A CEC Elastoplastic Benchmark Exercise with Complex Loading and Geometry

P. S. White
GEC Engineering Research Centre, Leicester, UK

INTRODUCTION

The calculations to be described formed the latest in a series of benchmark exercises conducted on behalf of the Commission of the European Communities through Activity Group 2 of the Working Group 'Codes and Standards' of the Fast Reactor Coordinating Committee. As in other exercises described in previous sessions of SMIRT (Corsi et al 1985, Corsi et al 1987, White et al 1987), comparisons for a cyclically loaded structural test were made among experimental measurements and various calculations. The latter were performed using different finite element programs and constitutive equations of frequent use within the nuclear industries of member countries. Acknowledgement is made to the Commission, to the contributors noted in Table 1 for original work and to NNC Ltd for providing computing facilities. This paper is published by permission of GEC plc.

The problems themselves were chosen to test computational tools and computational practices in situations involving typical aspects of design calculations or containing severe potential difficulties. Selection is difficult since realistic structural design looks to an endurance of some hundreds of major cycles in a life lasting a few decades whereas tests usually involve significant deformations or failure in much shorter histories of loading. Test conditions are usually much more severe than the design conditions in which computational methods (especially the constitutive equations) are intended to operate. Furthermore, with rare exceptions (White et al 1987), displacements (or strains) are the only measurable quantities for which direct comparisons are possible and measurements are not always available at the most interesting positions of test structures. Benchmarks of the series have therefore needed careful planning and in each case have examined only particular aspects of the analysis process.

THE SELECTED PROBLEM AND CONDITIONS FOR PRODUCING SOLUTIONS

Previous benchmarks had usually required only small meshes with fairly obvious modelling details. It was therefore desirable to seek a larger problem to test the computational efficiency of different programs and to allow examination of various modelling decisions. It was decided to choose a test performed in the United States, one of a large programme described in outline by Corum (1979). This test was of a circular plate made of Type 316 stainless steel, simply supported between two ball-races and cyclically loaded by a transverse central force. Test details and material properties were assembled from a number of documents (Corum et al 1977a, Corum et al 1977b, Hill et al 1977) and Fig. 1 shows a section of the geometrical configuration wherein, however, a number of detailed dimensions are not available and some variable areas of contact are possible. Fig. 2 shows the simulated part of the history of the applied loading which includes both cyclic variations and dwell times, at the temperature of 593°C at which creep is active. Assuming a perfectly plastic yield stress of around 100 MPa, the repeated maximum and minimum loads were a little below the classical limit load for this shape of structure but the isolated peak load was somewhat above. Even with material hardening, some quite large strains could be expected especially in the fillet region, and yielding almost through entire sections might occur. Moreover, owing to the high bending flexibility of a plate, this extensive plasticity could well also be associated with effects of large displacements.

Plans for producing accurate numerical simulations would have needed to include the following considerations (among others). (a) Assessment of the effect of unknown geometrical details and the possibility of losses of contact. (b) Suitable meshing to allow for severe stress-concentrations and a potentially very thin core of relatively stiff elastically behaving material. (c) Large spatial variation of strain range and so (for several types of constitutive equation) a need for zonal attribution of material properties. (d) The possibility of effects of large displacement.

The contributors to the work were all well-experienced in nonlinear analysis and all, given a free hand, would no doubt have produced similar solutions in adequate agreement with experimental results. However it was part of the exercise for most contributors to produce solutions which included some normal practices for problems of moderate severity. Thus it was hoped to demonstrate the consequences of failing to take special precautions for considerations (a)-(d)

The immediately available experimental results only comprised the complete history of the central displacement of the plate. However to facilitate intercomparison of solutions a list of required results was specified, including histories of stress and strain components at various positions and distributions of stresses and strains through certain sections at specified instants. Certain test data for plasticity and creep properties were available and contributors were required to fit their constitutive equations to these data using additional data for other batches of the same type of steel if necessary and following standard practices where these existed.

METHODS EMPLOYED AND GEOMETRICAL MODELLING

Table 1 shows the contributors, the analysis types used (small or large displacement) and the finite element programs employed (analysis 3 also used preliminary investigations and checks using MARC). Space only allows the following notes of the constitutive equations used (White 1989). All analyses used separate measures of (time-independent) plastic strains and (time-dependent) creep strains. Plasticity was described in analysis 1 by the well known ORNL model (10th cycle hardening but without alpha-reset). The other analyses used variations upon a model due to Chaboche (Lemaitre and Chaboche, 1985,ch5). Creep was described by strain-hardening, except for analysis 3 which used time-hardening, while analysis 1 also employed the ORNL auxiliary rules for stress-reversals. All analyses included a creep-plasticity interaction in which creep strains were added to plastic strains in hardening effects. Plasticity data were provided as monotonic tensile curves and some cyclic test data. Data fitting for analysis 2 used only the monotonic data and produced a single set of parameters. The other contributors also used cyclic data (including items from other sources) and produced sets of parameters corresponding to various different strain ranges. Different detailed forms of creep equation were employed among the analyses but all used the same set of test data and agreed fairly closely for reconstructed creep curves (except at very high stresses). All analyses treated load changes as instantaneous with creep allowed to be active only during the dwell periods. Procedures for choosing sizes of load/time

increments varied, as did the solution tolerances employed.
Most contributors performed preliminary elastic and cyclic elastic-plastic analyses to determine sensitivity to geometrical details and other aspects of the problem. All concluded that a number of different approaches gave similar results for the overall deformation and for details in the fillet (though differing in other regions). These approaches involved; (1) omission or inclusion as completely solid, of the threaded bar and surrounding gap (see Fig. 1); (2) termination of the model at the raised faces of the plate itself with these faces constrained to remain flat or inclusion of additional material representing part of the loading rod and the nut assembly. The loading was applied either as a point load or as a uniform pressure according to the choice in (2) above. Figure 3 shows the meshes (in the central region) used in analyses 1 to 4. Analyses 1 and 4 represented half the plate with suitable conditions of antisymmetry. Analysis 5 used a doubled form of the mesh of analysis 4. Use of half-models was permissible for small displacement analysis (not exactly so with regard to the loading which was applied only on one side, but preliminary analyses showed the error to be small). However a full model was obligatory with large displacements. Axisymmetric elements were used, all or nearly all being 8 noded quadrilaterals. Preliminary analyses had shown large variations of strain range over the structure and (except for analysis 2) iterative cyclic calculations were used to assign zonal plasticity parameters consistent with strain ranges. The chosen zones are shown in Fig. 4.

PERFORMANCE OF SOLUTIONS AND RESULTS

All solutions were successfully performed (solution 5 being terminated owing to cost constraints) but not always without difficulty. The large displacement solutions were in some ways easier since there is a stress-stiffening effect. That is, the large displacement assumption produces smaller values of displacements, reduces the tendency for through-section yield and gives easier convergence. This was particularly so for the peak load and the subsequent creep period. Table 1 also indicates the effort of peforming solutions including a relative measure (ratio of total CPU time to CPU time for one elastic solution). However the comparisons are strongly influenced by meshing details and choices of step sizes.

Comparisons for the measured central displacement are shown in Fig. 5a, with details of the rapid cycling phase omitted for clarity. The principal differences occur at the peak load and in the subsequent creep period. Both large displacement analyses agreed relatively well with experiment for the accumulated displacement. However all small displacement solutions substantially overestimated the displacement both in the second loading step and during creep. All solutions settled to nearly steady changes in the second half of the history. The displacement ranges during load changes then all agreed quite well but there were some significant differences for changes during creep periods and all small displacement solutions maintained significant 'zero-errors' for the cycles. For local values of stresses and strains there were both close agreements and striking differences. Fig. 5b shows the equivalent stress histories calculated at the stress concentration at the base of the fillet. The considerable differences appear to be more closely related to the descriptions of plasticity than to the use of small or large displacements. Fig. 5c shows the distributions of equivalent stress through the section at the fillet base at the end of the calculation. Despite the visible skewing of the large displacement distribution the general measure of agreement is quite high. Illustrations of strain comparisons are complicated by strains accumulated in the phase of peak loading as shown in Fig 5d.

CONCLUSIONS

Space forbids full details of results (White, 1989) but some important conclusions were as follows. (1) Neglect of large displacement effects in isolated overloads produces large permanent errors in solutions but need not be serious with regard to subsequent cyclic variations. (2) Local strain concentrations can be sensitive to plasticity descriptions especially with regard to zoning of properties based on strain-range, but the effort of zoning is excessive for normal analysis practice. (3) Strain ranges need not be sensitive to fine details of plasticity descriptions or to creep descriptions. (4) Analysis practices designed for problems of moderate severity can be very untrustworthy in severe cases and calibration against severe tests should be treated with caution.

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Analysis	Contributors	Program	Analysis Type
1	GEC (UK) White PS & Jakeman RR	ABAQUS	S.D.
2	CEA (France) Combescure A & Gisquet Ph	INCA	S.D.
3	Pisa Univ. (Italy) Vitale E & Marmorini L	INCA	L.D.
4	Milan Poly. (Italy) Maier G & Chillé F	INCA	S.D.
5	Milan Poly. (Italy) Maier G & Chillé F	INCA	L.D. (partial)
6	Experimental Results		

	Computer	No. of Elements	Total CPU(s)	Elastic CPU(s)	Relative Effort
1	VAX 8600	214	53409	63	848
2	Cray XMP	198	<12500	-	-
3	IBM 3081/KX	372	5466	10.11	541
4	-	129	4990	0.54	9240

TABLE 1 CONTRIBUTORS AND COMPUTING DETAILS

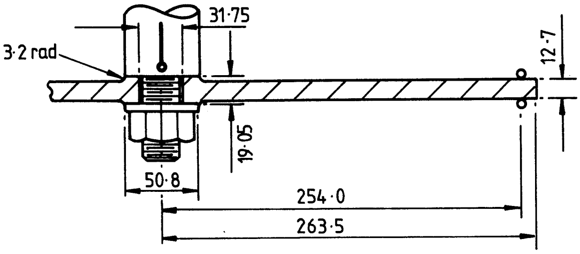


FIG. 1
Geometry of specimens

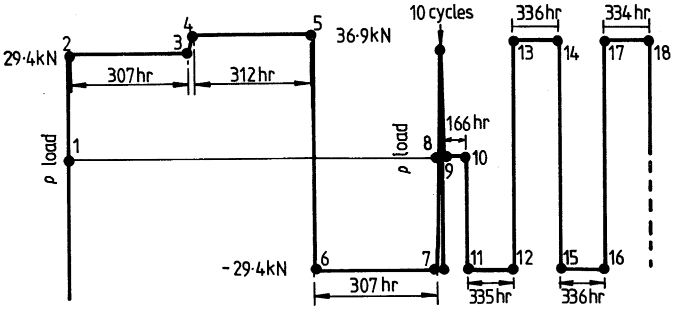
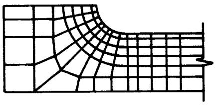
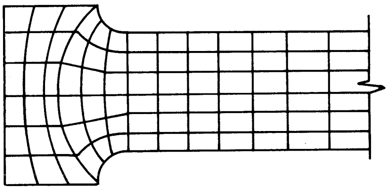


FIG. 2
Loading history for simulation (schematic)



Analysis 1



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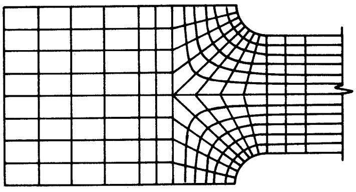
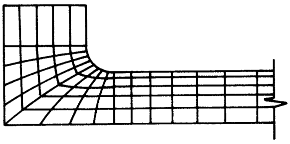
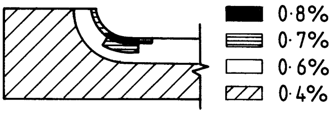


Analysis 3

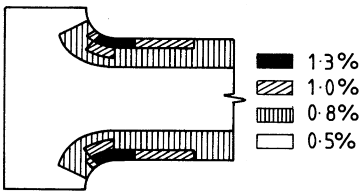


Analysis 4

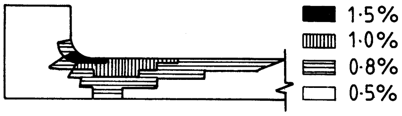
FIG. 3 Meshes



Analysis 1



Analysis 3



Analysis 4

FIG. 4
Strain ranges for zonal properties

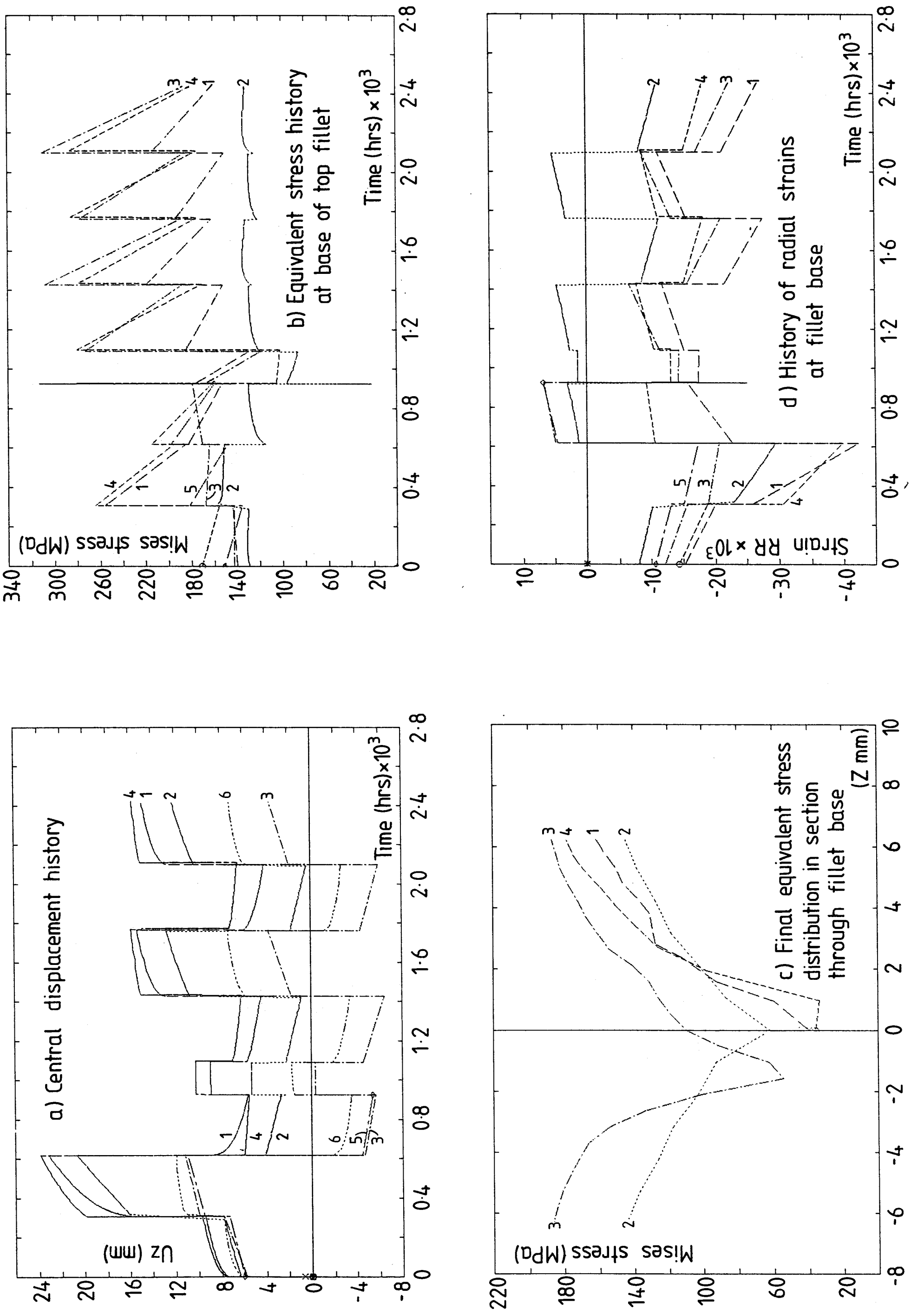


FIG. 5 Examples of results