DESIGN AND ANALYSIS OF ASME BOILER AND PRESSURE VESSEL COMPONENTS IN THE CREEP RANGE

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To our wives

Dixie and Betty

PREFACE

Many structures in chemical plants, refineries, and power generation plants operate at elevated temperatures where creep and rupture are a design consideration. At such elevated temperatures, the material tends to undergo gradual strain with time, which could eventually lead to failure. Thus, the design of such components must take into consideration the creep and rupture of the material. In this book, a brief introduction to the general principles of design at elevated temperatures is given with extensive references cited for further in-depth understanding of the subject. A key feature of the book is the use of numerous examples to illustrate the practical application of the design and analysis methods presented.

The book is divided into seven chapters. The first chapter is an introduction to various creep topics such as allowable stresses, creep properties, elastic analog, and reference stress methods, as well as a few introductory topics needed in various subsequent chapters.

Chapters 2 and 3 cover structural members in the creep range. In Chapter 2, the subject of members in axial tension is presented. Such members are encountered in pressure vessels as hangers, tray supports, braces, and other miscellaneous components. Chapter 3 covers beams and plates in bending. Components such as piping loops, tray support beams, internal piping, nozzle covers, and flat heads are included. A brief discussion of the requirements of ANSI B31.1 and B31.3 in the creep region is given.

Chapters 4 and 5 discuss stress analysis of shells in the creep range. In Chapter 4, various stress categories are defined and the analysis of various components using "load controlled limits" of ASME section III-NH is discussed. Comparisons are also given between the design criteria in VIII-2 and III-NH and the limitations encountered in VIII-2 when designing in the creep range. Chapter 5 covers the analysis of pressure components using "strain and deformation controlled limits." Discussion includes the requirements and limitations of the "A Tests" and "B Tests" outlined in III-NH.

Cyclic loading in the creep-fatigue regime is discussed in Chapter 6. Both repetitive and non-repetitive cycles are presented with some examples illustrating the applicability and intent of III-NH in non-nuclear applications.

Chapter 7 covers the issues related to buckling of components. Axial members as well as cylindrical and spherical shells are discussed. Simplified methods are presented for design purposes. The assumptions and limitations required to derive the simplified methods are also given.

The two appendices included in the book are intended as design tools. Appendix A discusses the derivation of the Bree diagram, used in Chapter 5, and the assumptions made in plotting it. Understanding the derivations will assist the designer in visualizing the applicability of the various regions in the Bree diagram to various design situations. Appendix B lists some conversion factors for English and metric units.

The design approaches illustrated in this book are based on the experience of the authors over the past 40 years, with assistance from colleagues. It is the intent of the authors that the methodology shown in the book will help the engineer accomplish a safe and economical design for boiler and pressure vessel components operating at high temperatures where creep is a consideration.

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NOTATIONS

Some of the symbols used in this book are defined below

A	=	area of structural member
A	=	ASME designation for compressive strain in heads and shells
B	=	ASME designation for compressive stress in heads and shells
c	=	corrosion allowance
C	=	flat head bending factor in ASME, VIII-1
d	=	diameter
D	=	$Et^3/12(1-\mu^2)$
$\mathcal{D}$	=	force-deflection matrix of a member
$\underline{D}_{cf}$	=	factor to account for the interaction of creep and fatigue damage
D_i	=	inside diameter
D_o	=	outside diameter
E	=	modulus of elasticity
E_H	=	modulus of elasticity at hot end of cycle
E_L	=	modulus of elasticity at cold end of cycle
E_o	=	joint efficiency factor in ASME, VIII-1, and ligament efficiency in ASME-I
E_t	=	tangent modulus
f	=	triaxiality factor
f	=	stress reduction factor in pipes
f'	=	thickness factor for expanded tube ends in ASME, Section I
F	=	force in axial members and beams
F	=	equivalent peak stress in plates and shells
F'	=	peak stress in plates and shells
G	=	multiaxiality factor
I	=	moment of inertia
k	=	P/EI
k'	=	constant
$\mathcal{K}$	=	stiffness matrix of an element
K	=	plastic shape factor
K_t	=	creep shape factor. Approximate value adopted by the ASME for a rectangular cross section = $(1 + K)/2$
K_{sc}	=	stress concentration factor
K'	=	constant
K'_v	=	plastic Poisson ratio adjustment factor
ℓ	=	effective length of column
L	=	length of member
n	=	creep exponent, which is a function of material property and temperature
n_c	=	number of applied cycles
N_d	=	number of allowable cycles
P	=	pressure
P_a	=	ASME allowable external pressure for heads and shells
P_b	=	equivalent primary bending stress
P'_b	=	primary bending stress

P_L = equivalent local primary membrane stress
P'_L = local primary membrane stress
P_m = equivalent general primary membrane stress
P'_m = general primary membrane stress
Q = equivalent secondary stress
Q' = secondary stress
r = radius of gyration = $(I/A)^{0.5}$
R_i = inside radius
R_m = mean radius of shell
R_o = outside radius
R_w = weldment reduction factor based on type of weld rod
S = allowable stress for I, VIII-1, and VIII-2 construction
S_a = alternating cycle stress
$\bar{S}_m$ = $(1.5S_m + 0.5S_t)/3$
S_m = allowable stress in III-NH
S_{mt} = membrane stress. It is the lower value of S_m and S_t obtained from III-NH
S_j = the initial stress level for cycle type j
S_o = Design stress values. The values are taken as equal to S_m except for a few cases at lower temperatures, where values of S_{mt} at 300,000 hours exceed the S_m values. In those limited cases, S_o is equal to S_{mt} at 300,000 hours
S_r = stress to rupture strength given in Table I-14.6 of III-NH
S'_r = relaxed stress level at time T adjusted for the multiaxial stress state
$\bar{S}_r$ = relaxed stress level at time T based on a uniaxial relaxation model
S_t = time-dependent stress intensity values obtained from III-NH
S_y = yield stress
S_{yH} = yield stress at the high temperature end of a cycle
S_{yL} = yield stress at the low temperature end of a cycle
t = thickness
T = time
$\mathcal{T}$ = temperature
X = primary stress/S_y
y = temperature coefficient in ASME, Section I
Y = secondary stress/S_y
$\mathcal{Z}$ = section modulus
Z = dimensionless effective creep parameter. It represents core stress values
α = coefficient of thermal expansion
ε_c = creep strain
β = $[3(1-\mu^2)/R_m{}^2t^2]^{0.25}$
γ = R_o/R_i
γ_1 = R_i/R_o
$\Delta\varepsilon_{max}$ = maximum equivalent strain range
$\Delta\varepsilon_{mod}$ = modified maximum equivalent strain range that accounts for the effects of local plasticity and creep
ε_t = total strain range
μ = Poisson's ratio
σ_c = elastic core stress at a cross section
σ_{cH} = elastic core stress at the high temperature end of a cycle

σ_{cL}	=	elastic core stress at the low temperature end of a cycle
σ_L	=	longitudinal stress
σ_r	=	radial stress
σ_R	=	reference stress
σ_y	=	yield stress
σ_θ	=	circumferential (hoop) stress
$\sigma_1, \sigma_2, \sigma_3$	=	principal stresses

Abbreviations for Organizations

AISC	American Institute of Steel Construction
ANSI	American National Standards Institute
API	American Petroleum Institute
ASM	American Society of Metals
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BS	British Standard
EN	European Standard
MPC	Materials Properties Council
UBC	Uniform Building Code
WRC	Welding Research Council

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