

Final Report

FEA SOFTWARE FOR DETERMINATION OF RESIDUAL STRESSES IN AUTOFRETTAGED TUBES FOR A RANGE OF GUN STEELS WITH BAUSCHINGER EFFECT

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ABSTRACT

There is a paucity of user-friendly, spreadsheet-based stress analysis software for calculation of stresses due to autofrettage of real gun steels. The objective of this work was to develop and deliver user-friendly, spreadsheet-based (Excel® /VBA) Finite Element software capable of calculating residual stresses in autofrettaged steel tubes which exhibit any combination of strain-hardening during loading and of Bauschinger effect during unloading. The latter behavior includes Bauschinger effect as a function of prior plastic strain, and hence of radius, during unloading. The software should also have the potential to determine stresses following low temperature heat soak and re-autofrettage. The software was to be pre-programmed with several existing candidate gun steels, including HB7. All these objectives were achieved. The software provides additional functionality, beyond the original objectives. Finally, the program was used to demonstrate specific effects arising during experimental measurement and interpretation of residual stress in autofrettaged gun tubes.

KEYWORDS:

Residual Stress, Autofrettage, High Pressure, Gun Tubes, Steels, Bauschinger effect, Numerical Stress Analysis, Finite Element Analysis

HISTORICAL BACKGROUND

Prediction of the safe lifetime and safe maximum pressure (SMP) of a cyclically pressurised gun tube requires knowledge of the residual stress introduced into the tube by processes such as shrink-fitting, wire-winding and autofrettage. The latter may be achieved hydraulically (with the entire length of the tube pressurised simultaneously) or by use of an oversized mandrel or swage which is pushed along the bore.

The ideal elastic-perfectly plastic stress state at the peak of autofrettage loading is well-known for the full range of possible end conditions, see Hill [1] or Chakrabarty [2]. Percentage overstrain (the proportion of the wall thickness which behaves plastically during initial autofrettage loading) has been accurately related to hydraulic autofrettage pressure [3]. If elastic-perfectly plastic behaviour without loss of yield strength during unloading is assumed, then residual stresses following removal of hydraulic autofrettage pressure may be calculated to a good approximation from a solution due to Hill [1, 3]. If there is a loss of yield strength that can simply be expressed as a proportion of the initial, constant tensile yield strength then residual stress may be calculated using an analytic method equivalent to that of Hill [4].

Crucially, behavior of pressure vessel steels during unloading is not bi-linear with magnitude of yield strength in compression equal to that in tension. A typical uniaxial stress strain plot is shown in Figure 1. There is a non-linear strain-hardening phase during loading and significant non-linearity at some point after load reversal. The non-linearity during load reversal is termed the Bauschinger effect and the value of compressive stress at the onset of non linearity, normalized with initial yield strength, is termed the Bauschinger effect factor (BEF). Both BEF and the shape of the non linear section are a function of prior tensile plastic strain and hence of radius within the gun tube. The shape of the Bauschinger profile is presented as equation (1) in ref. [5] and covers steels with yield strength up to 1150 MPa. Recent work has confirmed this equation and provided a wider range of fit for steels with yield strengths significantly in excess of 1150 MPa [6]. *The correct form of this profile is the essential input, as equivalent stress-strain data, to any refined numerical stress analysis of the autofrettage process.*

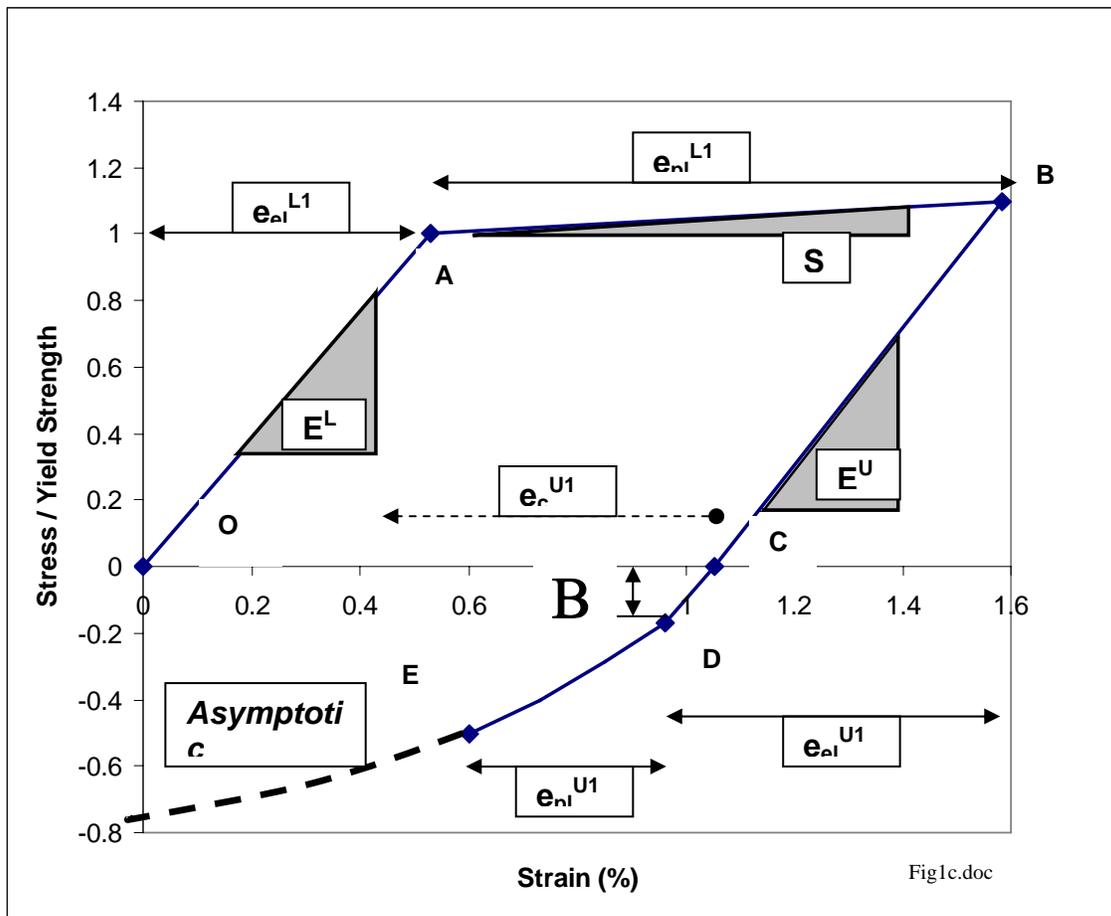


Figure 1 : Typical Bauschinger Effect Exhibited During Uniaxial Test

A wide-ranging set of post-autofrettage bore residual stress and strain solutions applicable to A723 type steel has been obtained for the case of hydraulic autofrettage with Bauschinger effect [3], including the crucial variation in the Bauschinger-affected

unloading profile as a function of radius. These solutions employ a numerical technique based upon an extension of a method proposed in [7]. This method is termed The *Hencky program*. After consideration by the relevant specialist ASME committee, the *ASME Pressure Vessel and Piping Code* [8] has been modified to incorporate results presented in [3]. Recent work by Huang [9] has provided a method for determining analytical solutions for a hydraulically autofrettaged thick cylinder with life-like Bauschinger effect. Unfortunately such solutions are for the special case of closed-end autofrettage of an incompressible material and they assume that unloading behavior is the same regardless of prior plastic strain. The obvious use of this technique is for validation of numerical programs.

Elastic-plastic Finite Element Analysis (FEA) programs such as ABAQUS® and ANSYS® have the potential to solve Bauschinger-affected configurations similar to those addressed by the *Hencky program*. However, unless the user is equipped to intervene in the standard packages by introducing pre- and/or post-processors and to implement any necessary iterative procedures, such solutions appear somewhat daunting. In addition such standard packages are likely to be too demanding to implement on a regular, stand-alone PC or notebook and may be expensive to license.

Recent numerical analyses of autofrettage using the *Hencky program* predict significant improvements in fatigue lifetime and in safe maximum pressure if gun tubes are subjected to re-autofrettage and low-temperature heat soak once or twice after initial autofrettage and low temperature heat soak [15]. Experimental tests at Benét Laboratories will, in the near future, assess whether the predicted benefits are observed in practice. If such benefits are evident it will clearly be important to have the ability to routinely model the re-autofrettage process, together with any associated material removal processes.

Representation of elastic-plastic behavior within the *Hencky program* is based upon an Elastic Modulus and Poisson's Ratio Adjustment Procedure (EMPRAP) proposed by Jahed and Dubey [7]. However EMPRAP is quite general and could, in principle, be implemented in a FEA program. Initial, unpublished validation tests by the principal investigator demonstrated that the procedure could likely be incorporated in a FEA program on an Excel®/VBA spreadsheet on a regular PC (Win98SE or later, Excel97 or later, 500MHz Pentium or faster, 512MB of RAM or more).

The procedure adopted previously to incorporate pre-existing residual stress fields, whether due to shrink-fitting [16] or prior autofrettage [15] could, potentially, be incorporated into such a FEA/spreadsheet scheme.

A specific candidate gun steel, HB7 produced by Giat of France, is under consideration by staff at Benét Laboratories. Before stresses in an autofrettaged tube made from this new steel could be evaluated it was necessary to characterize the uniaxial loading and unloading behavior of this steel. This involved a series of uniaxial pull-push tests, each to a different maximum plastic strain level, and subsequent curve-fitting this behavior. Results of this work, by Troiano and co-workers at Benet Laboratories, have now been published [13] and were available for inclusion in the FEA program.

SOFTWARE OBJECTIVES OF THIS CONTRACT

1. Develop a prototype user-friendly spreadsheet-based FEA program to calculate stresses in an autofrettaged tube manufactured from a range of previously characterized gun steels. Program to offer the following end-condition options:
 - a. Plane stress
 - b. Plane strain
 - c. Open ends
 - d. Closed ends
2. Test and validate the program by comparing with certain limited analytical solutions due to Huang [9] and numerical solutions calculated via the Hencky program [3].
3. Extend the FEA procedure to incorporate pre-existing residual stress fields. Test and validate this extension by comparing with numerical solutions for re-autofrettage calculated via the *Hencky program* [15].
4. Implement HB7 steel within the spreadsheet-based FEA program such that the program can be used to calculate stresses within autofrettaged tubes manufactured from this new steel.
5. Supply final, working version of spreadsheet-based FEA program to Benét Laboratories.

The above outcomes to be achieved via 10 weeks work in the following sequence:

- a. 3 weeks work in the UK ,
- b. 4 weeks secondment to Benét Laboratories,
- c. 3 weeks work in the UK.

CONFERENCE ATTENDANCE

The principal investigator (PI) was a member of the international organizing committee for Gun Tubes 2005 (GT2005), Oxford, England, April 2005; this conference was sponsored by US Army ARDEC and ERO. As a result he was invited to attend and to present a summary of GT2005 papers at the ARL/Benét Labs/ARDEC Advanced Gun Barrel Materials and Manufacturing Symposium, Maryland, 12-14 July 2005. In addition the PI has had papers on the subject of re-autofrettage [15] and a critical evaluation of an analytical autofrettage analysis procedure due to Huang [9] accepted for the ASME Pressure Vessels and Piping Conference, Denver, Colorado, July 2005. The PI therefore attended the following conferences:

- d. Advanced Gun Barrel Materials and Manufacturing Symposium, Maryland, 12-14 July 2005,
- e. ASME Pressure Vessels and Piping conference, Denver, Colorado, 17-21 July 2005,

CONTRACT OUTCOMES

1. The principal researcher, Professor Anthony P. Parker (APP), undertook initial development of the required finite element analysis (FEA) program in the UK from 3 May – 5 June 2005.
2. APP flew to the USA on 10 June 2005 and worked on further development of the FEA program with staff at Benét Laboratories, Watervliet, NY until 8 July 2005. The program formulation was verified by comparison with an available analytical solution procedure and with an independent numerical procedure. An interim version of the program was demonstrated at Benét Laboratories during a seminar on 6 July and made available to staff for evaluation.
3. During the week 11-16 July 2005 APP attended the specialized US Army Advanced Gun Barrel Materials and Manufacturing Symposium at St Michael's, Maryland. During the introductory session he presented a summary of relevant, complementary work from the 'Gun Tubes 2005' (GT2005) conference held in Oxford, England, April 2005. GT2005 was co-sponsored by Benét Laboratories and the US Army European Research Office, London.
4. During the week 17-21 July 2005 APP attended the ASME Pressure Vessels & piping Conference, Denver, CO. He presented two papers [17, 15] and received the *Journal of Pressure Vessel Technology* Editor's outstanding technical paper award for an earlier publication [18]. Reference [15] relates to a proposed manufacturing procedure for enhancement of fatigue lifetime and safe maximum pressure in gun tubes that is under evaluation by staff of Benét Laboratories.
5. An improved ('beta') version of the FEA program was supplied to staff of Benét Laboratories during August 2005.
6. The principal researcher undertook further development of the required finite element analysis (FEA) program in the UK during the period 1 August – 31 October 2005.
7. Following feedback on the initial 'beta' version of the program from Benét laboratories the program was modified to permit modeling of the sequence *autofrettage – material removal – reautofrettage*.
8. The software was used to predict residual stresses in autofrettaged tubes after material removal from bore and outside diameter, followed by the cutting of an axially-thin ring segment. These results were used by Benét staff to make comparisons with residual stress profiles that were determined experimentally using the neutron-diffraction technique.
9. Using the FEA program as a source of randomized, quasi-experimental data the PI drafted a paper "An Improved Method for Recovering Residual Stress from Strain Measurements in Cylinders and Rings". The revised procedure is intended to overcome the sensitivity of the traditional solution procedure, and to impose real physical constraints, such that more accurate stress values are recovered. In some cases an order of magnitude improvement in stress prediction is demonstrated. This paper has been accepted for presentation at the ASME Pressure Vessels & Piping Conference, Vancouver, 2006 [19].
10. The final version of the Excel/VBA/FEA software was supplied to Mr. E. Troiano of Benét Laboratories on 21 April 2006.

THE EXCEL/VBA FINITE ELEMENT ANALYSIS PROGRAM

Full programs and help sheets have been provided to Benet Laboratories. In summary, the program uses Excel linked to the Visual Basic (VB) programming option (Excel VBA). The VB coding includes an axi-symmetric finite element analysis (FEA) program. It can solve the following plane end conditions: plane strain, open-end, closed-end, specified end load. This program solves non-linear material problems using a modified elastic modulus and Poisson's ratio adjustment procedure (EMPRAP) that has been thoroughly tested in other numerical programs. The special feature of this FEA application is the ability to model a different material behavior within each element. Specifically, material unloading behavior can, in general, be a function of prior plastic strain and can thereby model real-life Bauschinger effect. Such behavior has been provided for six possible gun steels. In addition there are options for re-autofrettage, for elastic-perfectly plastic behavior and for a specialized fit for rapid predictions for new candidate steels on the basis of a single uniaxial loading-unloading test that models behavior at the bore of a tube. Figure 2 shows a flow diagram relating to the various operations.; the program permits numerical simulation of any of the following combination(s) of operation(s):

Autofrettage; Autofrettage + Reautofrettage; Autofrettage + Reautofrettage + Material Removal; Autofrettage + Material Removal + Reautofrettage; Autofrettage + Reautofrettage + Material Removal + 2nd Reautofrettage

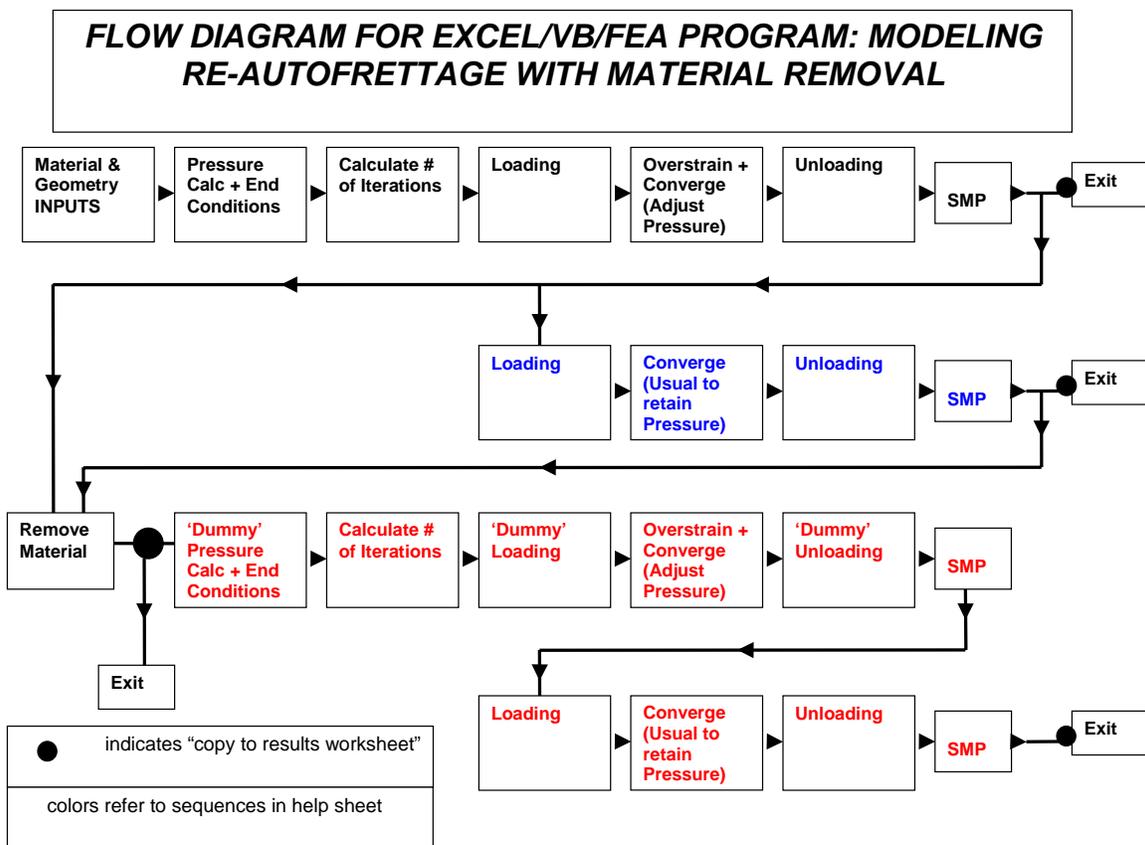


Figure 2: Flow Diagram Representing Combinations of Possible Autofrettage and Material Removal Operations Using Excel/VB/FEA Program.

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Professor A P Parker

27 April 2006

Annex

- (a) Unused funds remaining at end of period covered by this report : \$0-00.
- (b) No property was acquired with contract funds during the period of this report.