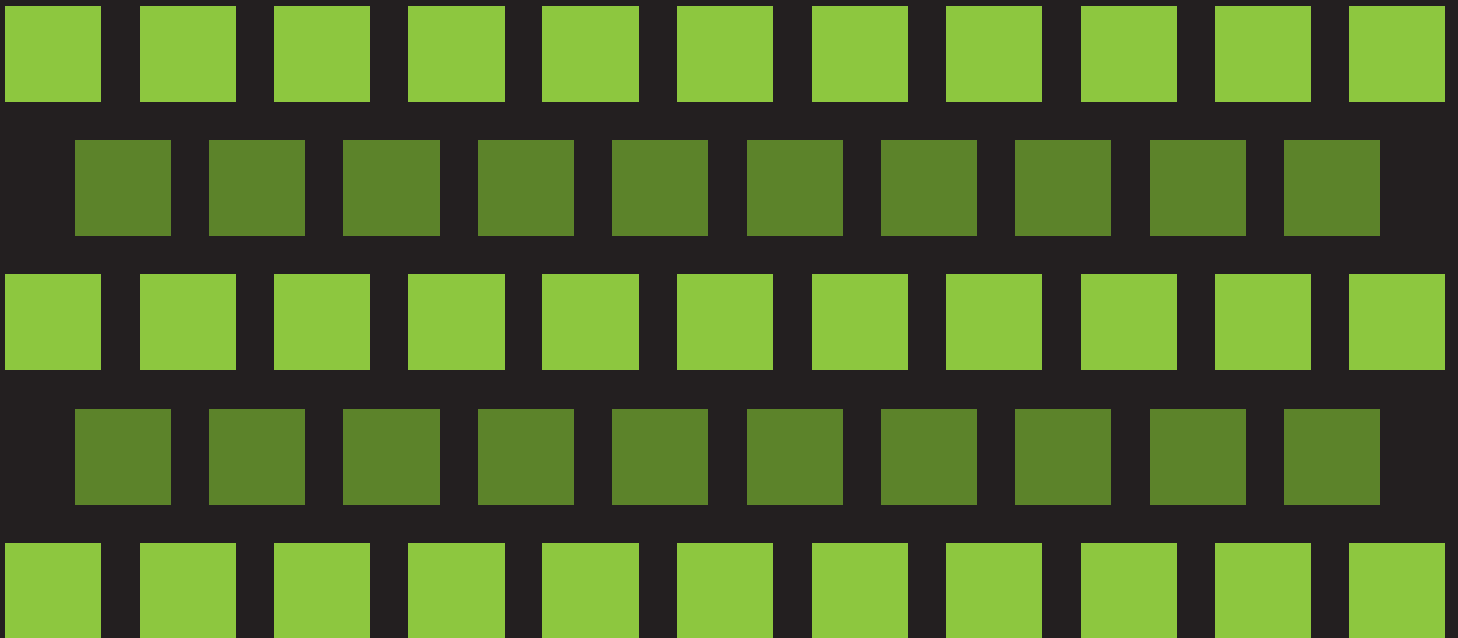


# EXTEND STRESS-STRAIN CURVE PARAMETERS AND CYCLIC STRESS-STRAIN CURVES TO ALL MATERIALS LISTED FOR SECTION VIII, DIVISIONS 1 AND 2 CONSTRUCTION



STP-PT-056

**EXTEND STRESS-STRAIN  
CURVE PARAMETERS AND  
CYCLIC STRESS-STRAIN  
CURVES TO ALL MATERIALS  
LISTED FOR SECTION VIII,  
DIVISIONS 1 AND 2  
CONSTRUCTION**

*Prepared by:*

Wolfgang Hoffelner  
RWH consult GmbH



Date of Issuance: April 5, 2013

This report was prepared as an account of work sponsored by ASME Pressure Technology Codes & Standards and the ASME Standards Technology, LLC (ASME ST-LLC).

Neither ASME, ASME ST-LLC, the author, nor others involved in the preparation or review of this report, nor any of their respective employees, members or persons acting on their behalf, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe upon privately owned rights.

Reference herein to any specific commercial product, process or service by trade name, trademark, manufacturer or otherwise does not necessarily constitute or imply its endorsement, recommendation or favoring by ASME ST-LLC or others involved in the preparation or review of this report, or any agency thereof. The views and opinions of the authors, contributors and reviewers of the report expressed herein do not necessarily reflect those of ASME ST-LLC or others involved in the preparation or review of this report, or any agency thereof.

ASME ST-LLC does not take any position with respect to the validity of any patent rights asserted in connection with any items mentioned in this document, and does not undertake to insure anyone utilizing a publication against liability for infringement of any applicable Letters Patent, nor assumes any such liability. Users of a publication are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, is entirely their own responsibility.

Participation by federal agency representative(s) or person(s) affiliated with industry is not to be interpreted as government or industry endorsement of this publication.

ASME is the registered trademark of the American Society of Mechanical Engineers.

No part of this document may be reproduced in any form,  
in an electronic retrieval system or otherwise,  
without the prior written permission of the publisher.

ASME Standards Technology, LLC  
Two Park Avenue, New York, NY 10016-5990

ISBN No. 978-0-7918-6883-6

Copyright © 2013 by  
ASME Standards Technology, LLC  
All Rights Reserved

## TABLE OF CONTENTS

|   |     |
|---|-----|
| Foreword .....  | vi  |
| Executive Summary .....   | vii |
| 1 INTRODUCTION .....  | 1   |
| 2 METHODS OF PARAMETERIZATION OF STRESS-STRAIN CURVES .....   | 3   |
| 2.1 Engineering Stress-Strain Curves.....   | 3   |
| 2.2 True Stress-Strain Curves.....  | 6   |
| 3 THE DILEMMA OF FINDING THE (USUALLY NOT AVAILABLE) ULTIMATE<br>TENSILE STRAIN.....                                | 13  |
| 3.1 Rasmussen Procedure.....  | 13  |
| 3.2 The MPC-approach .....  | 13  |
| 3.3 The UTS-YS Approach.....  | 15  |
| 4 CRITICAL ASSESSMENT OF THE DIFFERENT APPROACHES USING ACTUAL<br>STRESS-STRAIN CURVES.....                         | 19  |
| 4.1 Carbon Steels.....  | 19  |
| 4.2 Ferritic Steels.....  | 22  |
| 4.3 Martensitic Steels .....  | 22  |
| 4.4 Austenitic Steels.....  | 22  |
| 4.5 Gamma Prime Hardening Superalloys .....   | 23  |
| 4.6 Other Classes of Materials .....  | 23  |
| 5 TANGENT MODULUS .....   | 24  |
| 6 CYCLIC STRESS-STRAIN CURVES .....   | 26  |
| 7 PROPOSAL FOR IMPLEMENTATION OF STRESS-STRAIN CURVES INTO THE ASME<br>CODE.....                                    | 32  |
| 8 REFERENCES .....  | 35  |
| Appendix A – Determination of the stress-strain curve using two data points .....                                   | 37  |
| Appendix B – Comparison for IN 800H (rational polynomial, ASME II, Ramberg-Osgood) .....                            | 40  |
| Appendix C – Data-sheets (true stress-strain curves, modulus) for cross comparison.....                             | 44  |
| Appendix D – Excel map which calculates stress-strain curves and tangent moduli according to<br>MPC and RO-eng..... | 51  |
| Acknowledgments.....  | 52  |

### LIST OF TABLES

|  |    |
|--|----|
| Table 1—Parameters for Ultimate Tensile Strain ( $m_2$ ) and for Start of Plastic Deformation ( $\epsilon_p$ ) for<br>Different Classes of Materials as Defined in the MPC ASME VIII/2 Procedure ..... | 14 |
| Table 2—Measured Ultimate Tensile and Yield Stresses .....   | 17 |

**LIST OF FIGURES**

|   |    |
|---|----|
| Figure 1—Engineering and True Stress-strain Curves for 316 Measured at Room Temperature .....   | 4  |
| Figure 2—Engineering Stress vs. Engineering Plastic Strain for 316 Measured at Room Temperature .....   | 5  |
| Figure 3—True Stress vs. True Plastic Strain for 316 Measured at Room Temperature.....  | 5  |
| Figure 4—Shape of $(1+\tanh\psi(H))$ and $(1-\tanh\psi(H))$ for 304 L Stainless Steel at Room Temperature .....   | 8  |
| Figure 5—Comparison of Different Parameterizations of a True Stress-strain Curve for an Austenitic Steel at Room Temperature .....  | 9  |
| Figure 6—Comparison of a Modified MPC True Stress-strain Curve (Equal Slope) with the Other Stress-strain curve parameterizations shown in Figures 4 and 5 .....                  | 10 |
| Figure 7—Comparison of Results from MPC and RO-eng Results Omitting Data-points at the Transition from Low Strain to High Strain for the MPC Approach .....                       | 11 |
| Figure 8—Comparison of Different True Stress-strain Parameterizations.....  | 11 |
| Figure 9—Correlation between Yield Stress, Ultimate Tensile Stress and Ultimate Tensile Strain (replotted from Rasmussen [16]) .....  | 13 |
| Figure 10—Ultimate Tensile Strains Determined According to Table 1 for Different Classes of Materials as Function of Ratio between Yield Stress and Ultimate Tensile Stress ..... | 14 |
| Figure 11—Comparison of Predicted and Measured Ultimate Tensile Strains Experimental Data Exclusively from [1] .....  | 15 |
| Figure 12—Experimentally Determined Ultimate Tensile Strains (see Table 1) as a Function of the Differences between Ultimate Tensile Stress and Yield Stress .....                | 16 |
| Figure 13—Comparison between Calculated and Measured Ultimate Tensile Strains.....  | 16 |
| Figure 14—Comparison of RO-eng and MPC Curves as Calculated (a) and Using the Actually Measured Ultimate Tensile Strain (b).....  | 18 |
| Figure 15—Stress-strain Curves of Different Carbon Steels [17] .....  | 20 |
| Figure 16—Stress-strain Curves for SA-36 Determined According to MPC and RO-eng Procedures without Lueders Strain Corrections.....  | 20 |
| Figure 17—Comparison of Results from MPC and RO-eng Parameterizations of A514 (see Figure 15) with the Result from the Lueders-modified RO Approach (RO-eng_lueders).....         | 21 |
| Figure 18—Stress-strain Curve of a Carbon Steel Without Occurrence of Lueders Strain.....   | 21 |
| Figure 19—Occurrence of Secondary Hardening for Austenitic Steel at Temperatures below Room Temperature [18].....   | 22 |
| Figure 20—Comparison of Measured and Calculated Stress-strain Curves of IN-718 at Room Temperature .....  | 23 |
| Figure 21—Scheme for Determination of the Tangent Modulus According to the MPC Procedure Described in Section VIII/2 .....  | 24 |
| Figure 22—Comparison of Tangent Moduli Determined According to the MPC and to the RO-eng Procedure (Materials 2.25Cr-1Mo, RT).....  | 25 |

|   |    |
|---|----|
| Figure 23—Cyclic Response of a Ti-containing Austenitic Steel at 650°C in 20% Cold Worked and in Annealed Condition [21] .....                                  | 26 |
| Figure 24—Comparison of Cyclic Stress-strain Curves for 304 at Room Temperature.....  | 27 |
| Figure 25—Experimental Results from LCF-tests of the Austenitic Steel 316LN in Annealed Condition [20] .....  | 28 |
| Figure 26—Comparison of a Measured Cyclic Stress-strain Curve (b) with a Cyclic Stress-strain Curve Determined only from Two Data Points (a) Given in [20]..... | 28 |
| Figure 27—Proposal for Scaling of Cyclic Stress-strain Curve when Different Monotonic Curves Exist.....   | 28 |
| Figure 28—Monotonic and Cyclic Stress-strain Curves for Different Classes of SA-723 as Derived from Literature.....   | 29 |
| Figure 29—Cyclic and Monotonic Stress-strain Curves of 17-4 PH in Two Different Qualities.....  | 30 |
| Figure 30—Cyclic and Monotonic Stress-strain Curves of Grade 91 Martensitic Steel According to the Japanese NIMS [25] Database and the ASME Code.....           | 30 |
| Figure 31—Comparison of Cyclic and Monotonic Stress-strain Curves for Grade 91 in Current Code Edition.....   | 31 |
| Figure 32—Consideré Plot for the Determination of the Maximum Stress (UTS).....   | 38 |
| Figure 33—Comparison of the Polynomial Fit with a YS and UTS Based Power Law Fit .....  | 40 |
| Figure 34—Comparison of Different Parameterizations of Stress-strain Curves Applied to IN 800H Determined at 1100F .....  | 40 |
| Figure 35—Isochronous Stress-strain Curves from the German KTA .....  | 41 |
| Figure 36—Identification of the Points Taken for Digitization of the KTA Stress-strain Curve .....  | 41 |
| Figure 37—Comparison of YS-UTS Based Power Law Fit with KTA-data at Low Strains.....  | 42 |
| Figure 38—Comparison of YS-UTS Based Power Law Fit with KTA-data at High Strains .....  | 42 |
| Figure 39—Plastic Strains for the Stress-Strain Curves Determined in KTA.....   | 43 |
| Figure 40—Comparison of Plastic Strains Taken from Figure 39 with the Ones Determined with the Power Law Fit Procedure .....                                    | 43 |

## FOREWORD

Different approaches currently exist in the ASME code for the determination of monotonic stress-strain curves. ASME Section VIII Div. 2 and FFS-1 use predominantly a two power law approach based on Y-1 and U-table values for direct prediction of true stress-strain curves. Sometimes, also a single power law approach for direct determination of true stress strain curves is used. Section III uses a rational polynomial for determination of isochronous stress strain curves. The report evaluates capabilities and limitations of the different methods using experimental results from literature and elaborates on a method which could minimize current deficiencies without having severe impact on the huge amount of already existing evaluations and data. The method should have the capability to introduce stress-strain curves in future code editions.

Established in 1880, the American Society of Mechanical Engineers (ASME) is a professional not-for-profit organization with more than 127,000 members promoting the art, science and practice of mechanical and multidisciplinary engineering and allied sciences. ASME develops codes and standards that enhance public safety, and provides lifelong learning and technical exchange opportunities benefiting the engineering and technology community. Visit [www.asme.org](http://www.asme.org) for more information.

The ASME Standards Technology, LLC (ASME ST-LLC) is a not-for-profit Limited Liability Company, with ASME as the sole member, formed in 2004 to carry out work related to newly commercialized technology. The ASME ST-LLC mission includes meeting the needs of industry and government by providing new standards-related products and services, which advance the application of emerging and newly commercialized science and technology and providing the research and technology development needed to establish and maintain the technical relevance of codes and standards. Visit [www.stllc.asme.org](http://www.stllc.asme.org) for more information.

## EXECUTIVE SUMMARY

For the determination of monotonic stress-strain curves, different approaches currently exist in the ASME code. Section VIII/2 and FFS-1 use predominantly a two power law approach based on Y-1 and U-table values for direct prediction of true stress-strain curves (in the following referred to as MPC approach). Sometimes, also a single power law approach for direct determination of true stress strain curves is used (RO). Section III uses a rational polynomial for determination of isochronous stress strain curves. It was a major aim of the current report to evaluate capabilities and limitations of the different methods using experimental results from literature and to elaborate on a method which could minimize current deficiencies without having severe impact on the huge amount of already existing evaluations and data. The method should have the capability to introduce stress-strain curves in future code editions. With respect to the different methods the results are the following.

The MPC-approach gives good results for low strains and for high strains. However, it shows a kink which is a result of switching between the two different power laws employed. Another problem concerns the determination of the ultimate tensile strain which will be discussed later.

The RO-approach as used in FFS-1 is a one power law approximation of the true stress-strain curve. In this respect it differs from the original Ramberg-Osgood (RO) method which is based on the engineering stress-strain curve and not on the true stress-strain curve. The ASME RO-approach leads to smooth looking curves but they often do not match the experimental values which is a result of the mathematical structure of the power law when engineering stress and strain is replaced by true stress and strain.

The rational polynomial can only be applied for small strains (up to 2%) but there are some difficulties to match with the high strain regime (particularly with ultimate tensile strain).

Best results were obtained with the original Ramberg-Osgood parameterization based on engineering stresses and strains (called in the following RO-eng).

$$e = \frac{s}{E} + K \left( \frac{s}{s_0} \right)^n$$

Where e is engineering strain, s is engineering stress, E is Young's modulus, s<sub>0</sub> is normalizing stress (usually 0.2% yield stress).

The constants K and n can be determined from yield stress and ultimate tensile stress under the assumption that both stress values belong to the stress-strain curve. Yield stress and 1.1 x ultimate tensile stress can be found in Sect. II /D stress tables (Tables Y-1 and U) which means that the engineering stress-strain curve is fully determined with already existing code data. The true stress-strain curve is obtained by plotting the true stress vs. true strain values. Comparison of this RO-eng method with experimental data revealed that this approach nicely agrees with experimental results and it also matches the MPC-values for low and high strains without showing a kink. Compared with the RO-method based directly on true stresses and strains, it leads to much better results because it does not have the numerical problems with fitting stress-strain data dependent on each other with one power law. Comparisons with the rational polynomial led to a fair agreement as discussed in appendix B.

The problem of determination of the ultimate tensile strain remains the same for all approaches based on ultimate tensile stress. The MPC-method proposes materials dependent values which are governed by the ratio between yield stress and ultimate tensile stress which may not always provide satisfactory solutions. An alternative which was used in this report is materials independently based on the difference between ultimate tensile stress and yield stress. Although more accurate values than the MPC-method could be obtained, the determination of ultimate tensile strains cannot be considered to

be fully satisfactory and further improvements should be envisaged. However, it could be shown that most accurate parameterizations can be obtained with measured ultimate tensile strains which demonstrate the capability of the RO-eng approach. All methods described work only for materials possessing stress-strain curves with a power law shape. This is the case for a vast majority of metals and alloys. Specific effects like Lueders strains cannot be built into the MPC-method but they could be successfully implemented into the RO-eng approach.

Based on all these results the RO-eng approach is proposed for implementation of monotonic stress-strain curves into the code. Usually, reference to Y-1 and U-Tables would be sufficient. Specific issues like Lueder's strain, ultimate tensile strain, expected deviations from power law, etc. could be introduced as notes into code tables.

The MPC-curves for tangent moduli show expectedly also a discontinuity at the transition from low strain to high strain. The RO-eng curve allows an analytic expression of the tangent modulus of true stress-strain curves without discontinuity.

Cyclic stress-strain curves fulfill usually a power law relationship but they are strongly dependent on material and even pre-treatment and they can therefore not be constructed from Y-1 and U-values. It is necessary to define them on a case to case basis. Existing cyclic stress-strain curves in Section VIII/2 seem to be based on published results. Although for cyclic stress-strain curves the differences between RO and RO-eng are almost negligible (because usually only low strains are considered) RO-eng is also recommended for establishing those curves. Data for additional cyclic stress-strain curves can be taken from the literature and databases (e.g. NIMS [25]), where much LCF-work has been published. The RO-eng approach enables simple reconstruction of cyclic stress strain curves even from LCF data as usually published. An important point concerns the consistency between monotonic stress-strain curves (determined from Y-1/U-tables) and cyclic stress-strain curves from other sources. It must be taken into consideration that cyclic softening and/or hardening happens relative to the monotonic data. To avoid misinterpretations, scaling may have to be performed when comparing data from different sources. For different sources, scaling with the ratio of yield stresses is proposed.

The cyclic stress-strain curves can be used for construction of the hysteresis loop by scaling with a factor of two.

Although quite consistent results could be established still a few points would need further research:

- Method of determination of ultimate tensile strain
- Clear criteria when Lueders stress and/or other irregularities must be considered
- Determination of amount of Lueder's stress to be included
- Further proof of RO-eng-concept with additional experimental data and link with Y-1/U-table values
- Establishing missing cyclic stress-strain curves from literature
- Activating of stress-strain data available in different laboratories of ASME members
- Coupling of establishment of stress-strain curves with ASME database activities.

## 1 INTRODUCTION

This project resulted from ASME Pressure Technology Codes and Standards (PTCS) Standards Committee requests to identify, prioritize and address technology gaps in PTCS Codes, Standards and Guidelines, and is intended to establish and maintain the technical relevance of ASME codes and standards products. In this context the inclusion of sound stress-strain curves for design purpose is required. As a first step a study shall provide:

- a. Literature review to evaluate material strength models and the required material parameters for high priority materials in Section VIII, Divisions 1, 2 and 3.
- b. Modification of existing, or development of new, models for the monotonic and cyclic stress-strain curves.
- c. Collection of the required material parameters for these models and introduction into Divisions 2 and 3.
- d. Preparation of a proposal for providing information on lower priority materials.
- e. Documentation of materials where data does not exist including a proposal for a test program.

After evaluation of the data and examination of potential constitutive models to be used, a recommendation will be made to ASME for an efficient and simplified format of conveying behavior for the purposes of design.

Special emphasis will be placed on the most common materials or high priority materials, as determined by ASME, used for construction such as

- Carbon steel (all strength levels)
- Chromium molybdenum (vanadium) steels like 1.25Cr-1Mo and 2.25 Cr-1Mo, including enhanced alloys (all strength levels)
- Ferritic –martensitic steels (e.g. 9-12% Cr) including enhanced alloys
- Stainless steels (austenitic, ferritic-martensitic, duplex, precipitation hardening)
- Nickel-base alloys (e.g. N06600, N06625 and N08800)
- Aluminum based alloys
- Titanium based alloys
- Copper based alloys
- Zirconium based alloys.

True stress-strain diagrams should be made available for inclusion into the code. Currently, different approaches for determination of stress-strain curves are in use: For the true stress strain curves Sect. VIII Div. 2 employs a two-slope approach discriminating between low plastic strains and high plastic strains. Cyclic stress-strain diagrams (which show basically the same behavior) are covered with a traditional Ramberg-Osgood parameterization and within Sect. III NH, another (different) method is used. In the case of Sect. III Div. 2, formulae to determine the true strain for a given true stress and the tangent modulus are given for certain classes of materials using Y-1 and U-table values. The current project should develop a procedure along the following guidelines.

- The procedure shall be able to predict true (and engineering) stress-strain curves for the classes of materials specified in the whole stress range from elastic to ultimate tensile stress.
- The curves shall be based on yield strengths and ultimate tensile strengths given in the Y-1 and U-tables.
- The procedure shall allow a quick determination of the whole true and engineering stress-strain curves in the range specified.
- The procedure should cover several Code needs (true stress-strain, engineering stress strain, cyclic stress strain) for a wide temperature range.