
Contents

Preface ix

Conversion Factors xi

Chapter 1. Introduction 1

- 1.1 Introduction 1
- 1.2 Earlier Work on Curved Girders 2
- 1.3 Organization of the Text 4
- REFERENCES 6

Chapter 2. Basic Theory of Thin-Walled Beams 9

- 2.1 Introduction 9
- 2.2 Flexure 10
- 2.2.1 Flexural Normal Stress 10
- 2.2.2 Flexural Shearing Stress 12
- 2.2.3 Shear Lag Phenomenon and Effective Width 21
- 2.3 Torsion 61
- 2.3.1 Pure Torsion 61
- 2.3.2 Torsional Warping 79
- 2.4 Distortion 111
- 2.4.1 Phenomenon of Distortion 111
- 2.4.2 Derivation of the Fundamental Equation for Distortion 113
- 2.4.3 Beam-on-Elastic-Foundation Analogy 122
- 2.4.4 Parametric Analysis of Distortion 128
- 2.4.5 Design Formula for Distortion 133
- 2.5 Stress in Thin-Walled Beam 136
- 2.5.1 Cross-Sectional Quantities 136
- 2.5.2 Stress Formula 139
- 2.5.3 Design Criteria for Stress Combinations 140
- REFERENCES 141

Chapter 3. Fundamental Theory of Curved Girders for Analyzing Static and Dynamic Behavior 143

- 3.1 Introduction 143
- 3.2 Fundamental Theory of Curved Beams under Static Forces 145
- 3.2.1 Theory of Curved Beams Based on Flexure and Pure Torsion 145
- 3.2.2 Theory of Thin-Walled Curved Beam Based on Torsional Warping 149

3.2.3	Cross-Sectional Quantities and Stress Formulas for Flexure and Torsion	153
3.2.4	Shear Lag in Curved Girders	168
3.2.5	Distortion in Curved Box Girders	180
3.2.6	Theory of Sector Plates	194
3.3	Static Behaviors of Curved Girders	198
3.3.1	Torsional Warping Stress	198
3.3.2	Distortional Warping Stress	208
3.3.3	Deflection of Curved Girder Bridges	219
3.4	Fundamental Theory of Curved Girders under Dynamic Forces	224
3.4.1	Fundamental Equation for Forced Vibration	224
3.4.2	Approximate Method Using Modal Analysis	230
3.4.3	Analysis of Various Dynamic Forces	241
3.4.4	Response due to Moving Vehicles	250
3.5	Dynamic Behavior of Curved Girders	266
3.5.1	Natural Frequencies and Damping Coefficients of Curved Girder Bridges	266
3.5.2	Dynamic Response due to a Single Vehicle	270
3.5.3	Dynamic Amplification Factor (DAF) due to Traffic Vehicles	280
REFERENCES		290

Chapter 4. Analysis of Flexural and Torsional Stress Resultants and Displacements in Curved Girders 293

4.1	Introduction	293
4.2	Force Method (Pure Torsional Theory)	294
4.2.1	Statically Determinate System	294
4.2.2	Stress Resultants in a Statically Determinate System	295
4.2.3	Stress Resultants due to the Statically Indeterminate Torque	296
4.2.4	Stress Resultants and the Compatibility Condition for the Torsional Angle in a Curved Girder	297
4.2.5	Influence Lines of Stress Resultants for a Single-Span Curved Girder	298
4.2.6	Application of Analysis to Continuous Curved Girder	299
4.3	Analytical Method Based on Differential Equations (Torsional Warping Theory)	301
4.3.1	Loading Conditions	302
4.3.2	Solutions of Stress Resultants and Displacements for Single-Span Curved Girders	302
4.3.3	Application to Continuous Curved Girders	307
4.4	Transfer Matrix Method	309
4.4.1	Pure Torsional Theory	310
4.4.2	Torsional Warping Theory	329
REFERENCES		355

Chapter 5. Buckling Stability and Strength of Curved Girders 357

5.1	Introduction	357
5.2	Lateral Buckling of Multiple Curved I Girders	359
5.2.1	Lateral Buckling of I Girders	359
5.2.2	Experiments on Lateral Buckling of Multiple Curved I Girders	363
5.2.3	Analysis of Lateral Buckling for Curved I Girders	371
5.2.4	Lateral Buckling Strength of Curved I Girders	376
5.2.5	Application to Design of Multiple Curved I-Girder Bridges	378

5.2.6 Design of Floor Beams, and Sway and Lateral Bracings for Multiple Curved I-Girder Bridges	381
5.3 Buckling Stability and Strength of Web Plate in Curved Girders	381
5.3.1 Ultimate and Buckling Strength of Plate Girders	381
5.3.2 Buckling and Ultimate Strength of a Curved Girder	393
5.4 Design of Web Plates in Curved Girders	414
5.4.1 Web Slenderness of Plate Girders	414
5.4.2 Parametric Analysis of Stress and Displacement in Curved Web Panels	416
5.4.3 Required Web Slenderness of Curved Girders	431
5.4.4 Design Recommendation	432
5.5 Design of Longitudinal Stiffeners in Curved Girders	434
5.5.1 Design Method of Longitudinal Stiffeners in Straight Girders	434
5.5.2 Ultimate Strength of Longitudinal Stiffeners in Curved Girders	438
5.5.3 Proposition for Designing Longitudinal Stiffeners in Curved Girders	442
5.6 Design of Transverse Stiffeners in Curved Girders	444
5.6.1 Design Method of Transverse Stiffeners in Straight Girders	444
5.6.2 Ultimate Strength of Transverse Stiffeners in Curved Girders	448
5.6.3 Proposal for Designing Transverse Stiffeners in Curved Girders	459
5.7 Design of Flange Plates in Curved Girders	462
5.7.1 Slenderness of Flange Plates according to Buckling Theory	462
5.7.2 Ultimate Strength Analysis of Flange Plates in I Girders with Stress Gradients	471
5.7.3 Design Proposal for the Flange Plates of Curved Girders	474
REFERENCES	475

Chapter 6. Design Codes and Specifications 479

6.1 Introduction	479
6.2 Working Stress Design Method of Curved Steel Bridges	480
6.2.1 General Considerations in Determining the Radius of Curvature of Curved Girder Bridges	480
6.2.2 Selection of Structural Type for Curved Girder Bridges	482
6.2.3 Loads	488
6.2.4 Steel Material	500
6.2.5 Structural Analysis of Curved Girder Bridges	501
6.2.6 Check for Stress and Deflection	523
6.2.7 Design of Main Girders	528
6.2.8 Design of Structural Details	539
REFERENCES	549

Chapter 7. Fabrication, Details, Painting, and Erection of Curved Bridges 551

7.1 Introduction	551
7.2 Initial Imperfections in Curved Girder Bridges	553
7.2.1 Fabrication Tolerances	553
7.2.2 Initial Deflections	554
7.2.3 Residual Stresses	555
7.3 Fabrication of Main Girders	558
7.3.1 Flange Plates	558
7.3.2 Web Plates	560
7.3.3 Fillet Weld Joint of Flange and Web Plates	562

7.3.4	Welding of Longitudinal and Transverse Stiffeners	563
7.3.5	Field Bolted Joint of Main Girders	564
7.4	Fabrication of Floor Beam, Sway and Lateral Bracing	570
7.4.1	Connection of Floor Beam with Main Girders	570
7.4.2	Connection of Sway and Lateral Bracings with Main Girders	573
7.5	Fabrication of Diaphragms	575
7.5.1	Intermediate Diaphragm	575
7.5.2	Bearing Support Diaphragm	576
7.6	Fabrication of Bearing Shoes	577
7.6.1	Functions of Bearing Shoes	577
7.6.2	Types of Bearing Shoes	578
7.6.3	Earthquake Design Precautions	585
7.7	Painting	586
7.8	Erection	586
REFERENCES		590

Chapter 8. Design Examples 593

8.1	Introduction	593
8.2	Example of Multiple Curved I-Girder Bridge	595
8.3	Example of Curved Monobox-Girder Bridge	598
8.4	Example of Curved Twin-Box-Girder Bridge	601
REFERENCES		604

Appendix A. Application of Matrix Calculus to Estimate Cross-Sectional Quantities 607

A.1	Shape Matrix	607
A.2	Cross-Sectional Quantities for Bending	608
A.3	Cross-Sectional Quantities for Torsion	610
A.4	Estimation of Shear Flow due to Warping and Bending	614
A.4.1	Shear Flow due to Warping	614
A.4.2	Shear Flow due to Bending	618
A.5	Numerical Example	621
A.5.1	Cross-Sectional Quantities for Bending	621
A.5.2	Cross-Sectional Quantities for Warping	626
A.5.3	Estimation of Shear Flow	633
REFERENCES		641

Appendix B. Vibration Parameters $\psi_{i,r}$, $\chi_{i,r}$, $\zeta_{i,r}$, $\varphi_{i,r}$, $\mu_{i,r}$, $\kappa_{i,r}$, $\nu_{i,r}$ and $\Theta_{i,r}$ 643

REFERENCE		647
-----------	--	-----

Appendix C: Computer Programs for Designing Curved Steel Bridges 649

Author Index	655
Subject Index	659