Constitutive Model Calibration Data

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February 28, 2020

Introduction

Material characterization tests for calibration of constitutive models for use in BM1 and BM2 were conducted at the lab facilities of POSTECH and the US National Institute of Standards and Technology (NIST). The work conducted by these two labs include deformation of three specimens in each of the following tests: 1) uniaxial tension-compression testing along the RD, 2) hydraulic bulge testing for equal-biaxial tension, and 3) seven orientations of uniaxial tension testing in 15 degree increments to the RD from 0 to 90 degrees.

In addition to the test data from individual specimens, additional analysis of the test data is provided to report standard material properties, including elastic parameters, stress-strain relations and plastic strain ratios typically used for calibration of constitutive models. These data files also include determinations of the 0.2% offset yield stress, UTS, UE, and TE, which are used primarily for purposes of material characterization, but also sometimes for calibration of constitutive models. The data files also include calibrations of several constitutive models, including isotropic and kinematic hardening models, using commercially available software developed for this purpose. Participants are not expected to restrict their analysis to use the calibrated material models defined in the data files but may instead decide to use their own state of the art constitutive model, or to calibrate the parameters of any model from the raw test data using their own preferred calibration procedure.

It is gratefully acknowledged that all the material characterization testing as well as the data analysis and calibrations provided in the data files were provided without charge by the individuals and organizations identified in this report as a contribution the 2020 Numisheet Benchmark Study.

1.1 Tension-Compression Tests

Tension-compression tests were conducted at NIST by Dr. William Luecke using a custom-designed biaxial tension-compression system to provide anti-buckling support during the compression period of the test cycle. Details of the test equipment, procedure, and analysis for the steel and the aluminum alloys are provided in the following reference files:

TensionCompressionSummarySteel.pdf and *TensionCompressionSummaryAluminum.pdf,*

which can be found in the MaterialDataSourceFiles.zip package.

The processed data for the tension-compression tests are provided for calibration of kinematic hardening models and reported in the following Excel™ files:

BM1_DP980 Y-U.xlsx, and *BM1_6xxx-T4 Y-U.xlsx,*

are contained in the *BM1.zip* file package, and

BM2_DP1180 Y-U.xlsx, and *BM2_6xxx-T81 Y-U.xlsx*

are contained in the *BM2.zip* file package. Each file contains two worksheets: *Source* and a sheet containing the parameters for the Yoshida-Uemori model. The *Source Worksheet* contains the experimental stress-strain responses of three test specimens deformed under uniaxial tension along the RD to a nominal level of positive strain, followed by compression to nominally zero net strain, and then followed by tension until fracture. As noted in the two reference files, strains are defined from a virtual strain gauge with a length of approximately 23 mm created from DIC measurements of the deformation. This data is reported in columns A through Q of the worksheet. In addition, to supplement the kinematic model fitting with monotonic loading data, three specimens for uniaxial tension along the RD and three specimens for equal biaxial tension are included in columns S to AI and AL to BA, respectively. The data in these files is copied from the data reported in files described in Sections 1.2 and 1.3.

For convenience, Prof. Fusahito Yoshida compiled the data from the three specimens for each metal to calculate the Y-U model parameters using the MATPARA software, which he also generously provided, which are reported on the other worksheet.

1.2 Hydraulic Bulge Tests

Equal-biaxial tests were conducted at POSTECH by Prof. Jin-Hwan Kim in Prof. Frederic Barlat's lab using the ISO Standard 16808 for analysis of the bulge test. Details of the tests and data analysis for the steel specimens are provided in the reference file *BulgeTestSummary.pdf*. The data is provided for calibration of isotropic hardening functions, yield functions and, if non-associated flow models are used, the plastic potential function. Since these calibrations also require data from uniaxial tension tests, described in the next section of this report, the bulge test data are combined with the uniaxial tension data in the following Excel™ files for convenience:

BM1_DP980.xlsx, and *BM1_6xxx-T4.xlsx,*

are contained in the *BM1.zip* file package, and

BM2_DP1180.xlsx, and *BM2_6xxx-T81.xlsx*

are contained in the *BM2.zip* file package. The file names of these zipped packages may also include a date in the file name to avoid confusion if these download packages are later updated with new content.

Each of the files for the four metals contains two worksheets: *Tests* and *Models*. The *Tests Worksheet* contains the data for the three biaxial tests in three consecutive sets of 6 columns from Cells EI to EZ. The stress and strain data are reported in three columns labeled E11, E22, and S11 in row 10, with the data reported in successive rows starting in row 11. A fourth column labeled Time in row 10 records the time of each of the following stress and strain measurements, which can be used to estimate strain rates, if desired. For the three biaxial tests, the data in the E11 column records the total strain along the RD and the E22 column records the total strain along the TD. The S11 column records the magnitude of one of the components of the equal biaxial stress.

Calibration of material models based on both the uniaxial and equal biaxial tests are described in section 2.0 of this report, which describes the content of the *Models Worksheet*.

1.3 Uniaxial Tension Tests

Uniaxial tension tests were conducted at NIST by Dr. Evan Rust. As noted in Section 1.2, the uniaxial data is combined with the equal-biaxial test data in the same Excel™

BM1_DP980.xlsx, and *BM1_6xxx-T4.xlsx,*

are contained in the *BM1.zip* file package, and

BM2_DP1180.xlsx, and *BM2_6xxx-T81.xlsx*

are contained in the *BM2.zip* file package. As noted in Section 1.2, the file names of these zipped packages may also include a date in the file name to avoid confusion if these download packages are later updated with new content.

The three tests for each orientation of the uniaxial tension tests are reported in sets of 6 consecutive columns in the *Tests Worksheet*, in the 121 columns starting in column M and ending at column EH. The label "Uniaxial" in row 1 of the first of each set of 6 columns identifies the test specimen to be a uniaxial tension test, and the value in row 2 just below the "Uniaxial" label identifies the orientation of the loading axis to the RD of the sheet coil. Rows 4 and 5 of the first column respectively list the initial thickness and width of the gauge area of the tensile specimen for use in converting load to stress.

The stress-strain data is reported in the worksheets only up to the point of maximum load for the uniaxial tension tests. The data below the column heading E11 in row 10 records the axial total true strain defined by the stretch of the two end points of a 50 mm virtual strain gauge down the centerline of the tensile specimen at the start of the test, as recorded by DIC technology. This definition is true if the strain is uniform along the 50 mm gauge length. The axial true stress reported under the column heading S11 is computed from the load, cross-sectional area in the gauge area, and this axial true strain based on the 50 mm gauge, taking into consideration the elastic dilatancy.

The width strain and (a typically very small) shear strain in the coordinate system aligned with the loading axis is recorded below the column headings E22 and E12, respectively. These values are computed from the average of the strain tensor components measured by DIC at 201 points along the 50 mm line down the center of the specimen, whose end points are used to calculate E11. The plastic components of the axial E11 and width E22 strains are used to determine R Values.

As was the case for the biaxial test data the column labeled Time in row 10 records the time of each of the following stress and strain measurements, which can be used to estimate strain rates, if desired.

Calibration of material models based on both the uniaxial and equal biaxial tests are described in section 2.0 of this report, which describes the content of the first 6 columns of the *Tests Worksheet* and the content of the *Models Worksheet*.

2.0 Analysis of Bulge and Uniaxial Tension Test Data

The format of the data reported in columns M through EZ in the *Tests Worksheet* conforms with the format of the MasterFile used by the CalSysSmart™ software developed by Prof. Jeong-Whan Yoon. This format was initially designed to conform to specifications requested by Dr. Thomas B. Stoughton and Dr. John E. Carsley at GM several years ago.

CalSysSmart™ first reads the data for each test listed in the *Tests Worksheet* and automatically fits the elastic-plastic response to determine the elastic and plastic properties from each test. Then, if there are multiple tests for a given loading condition, CalSysSmart™ identifies and excludes outliers from the set of tests to determine representative properties for each test condition. The material properties computed for each test specimen, the classification of outliers, and the range of data points used in the determination of each property are recorded in specific cells of the 6 columns of the header for each test reported in rows 1 to 10 of the *Tests Worksheet*. Although it is not anticipated that participants will need to use the data in the header of *each* specimen test, for those interested in the information, the definitions of the header contents are explained in comments that have been appended to each cell.

CalSysSmart™ then reports the averages of non-outlier tests of most material properties useful for material characterization. These averages and statistics are reported in successive rows of the first 6 columns of the *Tests Worksheet*. After reporting the given property for each uniaxial orientation in successive rows, and average value of a given uniaxial property is computed based on assumed orthotropy using the following formula for calculation of the average behavior of an orthotropic material over all directions when the orthotropic axes are aligned with the RD and TD of the sheet coil:

$$\langle v \rangle = \frac{v_0 + 2v_{15} + 2v_{30} + 2v_{45} + 2v_{60} + 2v_{75} + v_{90}}{12}$$

For convenience, CalSysSmart™ also provides calibrations of a selected set of constitutive models in rows 1 to 25 of the *Models Worksheet,* reported in 10 consecutive columns per model. Although some of the reported information describes parameters used or determined by the CalSysSmart™ calibrations, the model "parameters" are reported in row 18 and beyond.

One of the advantages of the CalSysSmart™ program is that it fits the stress-strain data from all non-outlier uniaxial tension tests and biaxial tests to determine not only the parameters of the hardening law, but also the stress ratios for calibration of the shape of the yield function. To be more specific, all the non-outlier experimental stress-strain data are fit to 9 different hardening laws, including Swift, Voce, Hockett-Sherby, modified Voce, modified Hockett-Sherby, and combinations of Swift with each of the four others. These hardening laws have between 3 and 8 parameters. Combined with the a priori unknown 7 stress-ratio parameters that are required to scale the experimental stress and strain values for the data from the biaxial and the uniaxial test at angles other than along the RD to obtain a work equivalent function along the rolling direction for use in isotropic hardening models, the fitting algorithm used by CalSysSmart™ fits the 9 hardening laws to determine between 10 and 15 parameters, depending on the hardening law.

CalSysSmart™ then selects the best fit among the 9 hardening laws and reports its parameters in row 20 of the *Models Worksheet* for each model. Participants may find it convenient to use this fit to represent the isotropic strain hardening function, since it is the best fit to all the uniaxial and biaxial data. However, as is the case of all other calibration data, participants are welcome to apply their own methods of calibration of the constitutive model they will use in the benchmark.

The other 7 parameters of the best fit *define the stress ratios* that are then used for the calibration of the yield function. These stress ratios are reported in row 8, where the stress ratio along the RD is defined to be equal to 1. The stress ratios are also reported in the list of properties in the first 6 columns of the *Tests Worksheet*.

3.0 Alternate Analysis of the Uniaxial Tension Test Data

The axial strains reported in the uniaxial tension data defined in the files listed in Section 1.3 are based on a 50 mm virtual strain gauge defined using DIC technology. Consequently, the uniaxial stress-strain data is reported only up to the point of maximum load in these files. This restriction is particularly severe in the case of the DP 1180, since it limits the experimental definition of the stress-strain response to less than about 7% strain. While this limit is often handled in engineering analysis by supplementing the data with the stress-strain response from the bulge test under the assumption of isotropic hardening, the small strain range to maximum load limits the ability to effectively employ anisotropic hardening models, or otherwise avoid the assumption that the hardening is isotropic.

As an alternative to using a 50 mm strain gauge, methods have been proposed by Min, Stoughton, Carsley, Yoon and others to more aggressively use DIC technology to determine R values and stress strain responses in uniaxial tension to much higher strains than can be determined by using large strain gauges, and to detect onset of localized necking. The methods and data files required for this more aggressive application of DIC technology are described in a supplementary document *LocalDIC_StrainData.pdf* and the supporting data files are included along with the *LocalDIC_StrainData.pdf* in the zipped package

MaterialDataSourceFiles.zip.

The link to the supplementary data is available only from the homepage of the Numisheet Benchmark Study, not from the webpages for BM1 or BM2.

The BM1 and BM2 downloads deliberately include only the data from the tests based on virtual strain gauges and only up to the point of maximum load, which is the conventional way to characterize material behaviors in uniaxial tension. This was done to avoid accidental an unintended use of non-standard application of DIC technology to characterize material properties. The primary value of the information contained in the *MaterialDataSourceFiles.zip* download package is in documenting and accounting for anisotropic hardening, evolution of R values, and other evidence of evolution of the shape of the yield function. So this information is probably only useful for development and validation of the benefits and capabilities of the most advanced material models.