The spread of behaviour from widespread continuum damage failure to highly localised creep crack growth, triggered by variation of material ductility in superalloys, can be predicted by the same technique.

The same method has been used to predict the results of creep crack growth behaviour in a welded pressurised pipework branch connection; and, the CDM predictions have been shown to agree with the results of well-established C^* prediction methods based on non-linear fracture mechanics.

A simple CDM method of analysis has been used in all cases. The only difference being the material, applied stress levels and stress states, and consequently the physically based constitutive equations selected.

It is advocated that with the increasing speed, and data storage capacity of computer workstations such calculations will soon be trivial provided: (a) Accurate materials test data is available. (b) Techniques are available to select the relevant physical models for creep deformation and damage, and to fit the models to the data.

When such facilities are available, design by analysis will have much appeal over design by code. In this way, many aspects of the three barriers to progress, given in the introduction, will be removed; hence much of the present conservatisms may be confidently removed.

7. REFERENCES

1. British Standards Institution, Specification for Design and Construction of Ferrous Piping Installations for and in Connection with Land Boilers, BS 806, 1993.
2. British Standards Institution, Specification for Design and Manufacture of Water-tube Steam Generating Plant (including superheaters, reheaters and steel tube economisers), BS 1113, 1989.
3. British Standards Institution, Specification for Unfired Fusion Welded Pressure Vessels, BS 5500, 1991.
4. ASME, III NH (1999) Boiler Pressure Vessel Code, Code Case: Nuclear Components, Case N-47-29, class 1, components in elevated temperature service, Section II, Division 1, ~~1990.~~
5. Nuclear Electric, R5 Assessment Procedure for The High Temperature Response of Structures, Rept. R5, Nuclear Electric Ltd, UK.~~, 1990~~. Issue 2 Revision 2 (1998)
6. J. R. Rice, Mathematical Analysis in the Mechanics of Fracture, in H. Liebowitz (ed), *An Advanticed Treatise*, II, Academic Press, 1968.
7. D. R. Hayhurst, C. J. Morrison and P. R. Brown, Creep Crack Growth, *Proc. Of the 3rd IUTAM Symposium, Creep in Structures*, Leicester, UK, 1980, pp. 564-574, Springer-Verlag, Berlin, Heidelberg, New York, 1981.
8. D. R. Hayhurst, Creep Rupture Under Multi-Axial States of Stress, *J. Mech. Phys. Solids*, vol. 20, pp. 381-390, 1972.
9. D. R. Hayhurst, Engineering Approaches to High-Temperature Design, chap. 3, Pineridge Press, Swansea, 1983.
10. A. C. F. Cocks and M. F. Ashby, On Creep Fracture by Void Growth, *Progress in Materials Science*, vol. 27, pp. 189-244, 1982.
11. M. F. Ashby, A First Report on Deformation-Mechanisms Maps, *Acta Metall.*, vol. 20, pp. 887-892, 1972.
12. A. M. Othman, D. R. Hayhurst and B. F. Dyson, Skeletal Point Stresses in Circumferentially Notched Tensions Bars Undergoing Tertiary Creep Modelled with Physically-Based Constitutive Equations, *Proc. R. Soc. Lond.* A, vol. 441, pp. 343-358, 1993.
13. D. R. Hayhurst, Materials Data Bases and Mechanisms-Based Constitutive Equations for Use in Design, in A. Altenbach and J. J. Skrzypek (eds.), *Creep Damage in Materials and Structures*, pp.167-205, Springer-Wein, New York, 1999.
14. D. R. Hayhurst, Materials Data Requirements for Computer Simulation in Design and Manufacturing, Computer-Aided-Design and New Materials, in J. P. Caliste, A. Truyol and J. Westbrook (eds.), *Thermodynamic Modelling and Materials Data Engineering*, chap. 4, pp. 189-224, Springer, Berlin, Heilderberg, 1998.
15. D. R. Hayhurst, Stress Redistribution and Rupture Due to Creep in a Uniformly Stretched Thin Plate Containing a Circular Hole, *J. Appl. Mech*, vol. 40, pp. 244-256, 1973.
16. D. R. Hayhurst, P. R. Dimmer and M. W. Chernuka, Estimates of the Creep Rupture Lifetime of Structures Using the Finite Element Method, *J. Mech. Phys. Solids*, vol. 23, pp. 335-355, 1975.
17. D. R. Hayhurst and B Storakers, Creep Rupture of the Andrade Shear Disc, *Proc. R. Soc. Lond. A*, vol. 349, pp. 369-382, 1976.
18. D. R. Hayhurst, P. R. Dimmer and C. J. Morrison, Development of Continuum Damage in the Creep Rupture of Notch Bars, *Phil. Trans. Roy. Soc. Lond. A.*, vol. 316, pp. 103-129, 1984.
19. D. R. Hayhurst, Creep Continuum Damage Mechanics: A Unifying Theme in High-Temperature Design, in L. H. Larson (ed.), *High-Temperature Structural Design, ESIS 12*, Mechanical Engineering Publications, London, pp. 317-334, 1992.
20. M. F. Ashby and C. A. Abel, Material Selection to Resist Creep, *Phil. Trans. R. Soc. Lond. A*, vol. 351, pp. 451-466, 1995.
21. Z. L. Kowalewski, D. R, Hayhurst and B. F. Dyson, Mechanisms-based Creep Constitituve Equations for an Aluminium Alloy, *J. Strain Anal.*, vol. 29, pp. 309-316, 1994.
22. D. R. Hayhurst, C. J. Morrison and F. A. Leckie, The Effects of Stress Concentrations on the Creep-Rupture of Tension Panels, *J. Appl. Mech.*, vol. 42, pp. 613-618, 1975.

23. I. W. Goodall and R. A. Ainsworth, Failure of Structure by Creep, *Proc. 3rd Int. Conf. Press. Vess. Tech.*, Tokyo, vol. II, ASME, pp. 871-882, 1977.
24. P. W. Bridgman, *Large Plastic Flow and Fracture*, McGraw Hill, New York, 1952.
25. D. R. Hayhurst, P. R. Brown and C. J. Morrison, The Role of Continuum Damage in Creep Crack Growth, *Phil. Trans. R. Soc. A*, vol. 311, pp. 131-158, 1984.
26. F. R. Hall, D. R. Hayhurst and P. R. Brown, Prediction of Plane-Strain Creep-Crack Growth Using Continuum Damage Mechanics, *Int. J. Damage Mech.*, vol. 15, pp. 353-383, 1996.
27. D. R. Hayhurst, B. F. Dyson and J. Lin, Breakdown of the Skeletal Stress Technique for Lifetime Prediction of Notched Tensions Bars due to Creep Crack Growth, *Engineering Fracture Mechanics*, vol. 49, pp. 711-726, 1994.
28. D. R. Hayhurst and D. A. Miller, The Use of Creep Continuum Damage Mechanics to Predict Damage Evolution and Failure in Welded Vessels, *IMechE* S539/008, pp. 117-133, 1998.
29. F. R. Hall and D. R. Hayhurst, Continuum Damage Modelling of High-Temperature Deformation and Failure in a Pipe Weld, *Proc. Roy. Soc. Lond. A*, vol. 433, pp. 383-403, 1991.
30. M. C. Coleman, J. D. Parker, D. J. Walters and J A Williams, The Deformation of Behaviour of Thick Walled Pipes at Elevated Temperatures, *Proc. Of the Int. Conf. on Materials (ICM 3,)* vol. 2, pp. 193-202, Pergamon Press, Oxford, 1979.
31. B. J. Cane, Collaborate Programme on the Correction of Test Data for High-Temperature Design of Welded Steam Pipes: Presentation and Analysis of Materials Data, CEGB Laboratory Note No. RD/L/21: 01N81, 1981.
32. Z. P. Wang and D. R. Hayhurst, The Use of Supercomputer Modelling of High-Temperature Failure in Pipe Weldments to Optimise Weld and Heat Affected Zone Materials Property Selection, *Proc. R. Soc. Lond. A.*, vol. 446, pp. 121-148, 1994.
33. D. R. Hayhurst and I. J. Perrin, CDM Analysis of Creep Rupture in Weldments, *Proc. ASCE, Engineering Mechanics Conference*, vol. 1, pp. 393-396, 1995.
34. I. J. Perrin and D. R. Hayhurst, Creep Constitutive Equations for a 0.5Cr 0.5Mo 0.25V Ferritic Steel in The Temperature Range 600-675°C, *J. Strain Anal.*, vol. 31, pp. 299-314, 1996.
35. I. J. Perrin and D. R. Hayhurst, A Method for the Transformation of Creep Constitutive Equations, *Int. J. Press. Ves. & Piping*, vol. 68, pp. 299-309, 1996.
36. I. J. Perrin and D. R. Hayhurst, Continuum Damage Mechanics Analyses of Type IV Creep Failure in Ferritic Steel Crossweld Specimens, *Int. J. Press. Ves. & Piping*, vol. 76, pp. 599-617, 1999.
37. I. J. Perrin, D. R. Hayhurst and R. A. Ainsworth, Approximate Creep Rupture Lifetimes for Butt and Welded Ferritic Steel Pressurised Pipes, *European Journal of Mechanics*, A/Solids, vol. 19, pp. 223-258, 2000.
38. F. Vakili-Tahami, Prediction of Creep Damage Evolution in Pressurised Welded Ferritic Steel Pipework Made Using DAMAGE XX, DMM Research Report, Dept. of Mech. Eng., UMIST, UK., 2000.
39. B. F.Dyson and T. B. Gibbons, Tertiary Creep in Nickel-Based Superalloys: Analysis of Experimental Data and Theoretical Synergies, *Acta Metall.*, vol. 35, pp. 2355-2369, 2000.
40. Y.R Qian, Determination of Creep Crack Growth in Main Steam and Hot Reheat Drain Pot Welds, Heysham 1 by Axi-symmetric Finite Element Analysis, TD/SIB/REP/0163/91, British Energy, UK., 1991.

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9. NOMENCLATOR

A	Material constant (1/h)
B	Material constant (1/MPa)
C	Material constant, dimensionless
C^*	Steady state creep characterising parameter (MPa m/h)
D	Ductility factor (=1/3 ε_f), dimensionless
G	Material constant (mm/h)
H	Primary creep state variable, dimensionless
H^*	Material constant, dimensionless
h	Material constant (MPa)
K	Material constant (1/MPa h^{m+1})
k_c	Material constant (1/h)
M	Material constant, (1/MPa$^{\chi}$ h^{m+1})
m	Material constant, dimension less
n	Stress exponent in creep law, dimensionless
p	Internal pressure (MPa)
q	Material constant, dimensionless
s_{ij}	Deviatoric stress, $s_{ij}=\sigma_{ij}-\delta_{ij}\, s_{kk}/3$ (MPa)
t	Time (h)