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

ASME STANDARDS
TECHNOLOGY, LLC

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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.

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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 <u>engineering stresses and strains</u> (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_0 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.