Input of creep and shrinkage characteristics for a structural analysis program

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Presented is a computer program for the input of creep and shrinkage properties for a structural analysis program. The program either accepts numerical data on the compliance function and the shrinkage function at discrete load durations and ages at loading, or uses the recent BP Model for creep involving the double-power law. The most useful characteristic is the availability of thirteen different options for specifying the creep and shrinkage parameters; sealed conditions or drying conditions, creep values specified and interpolation to be used, parameter of a creep formula specified, or creep formula automatically fitted to given creep data, short time data specified and extrapolation done by a formula, etc. In addition to returning the compliance function, the program also calculates the relaxation function and the age-dependent elastic moduli of a Maxwell chain model that is equivalent to the given creep properties. The program is particularly suitable for the input of creep characteristics for a large-scale finite element analysis.

INTRODUCTION

Development of numerical structural analysis methods for creep and shrinkage of concrete has greatly enhanced our capability of realistic modeling and prediction of structural behavior. Implementation of such an analysis however requires the use of a realistic model for creep and shrinkage properties (constitutive equation) and optimum adaptation of this model to available data on the material.

Extending the work briefly outlined in a recent conference paper [1], we present here a complete listing of a computer program which serves the aforementioned purpose. This program allows for characterizing the creep and shrinkage properties by a set of measured or given values at discrete times or by formulas recently presented in this Journal [2]. Various

mixed modes of input, combining partial experimental data and automatic fitting of a formula are also available in this program. The most useful feature of the program is the availability of numerous options for the specification of creep (and shrinkage) properties by the user and for the type of representation of the compliance function. In addition to generating the compliance function, the program also automatically calculates discrete values of the relaxation function as well as discrete values of the age-dependent elastic moduli of a Maxwell-chain rheologic model — a model which allows the most efficient analysis of large structural systems by finite elements.

The FORTRAN IV listing which we present here includes numerous comments defining the meaning of

principal variables as well as the input. The output of the program is also made self-explanatory by the headings and comments. It is therefore possible to understand and use this program without a separate guide, which could not be anyhow condensed into a short paper. However, a detailed guide is available [3], as part of a manual for a complete finite element program for concrete creep at variable temperature.

CONSTITUTIVE RELATION

The present program characterizes creep in terms of a compliance function $J(t, t')$ (also called creep function), which represents the strain at age t caused by a unit constant stress acting since the age t' .

By using this function, we assume the constitutive equation to be linear, obeying the principal of superposition [4]. The linearity assumption is acceptable only at stresses less than about one-half of the strength of concrete. One must be aware, however, that even within this range significant deviations from linearity are observed upon sudden unloading and generally in regimes of decreasing strains. Further significant deviations from linearity are caused by a drying simultaneous with creep, chiefly due to microcracking produced by the drying. By considering the compliance function as a function of two variables (t, t') , the aging of concrete is taken into account.

To facilitate the analysis of large structural systems, the program also generates the material parameters for a rate-type constitutive law for the aging creep of concrete. The well-known Maxwell chain model with age-dependent elastic moduli is chosen for this purpose ([5], [6]). This formulation allows the storage of the history of stresses or strains to be dispensed with, and thus it greatly reduces the computational costs and increases the size of the structural system that can be handled on a given computer.

SIMPLIFIED FLOW CHART OF THE PROGRAM

1. Read the number of decades in log-time scale to be considered, the number of steps per decade, the number of elements in Maxwell chain, the time for the start of the first time step, and the first relaxation time.
2. Read the input option number and the corresponding material data from which the characterization of the compliance function is developed. When the case of drying is specified, read also the characteristics for shrinkage and drying creep.
3. Compute the discrete values of the relaxation function for various strain durations and various ages at the start of relaxation. (This consists in a direct numerical solution of a linear Volterra integral equation.) (RELAX).

4. Compute the discrete values of the Maxwell chain moduli at all discrete ages (MAXWL 1).

5. As a check, compute discrete values of the compliance function from the discrete values of Maxwell chain moduli for various ages (CRCURV). Print the resulting values of the compliance function and of their deviations from the initially specified values of the compliance function. Also calculate and print the coefficient of variation of these deviations.

During the determination of the relaxation function, a subroutine for the compliance function is repeatedly called. This subroutine has three options to be specified by the user:

1. The compliance function is evaluated by interpolation from a given array of discrete values. The interpolation is linear in the logarithm of elapsed time and in the logarithm of the age at loading. For durations and ages falling outside the range, extrapolation is automatically used.
2. The compliance function is evaluated from a formula corresponding to the double power law [7].
3. If drying is specified, the compliance function is evaluated from a formula consisting of the double power law enhanced by a drying term [7].

The ultimate result obtained in the subroutine MATPAR is the array of discrete values of the moduli of the Maxwell chain. For any specified age, the values of the Maxwell chain moduli are computed (in subroutine function EMUF) from these discrete values by a linear interpolation in the logarithm of the age of concrete. For arguments falling outside the time range, a linear extrapolation from the two values at the end of the array is used.

INPUT OPTIONS FOR MATERIAL CHARACTERIZATION

In practical applications, many different situations can arise. Sometimes measured values of the creep function for many different times and ages at loading may be available, as is often the case in the design of nuclear structures. For other than special sensitive structures, the typical situation is that no measured creep data are available for the concrete to be used in the structure under design, and then some prediction formulas for creep and shrinkage need be employed, for which the BP model [2] is adopted here. Often, however, at least some experimental information may exist for the particular value of the elastic modulus, or even measured short-time creep deformations for one loading age or a few short load durations. Furthermore, even when full or partial experimental data may be available, they may be too scattered or uncertain, in which case a smoothing of the data by a realistic creep formula is appropriate. Similarly, the use of a creep formula is inevitable for the extrapolation of short-time creep data to long durations.

To treat the various possibilities just outlined, the following options for the material characterization are provided in the program MATPAR:

1. The compliance function is specified as an array of discrete values for various load durations and various ages at loading. No drying is considered.
2. Drying is considered, and the mean compliance function for the cross section is specified as in option 1. Also, the values of the mean shrinkage strain of the cross section are specified for various durations of drying and the given age at the start of drying.
3. The compliance function is given by the double power law, for which all of its five parameters are read. No drying is considered.
4. Same as option 3 but all double power law parameters except the 28-day elastic modulus are generated from the given strength and composition parameters of concrete (the mix ratio of water, cement, sand and gravel, the cement type, and the unit weight of concrete).
5. Same as option 4 except that the 28-day elastic modulus is also predicted from the strength and composition parameters.
6. Drying is specified and the compliance function is defined by the double power law enhanced by the term for the creep increase due to drying [2]. A formula for the shrinkage strain evolution in time (according to Ref. [2]) is also specified. And all parameters for these formulas are read.
7. Same as option 6 but all material parameters except the 28-day elastic modulus and the final shrinkage strain are predicted from the strength and the composition parameters of concrete (and also from the given ambient humidity).
8. Same as 6 but all parameters except the 28-day elastic modulus are predicted from the strength and composition of concrete.
9. Same as option 6 but all parameters are predicted from the strength and composition of concrete.
10. Two of the five double-power law parameters (namely, E_0 and ϕ_1 , see Ref. [2]) are determined so as to obtain the best fit (in the least-square sense) of the given array of discrete values of the compliance function at various load durations and various ages. The remaining three double power law parameters are given. This option is used when the given array of discrete values for the compliance function is of limited range in time and/or age. No drying is considered in this option. As a check, the coefficient of variation for the deviations of the formula from the given limited array of values for the compliance function is automatically computed and printed.
11. Same as option 10 but the remaining three double power law parameters are not specified; they are predicted from given strength and composition of concrete.
12. Same as option 10 but drying is considered.

13. Same as option 11 but drying is considered.

The user selects his input option depending on the amount of information available to him before the analysis. If sufficient test data have been obtained, as is frequently done for nuclear concrete structures, then the measured discrete values of the compliance function should be used. However, if the range of these available data is too limited, it is preferable to approximate these values by the double power law.

If no experimental information is available, the double power law parameters are predicted from the strength and composition of concrete. However, if there exists some information on the double law parameters for a similar concrete, an adjustment of some of its parameters is appropriate. Moreover, if the short-time deformation (elastic modulus) is measured, it should be also used to improve the parameters of the double power law.

The choice of the proper input option has a great effect on the accuracy in representing the concrete properties.

OUTPUT AND APPLICATION

The ultimate result of the program is the subroutine EMUF which generates the values of the Maxwell chain moduli, and in case that drying is specified, also the subroutine SHRINK which generates the values of the mean shrinkage strain of the cross section. Subroutine EMUF may then be called from a structural analysis program performing a step-by-step numerical solution.

As an alternative in case of a structural system that does not involve too many degrees of freedom, one may prefer characterizing the creep properties in terms of the compliance function $J(t, t')$ and performing the structural analysis on the basis of the principle of superposition, which leads to integral equations in time. In that case, subroutines RELAX, MAXWL1, CRCURV, and EMUF can be discarded and the calls for these subroutines eliminated from the main program MATPAR.

CONCLUDING REMARKS

The present program would hopefully help increasing the accuracy of material representation in computer creep analysis. Available finite element programs make an accurate analysis of complex structures possible, but this possibility can be realized only if the material is characterized with a commensurate accuracy. It makes no sense to carry out a sophisticated finite element analysis and at the same time use some crude model for representing creep, a model of the type intended for hand calculations in a design office. In case of the analysis of concrete structures for creep and shrinkage, it is currently the material model which represents by

far the greatest source of error. Thus, devoting more effort to material modeling than to the structural calculations has the greatest potential pay-off.

The salient feature of the present program is its adaptiveness to the amount of information supplied. If the user supplies very little information about his concrete, the program automatically predicts reasonable values of material parameters but the resulting prediction of creep is of course crude. Various options allow the user to supply more information with the advantage of better prediction of creep.

ACKNOWLEDGMENT

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RÉSUMÉ

Introduction des caractéristiques de fluage et de retrait dans un programme d'analyse structurale. — On présente l'informatisation des propriétés de fluage et de retrait qui entre dans un programme d'analyse structurale. Le programme soit accepte les données numériques de la fonction d'adaptation plastique et de la fonction de retrait pour des durées de chargement et des âges au chargement discrets, soit utilise le récent modèle de fluage BP à loi de double puissance. La caractéristique la plus utile est qu'on dispose de treize options différentes pour spécifier les paramètres de fluage et de retrait : conditions

d'étanchéité ou conditions de séchage, valeurs spécifiées de fluage et interpolations, paramètres d'une formule spécifiée de fluage ou formules de fluage telles qu'elles donnent automatiquement les valeurs de fluage, valeurs spécifiées pour de courtes durées et extrapolations à partir d'une équation, etc. Outre qu'il restitue la fonction d'adaptation, le programme permet aussi de calculer la fonction de relaxation et les modules élastiques en relation avec l'âge d'un modèle HN de Maxwell, soit l'équivalent des propriétés de fluage données. Le programme se prête particulièrement à l'introduction des caractéristiques de fluage pour une analyse par éléments finis à grande échelle.

APPENDIX-FORTRAN IV listing of program MATPAR *

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      9280
      9290
      9300
      9310
      9320
      9330
      9340
      9350
      9360
      9370
      9380
      9390
      9400
      9410
      9420
      9430
      9440
      9450
      9460
      9470
      9480
      9490
      9500
      9510
      9520
      9530
      9540
      9550
      9560
      9570
      9580
      9590
      9600
      9610
      9620
      9630
      9640
      9650
      9660
      9670
      9680
      9690
      9700
      9710
      9720
      9730
      9740
      9750
      9760
      9770
      9780
      9790
      9800
      9810
      9820
      9830
      9840
      9850
      9860
      9870
      9880
      9890
      9900
      9910
      9920
      9930
      9940
      9950
      9960
      9970
      9980
      9990
      10000

```

* Note that in all statements COMMON/CRPAR/the variable CITO contains the digit "zero", not the letter "O".

```

WRITE(6,603)JOPT
READ(5,3100)NTSHR,(TSHR(I),I=1,NTSHR)
WRITE(6,3101)NTSHR,(TSHR(I),I=1,NTSHR)
3100 FORMAT(12,1X,F7.1,(7F10.1))
3101 FORMAT(1X//23H GIVEN SHRINKAGE VALUES ,3X,6HNTSHR=,12//13H TIMES(
10AYS)=,10E14.4))
READ(5,3105)(SHR(I),I=1,NTSHR)
WRITE(6,3107)(SHR(I),I=1,NTSHR)
3105 FORMAT(8E10.3)
3107 FORMAT(13+05+R,VALUES= 9E14.4/(15X8E14.4))
DO 3109 I=1,NTSHR
3109 TSHR(I)=ALOG10(TSHR(I))
C
C
610 IF ((JOPT . NE . 3 . AND . JOPT . NE . 4) . AND. (( JOPT . LT . 6
1. OR . JOPT . GT . 8) . AND .JOPT .LT. 10)) GO TO 620
C
C
FOR JOPT=3,4,6,7,8,10,12 FUNCTION J IS DEFINED BY DOUBLE POWER LAW
AND ITS COEFFICIENTS ARE SPECIFIED. HOWEVER, FOR JOPT .EQ. 10 OR
12 USE SOME DUMMY VALUES FOR E20 AND E020 BECAUSE E0 AND PHIL ARE
LATER REDEFINED, AND FOR JOPT=11 OR 13 PLACE A BLANK (DUMMY) CARD
FOR JOPT=8 OR 7 ONLY E20 IS NEEDED AND THE REST CAN BE BLANK SINCE
IT IS LATER REDEFINED BY INPUT FROM DATA CARD K.
WRITE(6,603)JOPT
C
C
DATA INPUT FOR DOUBLE POWER LAW.
NOTE THAT ON DATA CARD THE EXPONENT OF E-FORMAT MUST BE RIGHT-
ADJUSTED.
READ(5,4401) E20,EOE20,EXPN,EXPN,ALFA
WRITE(6,4402)E20,EOE20,EXPN,EXPN,ALFA
4401 FORMAT(10,3,F10.1)
4402 FORMAT(1X//34H GIVEN DOUBLE POWER LAW PARAMETERS//12X2H20-DAY EL.
MODULUS,12E10.3,4H PSI//5X,6HEOE20=,F8.4,5X,5HEXPN=,F7.4,5X,
15HEXPN=,F7.4,5X,3HALFA=,F8.5//)
IF(JOPT.NE.3.AND.JOPT.NE.6).AND.(JOPT.NE.10) GO TO 620
EO=EOE20
PHIL=(EOE20-1.)/(10.1*EXPN)*(20.*(-EXPN)+ALFA)
WRITE(6,4403)EO,PHIL
4403 FFORMAT(14H CALCULATED EO = ,E15.5,10X,5HPHIL=,F8.5//)
EO=1./EO
C
C
620 IF((JOPT.LT. 6 .OR. JOPT .GT. 9).AND.(JOPT.LT.12) GO TO 630
C
C
HERE JOPT=6 TO 9 OR 12 OR 13
FUNCTION J IS DEFINED AS DOUBLE POWER LAW, DRYING IS
CONSIDERED, AND SHRINKAGE AND DRYING CREEP IS GIVEN BY FORMULA.
DATA INPUT FOR SHRINKAGE AND CREEP TERM DUE TO DRYING
WRITE(6,623) JOPT
623 FORMAT(1X//37H23 MUST BE JOPT=6 TO 9 OR 12 OR 13,3X,5HJOPT=I2//)
CP=0.
C7=0.
CD=0.
PHID=0.
AKS=0.
WRITE(6,603)JOPT
READ(5,4501)DRYSTA,FINSHR,AVHUM,AKS,V5,C7,PHID,CD,CP
4501 FORMAT(9F8.1)
IF UNSURE ABOUT INPUT DATA USE ZEROS ON THE ABOVE CARD.
THE FOLLOWING AUTOMATIC ASSIGNMENTS ARE THEN MADE--
IF(AKS .EQ. 0.) AKS=1.
IF(C7 .EQ. 0.) C7=10.
IF(PHID .EQ. 0.) PHID=0.03
IF(CD .EQ. 0.) CD=1.4
IF(CP .EQ. 0.) CP=0.03
C
C
OPTIONS 8 AND 9-FOR C7,PHID,CP AND FINSHR ANY DUMMY VALUES CAN BE
USED SINCE THEY ARE LATER DETERMINED FROM COMPOSITION.
FOR OPTION 7 THE SAME EXCEPT FINSHR IS NOT LATER REDEFINED.
WRITE(6,6302) DRYSTA,FINSHR,AVHUM,AKS,V5,C7,PHID,CD,CP
6302 FORMAT(1X//55H GIVEN PARAMETERS FOR SHRINKAGE AND CREEP DUE TO DR
1YING //14H DRYING START= ,F9.1,4H DAYS,10X,16HFINAL SHRINKAGE= ,
1F9.6,10X,16H AVERAGE REL.HUM.= ,F7.3//5X,4H KS=,F5.2,5X,17HVOL.-SU
1RF. RATIO= ,F9.3,10HILINERS= ,9X,3HC7=,F12.5,14HMM-SQUARE/DAY ,
1//1X,5HPHID=,F7.3,5X,3HCD=,F7.4,5X,3HCP=,F7.4//)
C
C
630 IF (JOPT .LT. 4 .OR. (JOPT .EQ.10 .OR. JOPT .EQ. 6)) GO TO 640
IF (JOPT .EQ. 12) GO TO 640
C
C
PREDICT PARAMETERS OF DOUBLE POWER LAW WITHOUT DRYING TERMS FROM
STRENGTH AND COMPOSITION, USING FORMULAS OF BAZANT-PANULA (1978)
HERE JOPT=4 OR 5 OR 7 OR 8 OR 9 OR 11 OR 12 OR 13
WRITE(6,632) JOPT
632 FORMAT(1X//52H0 MUST BE JOPT=4 OR 5 OR 7 OR 8 OR 9 OR 11 TO 13
1,3X,5HJOPT=,I2//)
WRITE(6,603)JOPT
READ(5,691)FCP,WC,AC,SC,RO,ITYPE
WRITE(6,692)FCP,WC,AC,SC,RO,ITYPE
691 FORMAT(5F10.1,1I0)
692 FORMAT(1X,4HFCP=F10.3,5X3HWC=F10.3,5X3HAC=F10.3,5X3HSC=F10.3,
15X3HRO=F10.3,11HPOUND/CU-FT,5X,6HITYPE=,I5)
AL=1./((1.-SC)/AC)
AL=1.0
IF(ITYPE .EQ. 3) AL=0.93
IF(ITYPE .EQ. 4) AL=1.05
ALFA=0.025/WC
EXPN=0.28+1./(FCP*FCP)
X=((1.1*AC)/(SC*(1.-L4)))+(0.1*FCP**1.5)*(WC**0.3333333)*AG**2.2)
1*AL-4.
IF(X .LE. 0.) GO TO 810
EXPN=0.12+0.07/(1.+5130./(X**6))
GO TO 811
810 EXPN=0.12
X=ALFA*28.**(1-EXPN)
PHIL=(0.3*(1000.**EXPN))/X
IF(JOPT.EQ.5.OR.(JOPT.EQ.9) GO TO 813
HERE JOPT=4 OR 7 OR 8 OR 11 OR 12 OR 13
EO=1.5*E20
GO TO 814
813 Z1=(0.00009*(RO*RO))*FCP
EO=1.E6/(0.07+0.59824/(Z1*Z1))
E20=EO/(1.+(PHIL*(0.001*EXPN))*X)
FOR CHECK
X=EO/E20
WRITE(6,6789)X
6789 FORMAT(1X,10H CHECK IF ,F8.4,27H .NE.1.5 -ERROR- CORRECT IT //)
C
C
814 CONTINUE
EO=1./EO
WRITE(6,895)EO,PHIL,EXPN,EXPN,ALFA,E20
895 FORMAT(1X//58HDOUBLE POWER LAW PARAMETERS PREDICTED FROM FCP AND
1COMP./ 4H0E14.4, 5X,5HPHIL=F8.3, 5X,5HEXPN=F8.3, 5X,5HEXPN=F8.3,
1, 5X,5HALFA=F8.3,5X,4HE20=,E14.4 /80H HOWEVER FOR JOPT=7 OR 8 THE
1 ABOVE E20 IS NOT DETERMINED FROM COMPOSITION. //)
C
C
640 IF (JOPT.LT. 7 .OR. (JOPT .GT. 9 .AND. JOPT .NE. 13)) GO TO 650
HERE JOPT=7 OR 8 OR 9 OR 13
PREDICT PARAMETERS FOR SHRINKAGE AND DRYING CREEP FROM STRENGTH
AND COMPOSITION. DOUBLE POWER LAW PARAMETERS MUST ALREADY BE
ASSIGNED.
WRITE(6,643)JOPT
643 FORMAT(1X//30H43 MUST BE JOPT=7 OR 8 OR 9 OR 13 ,3X,5HJOPT=I2//)
READ(5,713)CEM
713 FORMAT(1F10.1)
714 FORMAT(16H0CEMENT CONTENT=,F8.1,2X18HKG PER CUBIC METER)
C
C
PARAMETERS FOR SHRINKAGE
C7=(0.125*WC)*CEM-12.
IF(C7 .LT. 7.) C7=7.
IF(C7 .GT. 21.) C7=21.
GS=AC/SC-1.
IF(JOPT .EQ. 7) GU TO 723
Z=(1.25*SQRT(AC) + 0.5 * (GS*GS))*(((1.+ SC)/WC) **0.33333333)*
1SQRT(FCP) - 12.
IF(Z .LT. 0.) Z=0.
Y=1./((300.*Z**(-4)) + 1.)
FINSHR=(1210.-880.*Y)*1.E-6
WRITE(6,603)JOPT
WRITE(6,712) FINSR,C7,GS
712 FORMAT(1X//19H CALCULATED FINSHR= , E13.4,10X,3HC7=,E13.4,10X,3HGS=,
1F7.3//)
C
C
PARAMETERS FOR DRYING CREEP
C
723 R=(56000.* ((FCP*(SC/AC))**0.3))*((GS**1.3)*((WC/(FINSHR*1.E6))
1**1.5)))-0.85
IF (R .LE. 0.) GO TO 715
U=1./((1.+0.74*(R**(-4))))
PHID=0.008+0.0274U
GO TO 716
715 PHID=0.008
716 CP=0.03
WRITE(6,716) PHID,CP
716 FORMAT(1X//17H CALCULATED PHID=, F8.4,13X,3HCP=,F7.3//)
718 IF(JOPT .LT. 6 .OR. (JOPT .GT. 9 .AND. JOPT .LT. 12)) GO TO 660
HERE JOPT=6 OR 7 OR 8 OR 9 OR 12 OR 13
CALCULATE SHRINKAGE AND CREEP PARAMETERS OF BAZANT-PANULA'S
FORMULA (1978) FOR MATERIALS E STRUCTURES, VOL.11,1978,P.308).
PARAMETERS FOR SHRINKAGE
WRITE(6,653) JOPT
653 FORMAT(1X//42H0MUST BE JOPT=6 OR 7 OR 8 OR 9 OR 12 OR 13, 3X5HJOPT=
1I2//)
C10=C7*(1.05+3*SQRT(6.3/DRYSTA))
TAUSH=(600.*AKS*(V5/75.1**2))*((10./C10)
E=SHINF*FINSHR*SQRT(1.16742*(1.85**4/(DRYSTA + TAUSH)))
EPSKH=E*SHINF*(1.-AVHUM**3)
C
C
PARAMETERS FOR CREEP TERMS DUE TO DRYING
AKHPP=1.-AVHUM**2
AKHP=1.-AVHUM**1.5
EXPM2=EXPN*0.5
PKE=(AKHP/C7)*E*SHINF * 1.E6
TAUI0=100.*TAUSH
TAUI00=100.*TAUSH
CDN=CD*EXPN
CPK=CP*AKHPP
EO1=1./EO
WRITE(6,603)JOPT
XX=10.**1./FLUAT(JA))
DO 4009 IA=2,NA
TP(IA)=TP(IA-1)*XX
DTR=10.**((1./FLUAT(JDEC))
WRITE(6,3900)(TP(IA),IA=1,NA,2)
3900 FFORMAT(1X//13+0 TP(IA)=,8E12.3/(13X,8E12.3))
WRITE(6,4000)
4000 FORMAT(1X//70H0CREEP FUNCTION VALUES INTERPOLATED FROM GIVEN DISCRET
1E ARRAY AJ(I,J) /55H TO BE APPROXIMATED BY DOUBLE POWER LAW.
1 UNITS (1./PSI) /42H IT T(I)T) AJ(I,1) AJ(I,2) )
DOJ020 IT=1,NT
IF(IT.GT.1) T(IT)=(T(IT-1)*DTR
DO 4010 IA=1,NA,2
4010 DDEF(IA)=CREEP(T(IT),TP(IA))
4020 WRITE(6,4030)IT,T(IT),(DDEF(IA),IA=1,NA,2)
4030 FORMAT(1X,12,F10.3,10E12.3/(13X,10E12.3))
WRITE(6,657) C10,TAUSH,E*SHINF,EPSKH,AKHPP,AKHP,CDN,CPK
657 FFORMAT(1X//6H C10=,E12.4,5X,6HTAUSH=,E12.4,5X,THESHINF=,E12.4,5X,
15HEPSKH=,E12.4,7H AKHPP=,E12.4,5X,5HAKHP=,E12.4,5X,4HCDN=,F8.4,
15X,4HCPK=,F8.4//)
660 IF(JOPT .LT. 10) GO TO 670
JOPT .GT. 10. MODIFY EO AND PHIL IN DOUBLE POWER LAW TO GIVE BEST
FIT OF LIMITED DATA SET AJ(I,J)
WRITE(6,603)JOPT
EO=1.
PHIL=1.
A2=0.
A22=0.
B1=0.
B2=0.
A11=NMU
DO 672 J=1,NJ
O3 672 J=1,NJ
XIJ=CREEPB(AT(I),ATP(J))-1.
Y=AJ(I,J)
IF(JOPT.GT.11) Y=Y-ORTERM(AT(I),ATP(J))
A12=A2+XIJ
A22=A22+XI*XI
B1=B1+Y
B2=B2+Y*XIJ
DET=A11*A22-A12*A12
EO1=(B1*A22-B2*A12)/DET
EO=1./EO1
PHIL=EO*(A11*B2-A12*B1)/DET
WRITE(6,671) EO,PHIL
671 FORMAT(1X//40HJOPT.GT.10 OPTIMIZED FROM GIVEN DISCRETE AJ, EO=
1E15.5,5X,5HPHIL=,F8.4,22H(FOR DOUBLE POWER LAW) //)
670 CONTINUE
C
C
PRESCRIBED STRAIN INCREMENTS FOR RELAXATION
C
DDEF(1) = 1.
DO 110 I=2,NT
110 DDEF(I) = 0.
WRITE(6,9999)
9999 FORMAT(1X//53H0 END OF INPUT AND OF GENERATION OF INPUT PARAMETERS )
C
C
COMPUTE DISCRETE VALUES ER OF THE RELAXATION FUNCTION
CALL RELAX(NDEC,JDEC,JA,DDEF,T,TT,NT,ER)
C
C
COMPUTE DISCRETE VALUES OF ELASTIC MODULI EMU OF MAXWELL CHAIN
CALL MAXWLL(ER,T,TT,NT,W1,W2,TAU, NMU)
C
C
IN DEBUGGING ARGUMENT NDEC AND JDEC AFTER TPL IN MAXWLL WERE
REMOVED. CHECK AGAIN LATER.
WRITE(6,1100)
WRITE(6,1110) (TAU(NU),NU=1,NMU)
C
1110 FORMAT(1X,10E10.3,2X)
1100 FORMAT(1X//23H RELAXATION TIMES )

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C NOW PRINT SHRINKAGE VALUE AS PRESCRIBED ABOVE.
IF(JOYT.LT.6)STOP
IF(1JOYT.GT.9).AND.(1JOYT.LT.12)STOP
WRITE(6,1425)
1415 FORMAT(//50HOPRINT SHRINKAGES VALUES AS PRESCRIBED //
14XX9HAGE(DAYS),11X,6HSTRAIN /)
DO 1420 IT=1,NT
A2=PHI1*(1+DRYSTA)
B2=SHRINK(A2)
1420 WRITE(6,1425)A2,B2
1425 FORMAT(1X,39X,F12.2,5X,F12.6)
STOP
END

FUNCTION CREEP(X,Y)
C COMMON/CRPAR/JOYT,E28,EO,PHI1,EXPX,EXPX,ALFA,DRYSTA,AVHUM,FINSR,
1ESHINF,TAUSH,PHID,CP,CD,AKS,VS,C7,C1TO,EPKSH,AKHPP,AKHP,EXPX2,
2FKE,TAU10,TAU100,CON,CPK,E01,CO
C IF(1JOYT.GT.2) GO TO 10
CREEP=CREEPA(X,Y)
RETURN
10 CREEP = CREEPB(X,Y)
RETURN
END

FUNCTION CREEPA(X,Y)
C *****
C CREEP RETURNS THE CREEP COMPLIANCE FUNCTION. J(X+Y,Y)=CREEP(X,Y)
C IS EVALUATED BY DOUBLE LINEAR INTERPOLATION OF DISCRETIZED DATA
C AJ IN LOG-SCALE INTERPOLATION OR EXTRAPOLATION IS DONE LINEARLY
C IN LOGARITHMIC SCALES OF TIMES AT LOADING AND LOAD DURATIONS
C
C X TIME ELAPSED FROM LOADING
C Y AGE AT LOADING
C
C INPUT
C AJ(16,8)=DISCRETE VALUES OF COMPLIANCE FUNCTION
C ATL(K)=VALUES OF DEC. LOGARITHMS OF LOAD DURATIONS
C ATPL(L)=VALUES OF DEC. LOGARITHMS OF AGES AT LOADING
C NI=NO. OF AGES AT LOADING
C NZ=NO. OF LOAD DURATIONS
C
C AFTER BAZANT, MATERIALS AND STRUCTURES (PARIS) VOL.5,NO. 7, 1972
C P.139
C *****
C COMMON/JFUNCT/AJ(16,8),ATL(16),ATPL(8),NI,NJ,AT(16),ATP(16),
1SHR(16),TSHR(16),TLSHR(16),NTSHR
C
C THIN = 10.*(ATL(1))
C YL = ALOG10(Y)
C L = 1
10 L = L + 1
A = ATPL(L) - YL
IF (A .LT. 0 .AND. L .LT. NJ) GO TO 10
AA = YL - ATPL(L-1)
IF (X .GT. THIN) GO TO 20
CREEPA = (AJ(L,L-1)*A + AJ(L,L)*AA)/(A+1)
RETURN
20 XL = ALOG10(X)
K = 1
30 K = K + 1
B = ATL(K) - XL
IF (B .LT. 0 .AND. K .LT. NI) GO TO 30
BB = XL - ATL(K-1)
CREEPA = ((AJ(K,L-1)*B + AJ(K,L)*BB) +
1 (AJ(K,L-1)*A + AJ(K,L)*AA)*BB)/
2 ((ATL(K) - ATL(K-1))*(ATPL(L) - ATPL(L-1))
C
100 RETURN
END

FUNCTION CREEPB(X,Y)
C *****
C DETERMINES CREEP FUNCTION J FROM DOUBLE POWER LAW WITHOUT OR WITH
C DRYING TERMS.
C Y=T-PRIME=AGE, X=T MINUS T-PRIME=LOAD DURATION.
C *****
C COMMON/CRPAR/JOYT,E28,EO,PHI1,EXPX,EXPX,ALFA,DRYSTA,AVHUM,FINSR,
1ESHINF,TAUSH,PHID,CP,CD,AKS,VS,C7,C1TO,EPKSH,AKHPP,AKHP,EXPX2,
2FKE,TAU10,TAU100,CON,CPK,E01,CO
C
C IF(1JOYT.LT.3) WRITE(6,99) JOYT
99 FORMAT(10JOYT=15,6HWRONG)
C DOUBLE POWER LAW (BAZANT-PANULA, MATERIALS AND STRUCTURES, 1978)
C CO = (PHI1*((ALFA+Y**(-EXPX))*X**EXPX))*E01
CREEPB=E01+CO
C ADD THE DRYING TERMS
C IF(1JOYT.GT.9 .AND. (1JOYT.NE.10 .AND. 1JOYT.NE.11)) CREEPB=
1CREEPB-DRTERM(X,Y)
RETURN
END

FUNCTION DRTERM(X,Y)
C *****
C CALCULATE DRYING TERM TO BE ADDED TO DOUBLE POWER LAW.
C *****
C COMMON/CRPAR/JOYT,E28,EO,PHI1,EXPX,EXPX,ALFA,DRYSTA,AVHUM,FINSR,
1ESHINF,TAUSH,PHID,CP,CD,AKS,VS,C7,C1TO,EPKSH,AKHPP,AKHP,EXPX2,
2FKE,TAU10,TAU100,CON,CPK,E01,CO
C
C PHIDP1=SQRT(1+(Y-DRYSTA)/TAU10)/PHID
C CAPCD=(1+Y*EXPX2)/(PHIDP1)*(FKE*(1+TAU10/X)**CON)
C Z=X*Y-DRYSTA
C IF(Z.LT.1.E-6) Z=1.E-6
C DRTERM=CAPCD-(CPK*CO)*((1+TAU10/Z)**(-EXPX))
RETURN
END

FUNCTION SHRINK(T)
C *****
C COMPUTES THE SHRINKAGE STRAIN FOR GIVEN DRYING DURATION T.
C *****
C COMMON/CRPAR/JOYT,E28,EO,PHI1,EXPX,EXPX,ALFA,DRYSTA,AVHUM,FINSR,
1ESHINF,TAUSH,PHID,CP,CD,AKS,VS,C7,C1TO,EPKSH,AKHPP,AKHP,EXPX2,
2FKE,TAU10,TAU100,CON,CPK,E01,CO
C
C IF(1JOYT.EQ.2).DR.(1JOYT.GT.11)GO TO 10
C IF(1JOYT.LT.6 .AND. 1JOYT.EQ.10) WRITE(6,11) JOYT
11 FORMAT(10HJOYT=15,17H = WRONG.CORRECT)

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C
C CALCULATES DISCRETE VALUES EMU(MU,IA) FOR VARIOUS RELAXATION
C TIMES TAU(MU) AND AGES TP(IA).
C INPUT
C ER(IT,IA),T(IT),TT(IT),TP(IA),TPL(IA),NDEC,JDEC,NT,NA-ALL FROM
C SUBROUTINE RELAX(SEE DEFINITIONS THERE).
C W1,W2=CHOSEN WEIGHTS(SUITABLE VALUES W1=0.01,W2=0.08)
C NMU=NO. OF RELAX. TIMES TAU(MU).
C OUTPUT
C EMU(MU,IA)=MAXWELL CHAIN MODULI FOR TAU(MU) AT AGES TP(IA)
C TAU(MU)=RELAXATION TIMES OF MAXWELL CHAIN
C
C IFROM = BAZANT AND ASGHARI : CEMENT AND CONCRETE RESEARCH,
C VOL.4,NO.4,1974,PP.567-579)
C *****
C COMMON/MAXW/EMU(10,8),TPL(8),TP(8),NA
C DIMENSION ER(30,8),T(30),TT(30),TAU(10)
C DIMENSION NK(4),O(8),CE(4),AAA(10),MUEX(10),IXEX(10)
C DIMENSION A(8,8),WKARLA(8),B(8,1),NU(8),A4(4,4),B4(4,1)
C
C WRITE(6,777)W1,W2
C 777 FORMAT('324 WEIGHTS USED IN MAXWELL ARE W1 = ,F8.4,X,7HAND W2 = ,
C ,F8.4//')
C
C CMOOSE RELAXATION TIMES TAU
C
C NMU = NMU - 1
C IF (TAU(1) .EQ. 0.) TAU(1) = T(1)/O.3
C DO 10 MU=2,NMU
C 10 TAU(MU) = TAU(MU-1)*10.
C TAU(NMU) = 1.E30
C
C PRINT RELAXATION TIMES
C
C WRITE(6,401)(TAU(MU),MU=1,NMU)
C 401 FORMAT('260RELAXATION TIMES TAU(MU)=7E14.4//')
C
C COMPUTE COEFFICIENTS A AND B OF LEAST SQUARE METHOD
C
C DO 100 IA=1,NA
C
C DO 30 MU=1,NMU
C DO 30 MU=1,NMU
C SUM = 0.
C DO 20 IT=1,NT
C X=T(IT)/TAU(MU)+T(IT)/TAU(MU)
C IF(X.LE.50.) SUM=SUM+EXP(-X)
C 30 A(MU,MU) = SUM
C SUM = 0.
C DO 40 IT=1,NT
C X=T(IT)/TAU(MU)
C IF(X.LE.50.) SUM=SUM+EXP(-X)
C 40 B(MU,1) = SUM
C
C ENFORCE A SMOOTH SPLCTRM BY ADDING WEIGHTS W1,W2 ON 1-ST
C AND 2-ND DIFFERENCES OF EMU AS FUNCTION OF MU
C
C W22 = 2.*W2
C W24 = 4.*W2
C A(1,1) = A(1,1) + W1
C A(1,2) = A(1,2) - W1
C A(2,1) = A(2,1) - W1
C A(2,2) = A(2,2) + W1
C NMU1 = NMU
C NMU2 = NMU - 2
C NMU3 = NMU - 3
C
C DO 60 MU=1,NMU3
C A(MU,MU) = A(MU,MU) + W2
C MU = MU + 1
C A(MU,MU) = A(MU,MU) - W22
C MU = MU + 2
C 60 A(MU,MU) = A(MU,MU) + W2
C
C DO 70 MU=2,NMU2
C MU = MU - 1
C A(MU,MU) = A(MU,MU) - W22
C A(MU,MU) = A(MU,MU) + W1 + W24
C MU = MU + 1
C 70 A(MU,MU) = A(MU,MU) - W1 - W22
C
C DO 80 MU=3,NMU1
C MU = MU - 2
C A(MU,MU) = A(MU,MU) + W2
C MU = MU - 1
C A(MU,MU) = A(MU,MU) - W1 - W22
C 80 A(MU,MU) = A(MU,MU) + W1 + W2
C
C SOLVE THE EQUATIONS BY A LIBRARY SUBROUTINE LEQTF.
C CALL LEQTF(A,1,NMU,8,8,0,WKARLA,IERR)
C
C ARG. NO. 2 = NO. OF RHS
C ARG. NO. 3 = NO. OF EQS.
C ARG. NO. 4 = DIMENSION OF MATRIX A
C ARG. NO. 5 = RHS, ON OUTPUT THE SOLUTION
C ARG. NO. 6 = 0 FOR NO ACCURACY TEST
C ARG. NO. 7 = WORK AREA, DIMENSION .GE. NO. OF EQS.
C ARG. NO. 8 = IERR = 128 + N, N = 1 SINGULAR.
C
C DO 90 MU=1,NMU
C 90 EMU(MU,IA) = B(MU,1)
C
C 100 CONTINUE
C
C WRITE(6,1000) T(1),T(NT)
C DO 110 IA=1,NA
C 110 WRITE(6,1010) IA,TP(IA), (EMU(MU,IA), MU=1,NMU)
C
C AS A CHECK, COMPUTE CREEP FUNCTION VALUES FROM EMU
C CALL CRCURV(TT,TAU,NT,NMU)
C RETURN
C
C 1000 FORMAT('430MAXWELL CHAIN MODULI FOR TIME RANGE FROM E11.3,3H TO ,
C ,E11.3,324 UNITS PSI/KOH0IA TP(IA) EMU(1,IA) EMU(2,IA) ... )
C 1010 FORMAT('1X12,F10.3,(E11.3))
C END
C
C SUBROUTINE CRCURV(TT,TAU,NT,NMU)
C *****
C CRCURV COMPUTES DISCRETE VALUES BJ OF CREEP COMPLIANCE
C FUNCTION AJ FROM RELAXATION MODULI OF MAXWELL CHAIN.
C (FROM : BAZANT AND ASGHARI : CEMENT AND CONCRETE RESEARCH,
C VOL.4,NO.4,1974,PP.567-579)
C
C INPUT-T,TT,TP,NT,NA,TAU,NMU,NMU, FROM SUBROUTINES RELAX AND
C MAXWELL (SEE DEFINITIONS THERE)
C
C OUTPUT-VALUES BJ(IT,IA) OF CREEP FUNCTION CALCULATED FROM MAXWELL
C CHAIN, TO BE COMPARED WITH ORIGINALLY GIVEN VALUES DJ(IT,IA)
C *****
C
C 8350 COMMON/MAXW/EMU(10,8),TPL(8),TP(8),NA
C 8360 DIMENSION T(30),TAU(10),CE(4),AAA(10),MUEX(10),IXEX(10)
C 8370 DIMENSION ELAM(10),SMU(10),EX(10),BJ(30,8),DJ(30,8)
C 8380 IF(NT.GT.30)GO TO 902
C 8390 IF(NA.GT.8)GO TO 902
C 8400 IF(NMU.GT.10)GO TO 902
C 8410 GO TO 904
C 8420 WRITE(6,903)
C 8430 903 FORMAT('62HMESSAGE FROM CRCURV..NT OR NA OR NMU EXCEEDS DIMENSION.
C 1 STOP )
C 8440 STOP
C 8450 904 CONTINUE
C
C LOOP OVER CREEP CURVES FOR VARIOUS AGES TP(IA) AT LOADING
C
C DO 300 IA=1,NA
C
C NOW INITIALIZE VARIABLES.
C
C DEF = 0.
C DO 10 MU=1,NMU
C 10 SMU(MU) = 0.
C DT = T(1).
C
C LOOP OVER DISCRETE TIMES T(IT) FROM LOADING
C
C DO 200 IT=1,NT
C
C IF (IT .GT. 1) DT = T(IT) - T(IT-1)
C EPP = 0.
C SUM = 0.
C
C DO 100 MU=1,NMU
C
C X = DT/TAU(MU)
C IF(X.LT.50.0) GO TO 9031
C EX(MU)=0.0
C GO TO 9041
C 9031 EX(MU) = EXP(-X)
C 9041 BD = 1. - EX(MU)
C IF(X.LT.1.E-7) GO TO 9045
C BDA = BD/X
C GO TO 9046
C
C WHEN X TENDS TO ZERO, LIMIT(BDA) = 0./0.
C COMPUTE BDA FROM TAYLOR SERIES ABOUT X = 0.
C
C 9045 BDA=1.-(0.5-0.16666667*X)*X
C 9046 ELAM(MU) = BDA*EMUF(MU,TT(IT)+TP(IA))
C EPP = EPP + ELAM(MU)
C SUM = SUM + BD*SMU(MU)
C
C 100 CONTINUE
C
C IF (IT .EQ. 1) SUM = SUM + 1.
C
C HERE 1.=VALUE OF STRESS INCREMENT AT INSTANT OF LOADING (ALL LATER
C INCREMENTS = 0.). DE=STRAIN INCREMENT, DEF=STRAIN, SMU(MU)=STRESS
C IN SPRING NO. MU, BDA=LAMSDA, EPP=E-DOUBLE PRIME, DT=TIME STEP.
C
C DE = SUM/EPP
C DEF = DEF + DE
C BJ(IT,IA) = DEF
C DO 150 MU=1,NMU
C
C 150 SMU(MU) = SMU(MU)*EX(MU) + ELAM(MU)*DE
C 200 CONTINUE
C
C 300 CONTINUE
C
C WRITE(6,990)(TP(IA),IA=1,NA)
C 990 FORMAT('113H TP(IA)= 8E12.3/(13X,8E12.3))
C WRITE(6,1000)
C 1000 FORMAT('10H0CREEP FUNCTION VALUES COMPUTED FROM MAXWELL CHAIN MODUL
C IT EMU/424 IT T(IT) AJ(IT,1) AJ(IT,2) ...)
C DO 310 IT=1,NT
C 310 WRITE(6,1010) IT,T(IT), (BJ(IT,IA), IA=1,NA)
C 1010 FORMAT('1X12,F10.3,10E12.3/(13X10E12.3))
C WRITE(6,1020)
C 1020 FORMAT('10H0COMPARE CREEP FUNCTION VALUES AS ORIGINALLY GIVEN//)
C
C WRITE(6,993)
C 993 FORMAT('97H HERE T(IT)= CURRENT TIME MINUS T-PRIME=STRESS DURATION
C 1S, TP(IA) = T-PRIME = AGE AT LOADING /)
C
C DO 330 IT=1,NT
C DO 320 IA=1,NA
C 320 DJ(IT,IA) = CREEP(T(IT),TP(IA))
C 330 WRITE(6,1010) IT,T(IT), (DJ(IT,IA), IA=1,NA)
C
C CALCULATE DEVIATIONS FROM GIVEN CREEP FUNCTION AND STATISTICS.
C
C J=0
C X=0.0
C DO 410 IT=1,NT
C DO 410 IA=1,NA
C J=J+1
C 410 X=X+DJ(IT,IA)
C X=X/J
C WRITE(6,2010)
C 2010 FORMAT('47H0 DEVIATIONS DIVIDED BY MEAN OF GIVEN J VALUES//)
C SUM=0.0
C DO 430 IT=1,NT
C DO 420 IA=1,NA
C DEVIATIONS
C DE=BJ(IT,IA)-DJ(IT,IA)
C SUM=SUM+DE*DE
C 420 BJ(IT,IA)=DE/X
C 430 WRITE(6,2015) IT,T(IT), (BJ(IT,IA),IA=1,NA)
C 2015 FORMAT('1X,12,F10.3,10F12.3/(13X,10F12.3))
C DE=(SORT(SUM/J))/X
C WRITE(6,2020)DE
C 2020 FORMAT('15H0COEFF. OF VARIATION FOR THE DEVIATIONS FROM GIVEN ,
C 11HJ-VALUES IS ,F8.4//)
C 500 RETURN
C END
C
C FUNCTION EMUF(MU,TPA)
C *****
C EMUF RETURNS THE ELASTIC MODULUS EMU OF UNIT NO. MU IN THE MAXWELL
C CHAIN, CORRESPONDING TO AGE TPA.
C *****
C
C COMMON/MAXW/EMU(10,8),TPL(8),TP(8),NA
C
C TPLA = ALOG10(TPA)
C DO 20 I =2,NA
C IA=I
C A=TPL(IA)-TPLA
C IF(A)20,30,30
C 20 CONTINUE
C 30 JA=IA-1
C EMUF=(EMU(MU,JA)+A*EMU(MU,IA)*(TPLA-TPL(JA)))/(TPL(IA)-TPL(JA))
C
C RETURN
C END

```