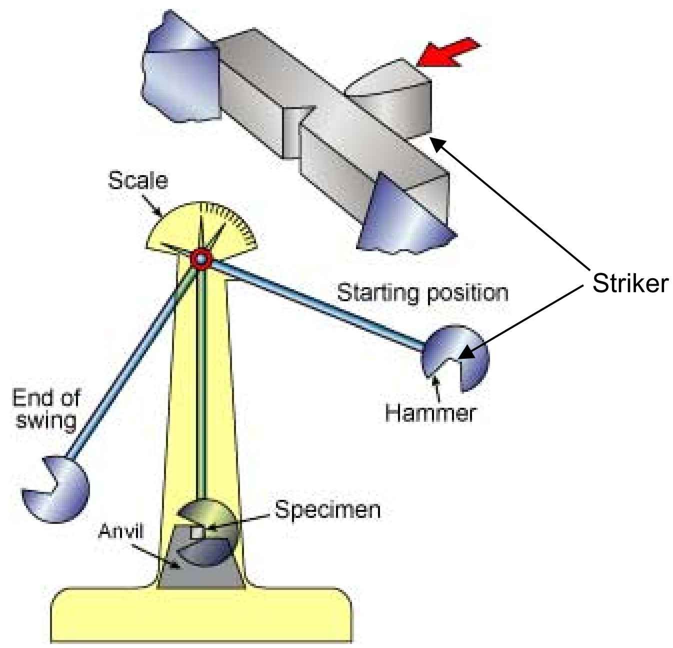

Figure 1 - Schematic drawing of a Charpy machine and a Charpy specimen being tested (image reproduced and modified from https://www.twi-global.com/technical-knowledge/faqs/faq-what-is-charpy-testing).

In the instrumented version of the Charpy test, strain gauges attached to the striker[4] transform it into a force transducer that provides a measurement of the force applied to the specimen during impact (Fig. 2). The force-time record derived from an instrumented Charpy striker provides additional information about the tested material's properties in comparison to a standard (*i.e.*, non-instrumented) impact test, such as dynamic tensile properties [6], estimated shear fracture appearance [7], and alternative definitions of the material's ductile-to-brittle transition temperature [8].

[4] In a Charpy machine, the striker is the part of the swinging hammer that impacts the specimen and, in the instrumented version of the test, is equipped with strain gauges to measure the deformation during the impact.

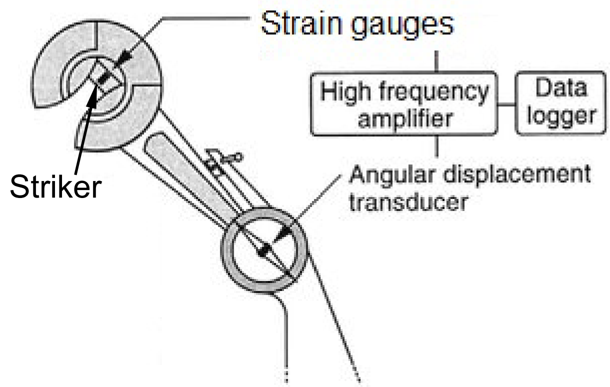

Figure 2 - Schematic of an instrumented Charpy test (image reproduced and modified from https://images.app.goo.gl/z57xgdHtNsZWSgfq6).

This document provides the user's manual for a software package (NICAS) that can be used to analyze instrumented Charpy tests on metallic materials in accordance with the most commonly used international standards [1,2].

2. Installation

The NICAS software package is provided as a compressed .zip file and must be extracted before installation. Inside the extracted file folder, there are several sub-folders, which contain software components, code and executables. If the computer running the software already has LabVIEW 2016 or a later version installed, or has a run-time engine for LabVIEW 2016 installed, then the executables should run and the remainder of this installation section can be skipped. If the computer does not have LabVIEW 2016 or its associated run-time engine, then the "Setup.exe" program found in the "Installer" folder should be run. Please note that this installation process may prompt you to restart your computer.

Once the installer for the LabVIEW run-time engine has completed, the executable file (CHARPY DATA ANALYZER 3.2.exe) should be usable. An explanation of its operation is provided in subsequent sections of this manual. In addition to the executable files, project files that contain fully commented LabVIEW source code and EXE build specifications for this software package can be found in the "Source Code" folder.

3. Operation of the NICAS software

The NICAS program (version 3.2) uses raw data files from instrumented Charpy tests in ASCII format. The input data files must contain only values of strain-gage output (in V or mV) in non-converted form, *i.e.*, before any transformation into force values. Time values should not be included, as they are automatically calculated based on the sampling rate. A set of sample data files, which can be used to test the functionality of the NICAS software, can be found in the "Sample Data Files" folder.

The following sub-sections will describe the steps required to analyze a test data set and obtain output in different forms.

3.1. Identification of the input and output folders

Upon launching the software, the user first needs to identify the folders where input and output files are located (can be the same folder). This is accomplished by either clicking the folder icons on the right side of the controls called “Data File Folder path” (input files) and “Analysis Folder path” (output files), or typing the folder address(es) directly inside the controls (red arrows in Fig. 3).

Note that the default value of “Specimen ID” in the leftmost window (green arrow in Fig. 3) is the file name (without extension), but it can be freely edited by the user if required.

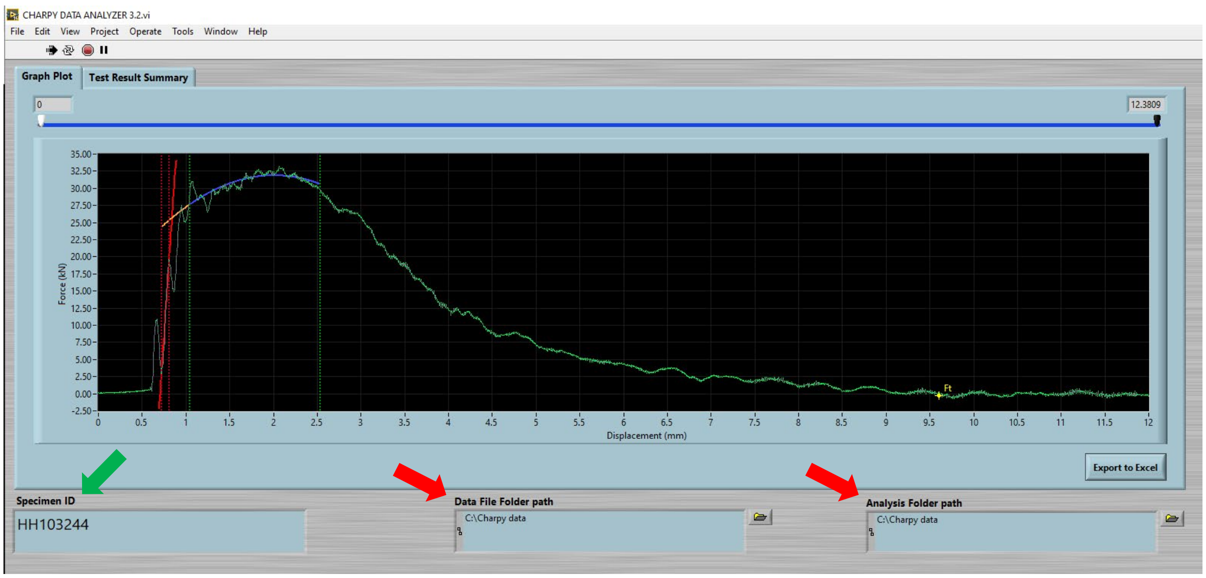

Figure 3 - Identification of input and output data folders, and specimen ID (if required).

3.2. Test file selection and definition of desired test range and test parameters

An input data file can be uploaded by clicking the button “**Load New Test**” in the lower right part of the screen and selecting the appropriate file.

As soon as the file is loaded, the window for the definition of the test range and test parameters opens (Fig. 4).

3.2.1. Test range selection

The portion of the test that will be visualized in the following steps of the analysis can be established in two ways:

a) In the upper force vs. time plot, by dragging the red (start) and blue (end) vertical lines (red arrows in Fig. 4);
b) In the lower right portion of the “Cursors” control (yellow arrow in Fig. 4), by clicking the green arrows to move (one data point at a time) the cursors corresponding to the beginning and end of the test. Specific values of time and force can also be manually entered under the column heading “X”.

NOTE: It is recommended to select the desired test range in two steps. First, drag the vertical lines as close as possible to the desired locations (step a above). Then, fine tune the cursors by means of the arrows (step b). This procedure is particularly suitable for defining the start point of the test range.

Figure 4 - Definition of desired test range and test parameters.

3.2.2. Test parameters

Test parameters are manually entered in the lower left region (blue arrow in Fig. 4). For every parameter, the required units (*e.g.* kg, °C, J, etc.) are indicated.

The coefficients required to convert strain-gage output into force are generally obtained from a static calibration of the striker [1,2]. The calibration (conversion) curve must have the following general form:

$$Y = AX + BX^2 \quad , \tag{1}$$

where X is strain gage output in V, Y is force in kN, and A, B are calibration (conversion) coefficients. Note that if the calibration curve is just a straight line, B = 0.

The default values in the fields are the values used in the previous analysis. This avoids the need to re-type parameters that generally don't change from one test to the next, such as pendulum mass, calibration coefficients, initial velocity, or sampling rate[5].

To proceed, click "**Continue**". Throughout the analysis, the test parameters will be shown in the lower left corner of the screen.

[5] The sampling rate, in Hz, corresponding to the inverse of the time interval, in seconds, between two consecutive data points in the input file.

3.3. Selection of the type of force/displacement curve

Before any analysis can be performed, the user must select the type of force/displacement curve, which corresponds to the mechanical behavior of the specimen (brittle, transitional, ductile). This is accomplished by first clicking the "**Please click here to choose the type of force/displacement curve**" box below the curve (red arrow in Fig. 5), and then clicking on the desired type of curve (green arrow in Fig. 5). The current type selected is highlighted with a blue rectangle.

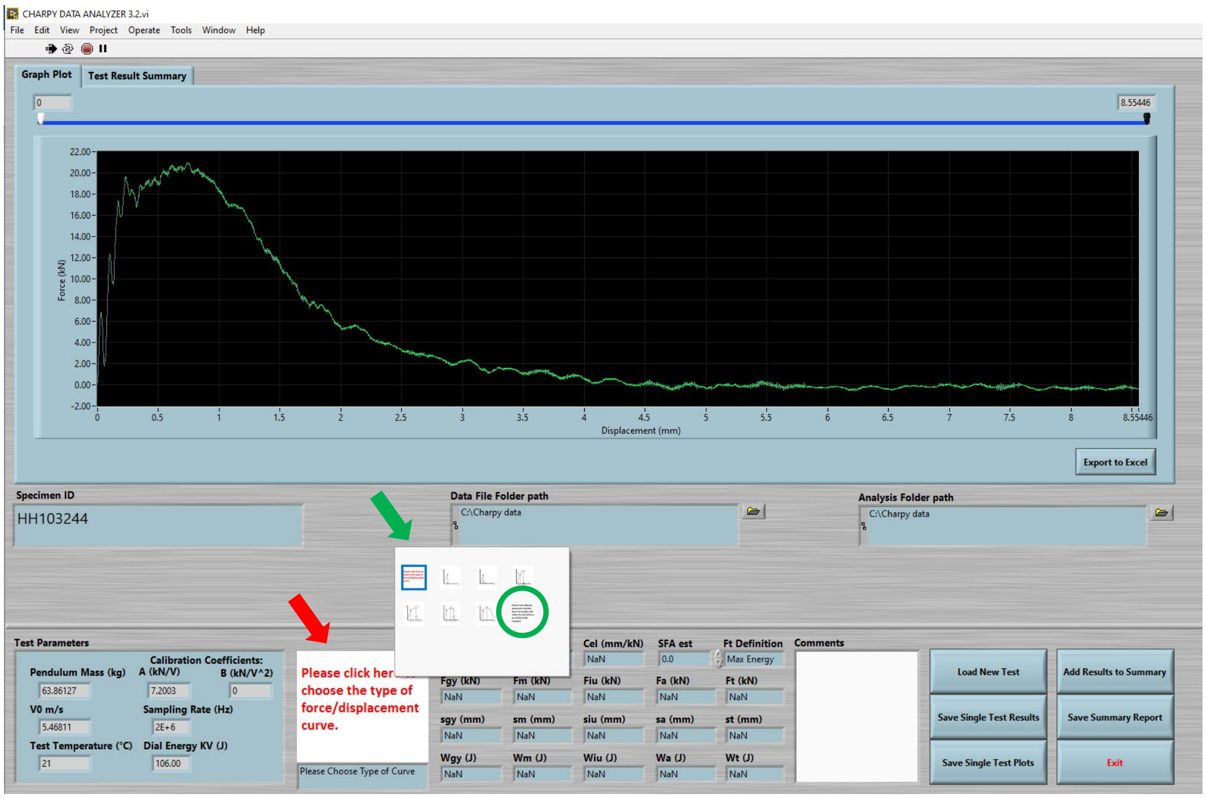

Figure 5 - Selection of the type of force-displacement curve.

In NICAS, we adopted the ISO 14556 classification, which distinguishes six types of curves (A through F). By contrast, ASTM E2298 only specifies three types of curves: A (corresponding to ISO type A), B (ISO type E), and C (ISO type F).

Selecting one of the curves A to F automatically identifies the corresponding characteristic force, displacement, and energy values, dependent on the type of curve:

- Type A (fully brittle): F_m, s_m, and W_m; F_t.
- Type B: F_m, s_m, and W_m; F_a, s_a, and W_a; F_t.
- Type C: F_{gy}, s_{gy}, and W_{gy}; F_m, s_m, and W_m; F_t. By definition, F_{iu}[6] $= F_m$ and $F_a = 0$.
- Type D: F_{gy}, s_{gy}, and W_{gy}; F_m, s_m, and W_m; F_a, s_a, and W_a; F_t. By definition, $F_{iu} = F_m$.
- Type E: F_{gy}, s_{gy}, and W_{gy}; F_m, s_m, and W_m; F_{iu}, s_{iu}, and W_{iu}; F_a, s_a, and W_a; F_t.

[6] F_{iu} is the ISO 14556 denomination of the force at the initiation of unstable fracture. The same parameter is identified as F_{bf} in ASTM E2298.

- Type F (fully ductile): F_{gy}, s_{gy}, and W_{gy}; F_m, s_m, and W_m; F_t.

A fully manual analysis option (not strictly compliant with either ASTM E2298 or ISO 14556) is also available by clicking on the last available option in the curve selection box (circled in green in Fig. 5). When this option is selected, the user can select the characteristic values by simply dragging the points along the curve. As points are moved, their characteristic values (force, displacement, energy) are updated in the results panel at the bottom of the screen.

With any curve type except A, the user can change the automatic analysis results in different ways (Fig. 6):

- the location of the general yield force can be changed by dragging/moving the two red dotted vertical lines that define the limits of the linear fit of the initial portion of the curve (red arrows in Fig. 6);
- the regression range for maximum force can be changed by dragging/moving the two green dotted vertical lines that define the limits of the parabolic fit (green arrows in Fig. 6);
- the locations of F_{iu} and F_a can be changed by simply dragging the corresponding points along the curve.

Before performing any analysis, the user can zoom on a part of the curve by dragging the sliders above the curve or entering numerical values for the limits of the X-axis just above the sliders, see the blue circles in Fig. 6.

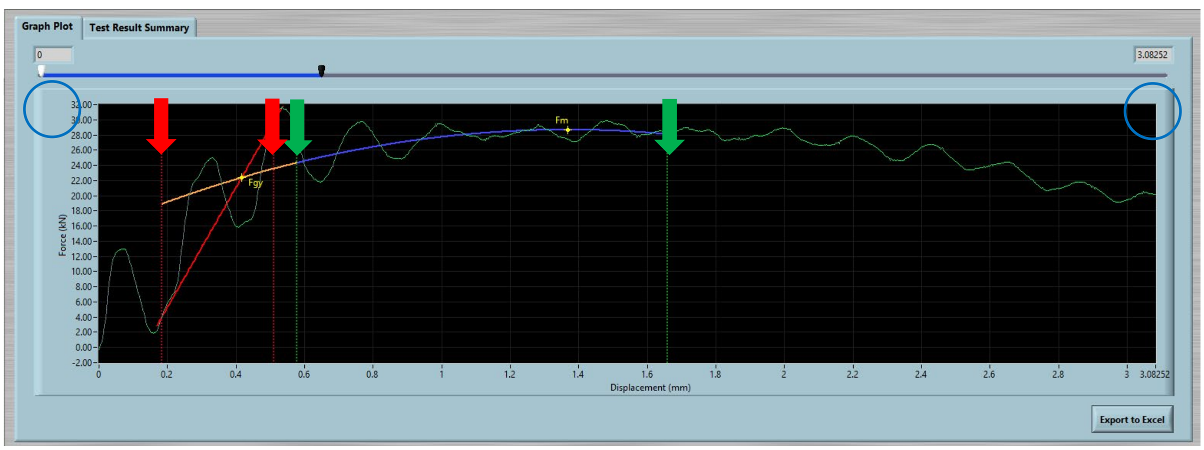

Figure 6 - Selection of fitting limits for F_{gy} and F_m, and options for zooming in.

3.3.1. Definition of F_t (test end)

ASTM E2298 and ISO 14556 provide different definitions of the point corresponding to F_t, s_t, and W_t.

The F_t definition to be used can be selected using the "Ft definition" control (red rectangle in Fig.7). There are four options provided:

- "ASTM E2298" – s_t is defined as "the displacement at which the force has decreased to the pre-test baseline value," *i.e.*, $F_t = 0$.
- "ISO 14566" – s_t is defined as "the abscissa value of the fitted curve through the oscillations corresponding to $F = 0.02\ F_m$," *i.e.*, $F_t = 0.02\ F_m$.

- "Manual" – The position of F_t can be adjusted by dragging the point along the curve.
- "Max energy" – When this option is selected, F_t corresponds to the largest value of absorbed energy, calculated by integrating force and displacement data.

Each of these four options yields a slightly different value of instrumented impact energy, W_t.

Figure 7 - Results panel.

3.3.2. Other parameters and calculations

3.3.2.1. Elastic compliance

The slope of the linear fit of the initial portion of the curve (solid red line in Fig. 6) corresponds to the experimental elastic compliance C_{el}[7], in mm/kN. See green rectangle in Fig. 7.

3.3.2.2. Estimate of Shear Fracture Appearance

Characteristic forces from an instrumented impact test can be used to obtain an estimate of Shear Fracture Appearance, SFA est (%) [7]. Both ASTM E2298 and ISO 14456 include the same four empirical correlations between SFA and characteristic instrumented forces. Based on our experience, we used the third correlation for NICAS (Eq. (6) in ASTM E2298 and Eq. (C.3) in ISO 14556):

$$SFA\ est\ (\%) = 1 - \frac{F_{iu} - F_a}{F_m + 0.5(F_m - F_{gy})} \times 100\ \% \qquad (2)$$

The estimated value of SFA, "SFA est", is reported in the top row of the results panel (blue rectangle in Fig. 7).

Note that, by definition, SFA = 0 % if the curve is of Type A, and SFA = 100 % if the curve is of Type F.

[7] The inverse of compliance is the experimental stiffness, in kN/mm.

3.3.2.3. Dynamic Force Adjustment

The comparison between dial energy, *KV*, and total instrumented energy, W_t, is a good indicator of the quality of the instrumentation, and the calibration of the instrumented striker in particular.

ISO 14556 states that if differences between *KV* and W_t exceed ±5 J, the user should investigate machine friction, calibration of the measuring system, and software used. ASTM E2298, on the other hand, is more prescriptive:

a) If the difference is less than the larger of 15 % or 1 J, no adjustment is needed.

b) If the difference is between 15 % and 25 % or 1 J and 2 J, whichever is larger, force values shall be adjusted[8] until $W_t = KV$.

c) If the difference exceeds the larger of 25 % or 2 J, the test shall be discarded and the instrumented striker re-calibrated.

The NICAS software allows the user to perform step b) above, which has been labelled "Dynamic Force Adjustment" (DFA) [9], by clicking the button "**Adjust Force**" on the top row of the results panel (yellow rectangle in Fig. 7). The value of the resulting correction factor (CF) for the forces is provided next to the button. Note that the user can click "**Adjust Force**" multiple times, thus performing successive iterations, until the values of *KV* and W_t effectively coincide.

3.3.2.4. Optional comments

The user can add comments inside the "**Comments**" control to the right of the results panel (purple rectangle in Fig. 7).

3.4. Software output

The NICAS software provides multiple types of output, as detailed below.

3.4.1. Test Results Summary

After analyzing a test in accordance with section 3.3, results can be added to the "**Test Results Summary**" tab (Fig. 8) by clicking "**Add Results to Summary**" on the lower right side of the screen. Test results are added in the rightmost column of the window. The window can be visualized by clicking the tab "**Test Results Summary**" at the top of the screen.

The last added column of results can be removed by clicking "**Remove last results**" below the window on the right (red arrow in Fig. 8).

An existing summary file created during a previous analysis can be loaded by clicking "**Load Summary Report**" below the window on the left (green arrow in Fig. 8). Any additional analysis can be added on as the rightmost column.

Once analyses are completed for a series of tests, the Summary Report can be saved as an ASCII (text) file by clicking "**Save Summary Report**" on the lower right side of the screen.

[8] Note that, when adjusting force values, displacement values are also recalculated.

The default filename is "*MM_DD_YYYY_Summary.txt*". An example of Summary Report is provided in Appendix 1.

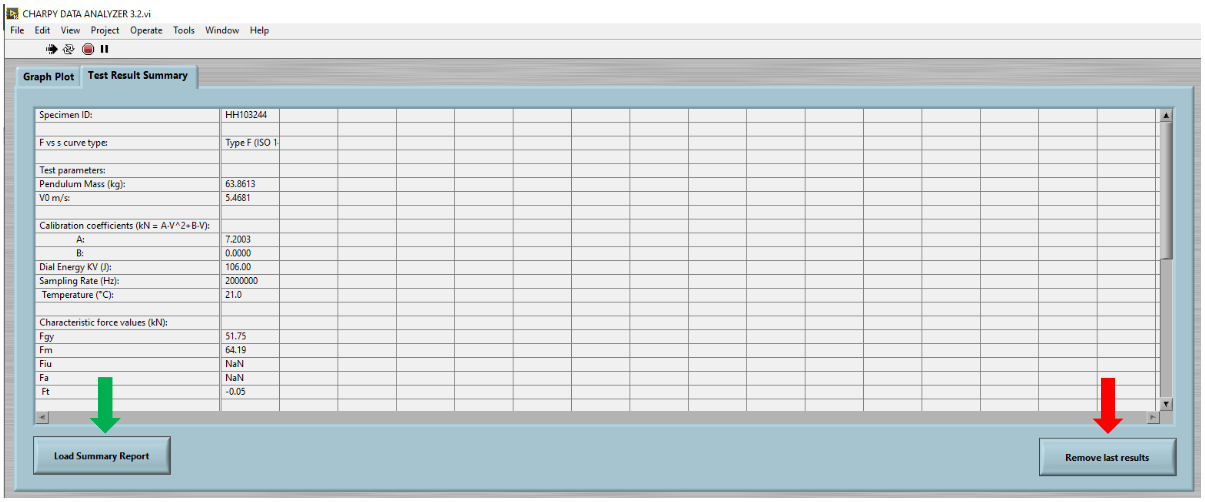

Figure 8 - "Test Results Summary" tab.

3.4.2. Individual test results

The results for an individual test can be saved in an ASCII file by clicking "**Save Single Test Results**" on the lower right side of the screen. The default filename is "*Specimen_ID_Out.txt*". An example of individual test result file is provided in Appendix 2.

3.4.3. Individual test data for plotting

Complete data for an individual test can be saved in an ASCII file by clicking "**Save Single Test Plots**" on the lower right side of the screen. The file contains, as headers, the specimen ID and the test parameters (Sec. 3.2.2), followed by values of force, velocity, energy, displacement, and time organized in columns. These data can easily be imported for plotting with a spreadsheet-based program, such as Microsoft Excel. The default filename is "*Specimen_ID_Plots.txt*". An example of a single test data file is provided in Appendix 3.

3.4.4. Exporting data to Excel

By clicking "**Export to Excel**" just below the force-displacement plot in the "Graph Plot" main tab (red arrow in Fig. 9), the NICAS software will automatically create a temporary Microsoft Excel file containing complete displacement and force data, organized in columns, for the different curves and regressions: raw curve, quadratic fit, extended quadratic fit, and linear fit of the initial part of the curve[9]. These data points allow the user to reproduce in Excel the test diagram exactly as visualized in the "Graph Plot" window, including the regression curves (Fig. 9). If the user has zoomed on a part of the curve (as described at the end of section 3.3.2.2), only the currently visible data is exported.

As mentioned above, the file is temporary (*.tmp), and must be saved as *.xls or *.xlsx if the user wants to keep it.

[9] With reference to Fig. 6: the raw curve is in green, the quadratic fit is in blue, the extended quadratic fit corresponds to the orange + blue curves, and the linear fit is the red solid line.

An example of a temporary Excel file is provided in Appendix 4.

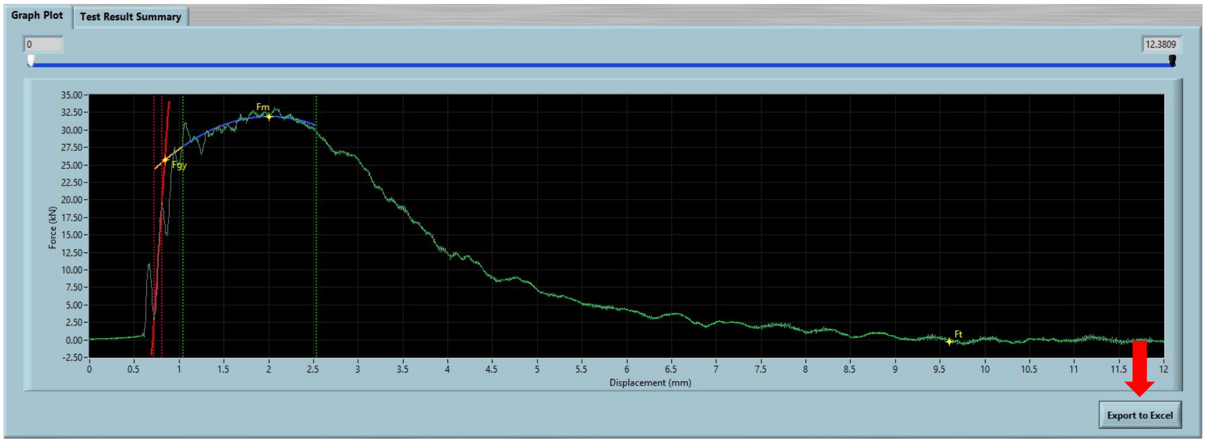

Figure 9 – "Graph Plot" window.

3.5. Exiting the program

Clicking "**Exit**" in the lower right corner closes the program.

4. Dissemination

The NICAS software package will be made available free of charge through a link on the NIST Charpy Machine Verification Program web page (https://www.nist.gov/programs-projects/charpy-machine-verification-program).

The LabVIEW code will also be made available through the development platform GitHub (https://github.com/), which is a collaborative hosting repository for software development control providing bug tracking, feature requests, task management, and wikis for every project. It is currently the largest host of source code in the world [10].

References

[1] ASTM E2298-18, Standard Test Method for Instrumented Impact Testing of Metallic Materials, American Society for Testing and Materials International, West Conshohocken, PA.

[2] ISO 14556:2015, Metallic materials — Charpy V-notch pendulum impact test — Instrumented test method, International Standards Organization, Geneva, Switzerland.

[3] Russell SB (1898) Experiments with a New Machine for Testing Materials by Impact. *Transactions ASCE*, 39:237–250.

[4] Charpy G (1901) Note sur l'essai des metaux à la flexion par choc de barreaux. *Soc. Ing. Civ. de Français*, pp 848–877.

[5] McCowan CN, Siewert TA, Vigliotti DP (2003) Charpy verification program: reports covering 1989-2002. NIST Technical Note 1500-9, Materials Reliability Series.

[6] Server WL (1978) General Yielding of Charpy V-Notch and Precracked Charpy Specimens. *J. Eng. Mater. Technol.*, 100(2):183–188. https://doi.org/10.1115/1.3443469

[7] McCowan CN, Lucon E, Santoyo RL (2018) Fracture Appearance of Steels in Transition: Experimental Observations and Measurements. *J. Test. Eval.*, Vol. 47, Issue 2. https://doi.org/10.1520/JTE20170448
[8] Chaouadi R, Fabry A (2002) On the utilization of the instrumented Charpy impact test for characterizing the flow and fracture behavior of reactor pressure vessel steels. European Structural Integrity Society, ESIS, Vol. 30, pp 103-117. https://doi.org/10.1016/S1566-1369(02)80011-5
[9] Lucon E (2008) On the Effectiveness of the Dynamic Force Adjustment for Reducing the Scatter of Instrumented Charpy Results. *J. of ASTM Int.* 6(1):1–9. https://doi.org/10.1520/JAI102100
[10] Gousios G, Vasilescu B, Serebrenik A, Zaidman A (2014), Lean GHTorrent: GitHub Data on Demand. *MSR'14*, May 31-June 1, 2014, Hyderabad, India, pp 384-387. http://dx.doi.org/10.1145/2597073.2597126

Appendix 1

Example of Summary Report

Specimen ID:	30-1	35-1	64-1
F vs s curve type:	Type F	Type F	Type E
Test parameters:			
Pendulum Mass (kg):	63.8613	63.8613	63.8613
V0 m/s:	5.4681	5.4681	5.4681
Calibration coefficients (kN = A‡V^2+B‡V):			
A:	31.1159	31.1159	31.1159
B:	0	0	0
Dial Energy KV (J):	230	311	224
Sampling Rate (Hz):	2000000	2000000	2000000
Temperature (−C):	21	21	21
Characteristic force values (kN):			
Fgy	18.86	16.07	18.75
Fm	22.46	21.45	22.48
Fiu	NaN	NaN	15.77
Fa	NaN	NaN	14.05
Ft	-0.01	-0.03	-0.04
Characteristic displacement values (mm):			
sgy	0.65	0.28	0.32
sm	3.54	4.38	3.30
siu	NaN	NaN	7.53
sa	NaN	NaN	7.57
st	37.96	32.20	61.89
Characteristic energy values (J):			
Wgy	4.17	2.03	2.57
Wm	65.48	82.70	64.00
Wiu	NaN	NaN	149.72
Wa	NaN	NaN	150.28
Wt	227.42	306.31	221.70
Elastic compliance (mm/kN):			
Cel	0.01270	0.00661	0.00790

Appendix 2

Example of Individual Test Result File

Specimen ID:	30-4
F vs s curve type:	Type E
Test parameters:	
Pendulum Mass (kg):	63.8613
V0 m/s:	5.4681
Calibration coefficients (kN = A·V^2+B·V):	
A:	31.1159
B:	0
Dial Energy KV (J):	228
Sampling Rate (Hz):	2000000
Temperature (°C):	-40
Characteristic force values (kN):	
Fgy	18.74
Fm	23.33
Fiu	19.81
Fa	17.00
Ft	-0.01
Characteristic displacement values (mm):	
sgy	0.29
sm	3.38
siu	6.30
sa	6.36
st	37.97
Characteristic energy values (J):	
Wgy	2.16
Wm	69.53
Wiu	133.65
Wa	134.61
Wt	227.54
Elastic compliance (mm/kN):	
Cel	0.00625

Appendix 3

Example of Individual Test Data File
(first part)

Specimen ID: HH103244 Pendulum Mass (kg): 63.8613 V0 m/s: 5.4681
Calibration coefficients (kN = A·V^2+B·V): A= 7.2003 B= 0.0000

Dial Energy KV (J): 106.0000 Sampling Rate (Hz); 2000000.0000 Temperature (°C): 21.0000
Comments:

F(kN)	V(m/s)	W(J)	s(mm)	T(s)
0.62577	5.46811	0.00000	0.00000	0.00000
2.72332	5.46810	0.00000	0.00273	0.00000
3.41021	5.46807	0.00458	0.00547	0.00000
6.37190	5.46804	0.01296	0.00820	0.00000
10.95111	5.46797	0.02634	0.01094	0.00000
13.26287	5.46787	0.05002	0.01367	0.00000
16.03254	5.46776	0.08312	0.01640	0.00000
18.52155	5.46762	0.12316	0.01914	0.00000
20.95887	5.46747	0.17039	0.02187	0.00000
21.35771	5.46730	0.22436	0.02461	0.00000
21.43896	5.46714	0.28220	0.02734	0.00000
21.79347	5.46697	0.34069	0.03007	0.00001
20.48617	5.46680	0.39978	0.03281	0.00001
19.82884	5.46664	0.45757	0.03554	0.00001
18.15966	5.46649	0.51267	0.03827	0.00001
16.52000	5.46636	0.56458	0.04101	0.00001
13.18162	5.46624	0.61198	0.04374	0.00001
10.47840	5.46615	0.65256	0.04647	0.00001
9.04556	5.46607	0.68490	0.04921	0.00001
7.11048	5.46601	0.71158	0.05194	0.00001
5.78105	5.46596	0.73365	0.05467	0.00001
5.80320	5.46591	0.75127	0.05740	0.00001
7.25821	5.46586	0.76710	0.06014	0.00001
7.69481	5.46581	0.78495	0.06287	0.00001
8.93479	5.46574	0.80538	0.06560	0.00001
11.53459	5.46566	0.82810	0.06834	0.00001
13.51397	5.46556	0.85607	0.07107	0.00001
14.82865	5.46545	0.89030	0.07380	0.00001
18.62495	5.46532	0.92903	0.07653	0.00001
22.96043	5.46516	0.97474	0.07927	0.00001
25.59716	5.46497	1.03156	0.08200	0.00001
28.78044	5.46475	1.09790	0.08473	0.00002
32.38471	5.46451	1.17219	0.08746	0.00002
34.28287	5.46425	1.25575	0.09020	0.00002
35.96684	5.46398	1.34683	0.09293	0.00002
37.77638	5.46369	1.44279	0.09566	0.00002
39.36433	5.46339	1.54352	0.09839	0.00002
39.19445	5.46308	1.64888	0.10112	0.00002
38.57404	5.46278	1.75618	0.10385	0.00002
37.50309	5.46248	1.86239	0.10659	0.00002
36.81622	5.46219	1.96629	0.10932	0.00002
34.96977	5.46191	2.06778	0.11205	0.00002
33.68463	5.46164	2.16580	0.11478	0.00002
32.89434	5.46138	2.25954	0.11751	0.00002
30.90018	5.46113	2.35045	0.12024	0.00002
30.84108	5.46089	2.43755	0.12297	0.00002
30.93710	5.46064	2.52184	0.12570	0.00002
29.97696	5.46041	2.60618	0.12843	0.00002
30.67120	5.46017	2.68934	0.13116	0.00002
32.25178	5.45992	2.77212	0.13389	0.00002
34.06869	5.45966	2.85802	0.13662	0.00002
36.32874	5.45939	2.94854	0.13935	0.00003
38.83994	5.45909	3.04462	0.14208	0.00003
41.99367	5.45878	3.14721	0.14481	0.00003
43.72195	5.45844	3.25753	0.14754	0.00003

Appendix 4

Example of Temporary Excel File
(first part)

	A	B	C	D	E	F	G	H
1	Displacement (mm) - Raw Data	Force (kN) - Raw Data	Displacement (mm) - Quadratic Fit	Force (kN) - Quadratic Fit	Displacement (mm) - Extended Quadratic Fit	Force (kN) - Extended Quadratic Fit	Displacement (mm) - Linear Fit	Force (kN) - Linear Fit
2	0	0.15	1.04921	27.7	0.721739	24.36	0.694411	-2.2
3	0.005468	0.06	1.05466	27.75	0.727204	24.42	0.699877	-1.16
4	0.010936	0.07	1.06011	27.79	0.73267	24.48	0.705343	-0.13
5	0.016404	0.12	1.06555	27.84	0.738135	24.55	0.710808	0.9
6	0.021872	0.1	1.071	27.89	0.7436	24.61	0.716274	1.94
7	0.027341	0.18	1.07644	27.93	0.749065	24.67	0.721739	2.97
8	0.032809	0.1	1.08189	27.98	0.75453	24.73	0.727204	4
9	0.038277	0.14	1.08733	28.03	0.759995	24.8	0.73267	5.04
10	0.043745	0.12	1.09277	28.07	0.76546	24.86	0.738135	6.07
11	0.049213	0.12	1.09822	28.12	0.770925	24.92	0.7436	7.1
12	0.054681	0.07	1.10366	28.16	0.776389	24.98	0.749065	8.14
13	0.060149	0.14	1.1091	28.21	0.781853	25.04	0.75453	9.17
14	0.065617	0.12	1.11454	28.25	0.787317	25.1	0.759995	10.2
15	0.071085	0.11	1.11998	28.29	0.792781	25.16	0.76546	11.24
16	0.076553	0.13	1.12542	28.34	0.798244	25.22	0.770925	12.27
17	0.082021	0.15	1.13086	28.38	0.803707	25.28	0.776389	13.3
18	0.08749	0.13	1.1363	28.43	0.80917	25.34	0.781853	14.34
19	0.092958	0.14	1.14174	28.47	0.814632	25.4	0.787317	15.37
20	0.098426	0.16	1.14718	28.51	0.820094	25.46	0.792781	16.4
21	0.103894	0.15	1.15262	28.55	0.825556	25.52	0.798244	17.43
22	0.109362	0.16	1.15806	28.6	0.831018	25.58	0.803707	18.47
23	0.11483	0.15	1.1635	28.64	0.836479	25.64	0.80917	19.5
24	0.120298	0.15	1.16893	28.68	0.84194	25.7	0.814632	20.53
25	0.125766	0.16	1.17437	28.72	0.847401	25.75	0.820094	21.57
26	0.131234	0.16	1.1798	28.76	0.852861	25.81	0.825556	22.6
27	0.136702	0.15	1.18524	28.8	0.858321	25.87	0.831018	23.63
28	0.14217	0.16	1.19068	28.84	0.863782	25.93	0.836479	24.66
29	0.147638	0.15	1.19611	28.88	0.869241	25.98	0.84194	25.7
30	0.153106	0.18	1.20155	28.92	0.874701	26.04	0.847401	26.73
31	0.158574	0.13	1.20698	28.96	0.88016	26.1	0.852861	27.76
32	0.164042	0.15	1.21241	29	0.885619	26.15	0.858321	28.79
33	0.169511	0.13	1.21785	29.04	0.891078	26.21	0.863782	29.83
34	0.174979	0.15	1.22328	29.08	0.896536	26.26	0.869241	30.86
35	0.180447	0.12	1.22871	29.12	0.901995	26.32	0.874701	31.89
36	0.185915	0.2	1.23414	29.16	0.907452	26.37	0.88016	32.92
37	0.191383	0.15	1.23957	29.2	0.91291	26.43	0.885619	33.95
38	0.196851	0.18	1.245	29.23	0.918367	26.48		
39	0.202319	0.16	1.25043	29.27	0.923824	26.54		

lvtemporary_77161