

Index

Note: Page numbers in *italics* refer to figures and those in **bold** to tables.

a

- ABAQUS finite element modeling
 - package 64, 67, 132
- American Welding Society (AWS)
 - hot-spot stress definition 34
 - standards **13**, 100, 101, 144
 - weldability definition 15
- arc welding 13–15
 - electrodes 4, 14
 - flux-cored arc welding 14, 77, 100, 101, 130
 - shielded metal arc welding 14, 39, 40, 72, 77
 - welding speed controlled by welder 130
- ASTM standards
 - brace plate cutting 38, 47, 52–54, 61
 - calibration tests 45, 46, **46**, 107
 - hole drilling method for residual stress investigation 24, 28, 37, 38–39
 - materials specifications **13**
- austenite, transformation from
 - and to other structures 9, 10, 17, 18
- AWS *see* American Welding Society
- axial load (AX)
 - hot-spot stress 35
 - nominal stress 33
 - stress concentration factors 153, 154, 155, 158–160, 160, 164

b

- bainite, transformation to ferrite and cementite 10
- b/c *see* brace width to chord width ratio
- boundary conditions, numerical
 - modeling of plate-to-plate welded joints 90, 90, 91, 91
- box hollow section (BHS) joints
 - CIDECT design guide 35, 161
 - classification and parameters 31, 32
 - experimental investigations, stress concentration factors 153–164
 - experimental residual stress investigation 99–123
 - analysis and discussion 118–123
 - box section fabrication 104
 - chord edge effects 118, 120, 120, 123
 - corner effects 120–121
 - fabrication procedure 101–105, 102, 103, 104, 105
 - joint intersection fabrication 104–105
 - preheating effect analysis 118–119
 - residual stress computation
 - procedures 107–108, 109
 - stress variation in depths 121–122, 121–122, **122–123**
 - test results 109–118
 - test setup and procedure 105–107, 105, 106
 - welding design 101–103

- fatigue analysis 31–35
 - numerical modeling of residual stress 125–151, 181–194
 - arc touch movement 130, 131
 - fully coupled thermo-mechanical analysis 125, 126, **131**, 136–141
 - heat source modeling 129, 175–179
 - methods 125–126
 - modeling procedure 126–132, 127, 128, 132
 - parametric study 141–150
 - plate-to-plate modeling joint
 - comparison **131**
 - preheating 129–130, 132–136
 - source code 175–177, 181–194
 - thermal interactions 129–130, 131
 - stress (fatigue) analysis 32–35
 - versus plate-to-plate joints 99, 126
 - brace width to chord width ratio (b/c), numerical modeling of box welded joints parametric study **142**, 145–147, 146, 149
- C**
- calibration coefficients, hole-drilling
 - methods 24, 38, 46, **46**
 - calibration plates 45
 - calibration tests
 - ASTM standards 45, 46, **46**, 107
 - residual stress investigations 45–46, 46
 - carbon
 - effects in steel 15–16
 - interactions with other elements in steel 15–16
 - carbon equivalent (CE)
 - weldability equations 16
 - yield stress relationship 11, 16
 - carbon-equivalent limit (C_{equiv}) 15
 - CCT *see* continuous cooling transformation diagrams
 - CE *see* carbon equivalent
 - CGHAZ *see* coarse-grained heat-affected zone
 - chord and brace hollow section fabrication
 - for tubular structures 99, 100, 101–102
 - chord-brace intersection
 - analysis area for numerical study 126
 - joint fabrication 104
 - weld influence on residual stress 140–141
 - welding speed variation in box joints 130, 131
 - weld simulation 127, 127
 - CIDECT design guide 35, 161, 164
 - coarse-grained heat-affected zone (CGHAZ) **12**, 17
 - codes and standards
 - American Welding Society **13**, 100, 101, 144
 - CIDECT design guide 35, 161, 164
 - HSS applications 12, **13**
 - see also* ASTM standards
 - coefficient of thermal expansion (CTE), different materials linked together causing stress 21
 - cold cracks 19
 - computational costs
 - balancing with accuracy 150
 - see also* lumping technique
 - continuous cooling transformation (CCT) diagrams 17, 18
 - cooling rate
 - calculating average rate 6
 - effect of heat input rate 14
 - effect of preheating 76, 76, 92–93, 92, 118
 - effects of lumping schemes 94, 94
 - effect on weld 4, 15, 18, 18
 - effect of welding sequence 96, 96
 - effect of welding speed 94, 95
 - residual stress relationship 52, 52
 - variation across different locations of box joint 134–136, 135, 150
 - crack growth rate, residual stress effects 30–31, 31
 - CTE *see* coefficient of thermal expansion
 - cyclic loading
 - box joints 4, 99, 126, 153
 - plate-to-plate joints 37
 - cyclic plastic deformation at weld toes, eliminating tensile residual stresses 29

d

- Dearden equivalent, carbon equivalent equation 16
- delivery condition of high strength steel 10–11
- discretization of plate-to-plate joints, finite element modeling 65, 66

e

- EC3 *see* Eurocode 3
- electrodes
 - arc welding 4, 14
 - used in experimental investigations 39–40, **40**, 100–101, **101**
- element birth and death method
 - residual stress in box joints **131**, 150
 - weld filler simulation 67, 67, 96
- element movement method, weld filler addition modeling 67
- element types, modeling box joints versus plate-to-plate joints **131**
- energy balance principle, heat conduction through a volume element 23
- equivalent carbon content *see* carbon equivalent
- Eurocode 3 (EC3) 34, 68, 69, 69, 70–71, 70
- experimental residual stress investigations
 - future research recommendations 168
 - overall conclusions 166–167
 - overview 24–25, **25**, 165
 - plate-to-plate joints 37–61
 - welded box T-joints 99–123
- external loading (tensile stress)
 - residual stress reduction effects 29, 29
 - static tensile testing, plate-to-plate welded joints 54–57

f

- fatigue problems in HSS
 - structures 11–12
- FCAW *see* flux-cored arc welding
- ferrite, transformation from and to austenite 10, 17

- FGHAZ *see* fine-grained heat-affected zone
- filler material addition in welding,
 - numerical modeling of plate-to-plate joints 27–28, 67–68, 78–79, 78, 79, 80, 96
- fine-grained heat-affected zone (FGHAZ) 17
- finite element modeling
 - ABAQUS package 64, 67, 132
 - plate-to-plate welded joints 63–97
 - ambient temperature results 81–83, 87
 - comparison with testing results **72**, **73**
 - discretization of joints 65, 66
 - heat source model 77–78, 77
 - heat transfer analysis 68–70, 72–73
 - lumped/lumping techniques 27, 64–66, 78–79, 78
 - lumping schemes 90, 90, 91, 93, 94
 - mechanical analysis 70–71, 70
 - mechanical boundary conditions 90, 90, 91, 91
 - modeling procedures 64–67, 65, **66**, 76–80
 - model validation 71–72, 80–81
 - number of weld lumps 93–94, 93, 94
 - parametric study 87–96
 - preheated joint results 83–87, 97
 - residual stress results 74–76, 74, 75, 76
 - results **71**, 72–76, 81–87, 171–173
 - three dimensional models 76–87, 171–173
 - two-dimensional models 64–76, 87–96
 - weld filler addition 27–28, 67–68, 78–79, 78, 79, 80, 96
 - welding sequence effects 90, 90, 91, 95–96, 96
 - welding speed effects 94, 95
- flux-cored arc welding (FCAW) 14, 77, 100, 101, 130
- Fourier's law of heat conduction 22, 77

- fracture mechanics
 - distribution of average critical linear elastic fracture mechanics parameter at ambient temperature **12**
 - fatigue performance investigation of tubular/box joints 153
 - fatigue problems in HSS structures 11–12
 - offshore analysis 30
 - see also* hot-spot stress/strain
 - fracture toughness property 12, **12**, 18
 - full element method, weld filler addition modeling 67
 - fully coupled thermo-mechanical analysis
 - box joints
 - advantages over sequential coupling 125
 - modeling validation 136–137
 - residual stress modeling 125, 126, **131**, 136–141
 - residual stress results 138–141
 - temperature history results 137–138
 - fusion welding
 - processes 13, 14–15, 15
 - residual stress production 63
 - see also* arc-welding
 - future research recommendations 168
- g**
- grain size and structure
 - cooling rate 14
 - high strength steel production methods 11, 11
 - welding effects 14, 17–19, 18
 - welding speed effect 149
 - weld zones **12**, 14, 18
- h**
- heat-affected zone (HAZ)
 - welding **12**, 14, 15, 17–18, 51, 63, 68, 149
 - see also* residual stress
 - heat generation by plastic dissipation 125
 - heat source modeling, plate-to-plate welded joints 3D analysis 77
 - heat transfer analysis
 - Fourier’s law of heat conduction 22
 - residual stress generation in the welding process 22–24, 23
 - sequentially-coupled thermal-stress analysis 63, 64, **66**, 68–70, 72–73
 - heat transfer process
 - numerical analysis
 - plate-to-plate welded joints 68–69
 - preheated box joint welding 132–136, 133, 134, 135, 150
 - high-strength steel (HSS)
 - applications 1, 2
 - box joints versus plate-plate joints 99
 - mild steel comparisons 1, 3, 9, 12, 30, 31, 37, 71
 - historical perspectives
 - hole drilling methods 24, 38
 - production processes for rolled steel products 3
 - hole drilling methods for residual stress investigation
 - ASTM standard procedure 24, 37, 38–39
 - features 24, **25**
 - modification for plate-to-plate welded joint investigation 43, 44
 - welded box T-joints 105–106
 - hollow sections, chord and brace
 - fabrication for tubular structures 99, 100, 101–102
 - hot cracks, welding 19, 19
 - hot-spot stress/strain
 - definitions 34
 - stress concentration factors 35, 54–56, 55, **57**, 153
 - tubular joints 34–35, 34, 153, 154, 156, 159, 166
 - HSS *see* high-strength steel
 - hydrogen-induced cracks 19
- i**
- ICHAZ *see* inter-critical heat-affected zone
 - in-plane bending (IPB)

hot-spot stress 35
 residual stress measurement 39
 stress concentration factors 153, 154,
 155, 158–160, 160
 Instron Model 8506 Dynamic
 Materials Testing System 54–57
 inter-critical heat-affected zone
 (ICHAZ) 17
 International Institute of Welding (IIW)
 carbon equivalent 11, 16
 hot-spot definition 34
 IPB *see* in-plane bending

j

joint corners
 effects on experimental residual stress
 results 120–121
 stress concentration factors of box
 joints 163, 164
 welding speed variation 130, 131
 joint intersection fabrication, residual
 stress investigation of welded box
 T-joints 104–105

l

LB-70L electrode, use in
 experimental investigations
 39–40, **40**
 literature review 9–35
 load types
 stress concentration factors 153
see also axial load; in-plane bending;
 out-of-plane bending
 local stress 24, 29, 33, 34
 lumping techniques
 numerical modeling of multi-pass
 welding 27
 box joint welding 127, **131**, 150
 plate-to-plate welding 64–66,
 78–79, 78, 167

m

manganese, effects in steel 15
 manual arc welding process *see* shielded
 metal arc welding
 martensite

cooling rate effects 18
 transformation to and from other
 structures 9, 10, 10, 18
 mean stress, fatigue strength and external
 loading effects 29
 mechanical analysis, numerical modeling
 of plate-to-plate welded
 joints 70–71, 70
 mechanical properties of steel, welding
 effects 18–19, 20
 meshing, numerical analysis of weld
 64, 66, 132, 133
 microstructure of steel 9
 modeling *see* finite element modeling;
 numerical modeling
 multi-pass welding
 numerical modeling
 ambient temperature versus
 preheating 76
 direction of passes 78, 79
 lumping techniques 27, 64–66,
 78–79, 78, 97, 127, 131, 150, 167
 preheating effect on later passes 96

n

neutron diffraction method for residual
 stress investigations 24–25, **25**,
 28, 37, 125, 168
 nominal stress
 plate-to-plate joints 58, 59, 60
 tubular/box joints 33, 34, 35, 159
 notch stress, tubular joints 35
 numerical modeling of pure heat transfer,
 preheated box joint welding
 132–136, 133, 134, 135
 numerical modeling of residual
 stress 26–28, 26, **27**
 plate-to-plate welded joints 63–97,
 78, 167
 2D modeling 64–76, 87–96
 3D modeling 76–87, 171–173
 lumping techniques 64–66, 78–79,
 78, 167
 welded box joints 125–151
 2D modeling 125–126

- 3D modeling 126–151, 171–179, 181–194
 - lumping techniques 97, 123, 127, 131, 150
 - parametric study 141–150
 - versus plate-to-plate joints **131**
 - see also* finite element modeling
 - numerical modeling of welded joints 5, 6
 - future research recommendations 168
 - overall conclusions 167–168
 - overview 165–166
- O**
- offshore structures, fatigue and fracture 11–12
 - OK Tubrod 15.09 electrode 100–101
 - out-of-plane bending (OPB), stress concentration factors 153, 154, 155, 158–160, 161
- P**
- parametric studies
 - 2D numerical modeling of plate-to-plate welded joints 87–96
 - boundary conditions 91, 91
 - lumping schemes 93–94, 93, 94
 - preheating temperature 91–93, 92
 - welding sequence 95–96, 96
 - welding speed 94, 95
 - numerical modeling of box welded joints 141–150
 - b/c ratio (brace width to chord width) **142**, 145–147, 146, 149
 - joint angle 142–145, 142, **142**, **143**
 - preheating temperature **142**, 143–145, 144, 145–146, 145, 146, 147–149, 148
 - welding speed **142**, 147–150, 149
 - weld starting location 142–143, 142, **142**, 143, 146–147, 147
 - pearlite (ferrite plus cementite), transformation from and to other structures 10, 17, 18
 - phase transformation, welding 16–18, 17
 - phosphorus, effects in steel 16
 - plastic dissipation, heat generation 125
 - plastic strain, hot cracks 19
 - plate-to-plate welded joints
 - experimental residual stress investigation 37–61
 - brace plate cutting effects 52–54, 53, 54, 61
 - brace plate cutting procedure 47, 47, 48
 - calibration test 45–46, 46, **46**
 - distribution along weld toe 49, 49, 50
 - experimental results 47–54, **48**
 - hole drilling method 38–39, 43
 - joint angle effects 50–51, 51, 52, 61
 - measurement procedure 46–47
 - plate thickness effects 51–52, 61
 - preheating effects 49–50, 50, 52, 54, 60
 - setup 43, 44
 - specimen specifications 39–41
 - strain gauge locations 44–45, 45
 - welding specifications 41–43
 - numerical modeling 63–97
 - parametric study 87–96
 - three dimensional finite element analysis 76–87, 171–173
 - two dimensional finite element analysis 64–76, 87–96
 - static tensile testing 54–57
 - versus box hollow section joints 99, 126
 - welding profile/geometry 41, **41**
 - preheating of weld joints
 - experimental investigation of plate-to-plate joints
 - effects on residual stress 49–50, 50, 52, 54, 60
 - hole drilling stress test method 41–42, 42
 - experimental investigation of welded box T-joints
 - analysis/conclusions 118–119, 123
 - results 109–118, 117, 119

specimen fabrication 101, 104, 104, 105
 test setup 106–107, 107
 numerical modeling of box joints 129–130
 allowing for cooling/heat transfer 132–136, 133, 134, 135
 parametric study 142, 143–146, 144, 145, 146, 147–149, 148
 numerical modeling of plate-to-plate joints
 2D modeling 69, 71–76, 92–93, 93
 3D modeling 76, 78, 81
 temperature effects, 2D numerical modeling of plate-to-plate welded joints 91–93, 92
 production methods of high strength steel 9–11, 10, 11
 pure heat transfer, modeling preheated box joint welding 132–136, 133, 134, 135

q

quenching and tempering (QT),
 procedure effects on steel microstructure 9, 10, 11

r

research background 1–8
 residual stress 20–31
 box joints versus plate-plate joints 99
 computation procedures 107–108, 109
 eliminated by cyclic plastic deformation at weld toes 29
 experimental investigations 24–25, 25
 plate-to-plate joints 37–61
 welded box T-joints 99–123, 153–164
 exploration of effects 28–31
 generation by welding 22–24, 23
 numerical modeling 26–28, 26, 27
 plate-to-plate joints 63–97
 welded box joints 125–151
 welded box T/Y-joints 125–151
 origins 20–22, 21

reduced by high applied stresses in box joints 164
 removal by thermal stress relief 29
 sign conventions 110
 types by magnitude 22, 22
 residual stress factor (RSF),
 calculations 58–60, 59, 60
 RQT701 HSS plate for use in experimental investigations,
 specifications 39–40, 40
 RS-200 milling guide, hole drilling
 method for residual stress measurement 43, 44

S

SCFs *see* stress concentration factors
 SCHAZ *see* sub-critical heat-affected zone
 semi-automatic arc welding process *see* flux-cored arc welding
 sequentially coupled thermo-mechanical analysis
 numerical modeling of plate-to-plate joints 64, 66, 71, 96, 131, 165, 167
 versus fully coupled 125, 131
 shielded metal arc welding (SMAW) 14, 39, 40, 72, 77
 sign conventions, residual stress 110
 silicon, effects in steel 15–16
 SMAW *see* shielded metal arc welding
 S–N curve approach
 fatigue performance investigation of tubular/box joints 32–34, 33, 153
 fatigue performance of welded joints dependent on mean strength 29
 solid-phase welding 13, 14
 Sony Center, Berlin 1, 2
 standards *see* codes and standards
 static testing
 box joints 5, 153–164
 equipment and procedures 154–159
 residual stress effects 162–163
 test results 159–161
 plate-to-plate joints 5, 54–57

- equipment and procedures 54–56, 55, 56, 57
 - test results 56, 57
- strain gauges
 - rosette design for hole drilling method of residual stress testing 34, 37, 39, 44–45, 45, 105–106
 - schemes for residual stress measurement, box T-joints 106–107, 107, 108
 - schemes for stress concentration factors assessment on box T-joints 156–157, 156, 157, 158
- strain hardening, reduced in high-strength steel 3, 9, 37
- strength of steel
 - wall thickness and weight relationships 3
 - see also* tensile strength; toughness properties; weldability
- stress concentration factors (SCFs)
 - different load types 153
 - hot-spot stresses 35, 54–56, 55, 57, 153
 - influences of residual stress 57–60, 59, 60, 162–163
 - plate-to-plate joint residual stress effects 55, 56, 57–60, 57
 - static test on large-scale preheated box joints 153–164
 - axial load 153, 154, 155, 158–160, 160, 164
 - comparison with CIDET guide 161, 161, 164
 - corners 163, 164
 - in-plane and out-of-plane bending 153, 154, 155, 158–160, 160
 - residual stress effects 162–163, 162, 163, 164
 - results 159–160, 160–161
 - setup and specimens 154–156
 - strain gauge schemes 156–157, 156, 157, 158
 - test procedure 158–159
 - strain gauges 55
 - stress-life *see* (S–N) curve approach
 - sub-critical heat-affected zone (SCHAZ) 17
 - sulfur, effects in steel 16
 - surface quality of steel, effects of carbon and additional elements 15–16

t

 - temperature (thermal) history 10, 10, 68–70, 73, 74
 - tempering of high-strength steel 9, 10, 10, 11
 - tensile strength
 - steel composition and structure 9, 11, 15
 - weldability relationship 12
 - tensile stress
 - hot cracks 19
 - residual stress reduction 29, 29
 - thermally generated stresses 21
 - thermo-mechanical analysis of residual stress 125
 - see also* fully coupled thermo-mechanical analysis; sequentially coupled thermo-mechanical analysis
 - thermo-mechanical control process (TMCP), HSS production 11
 - three dimensional numerical modeling
 - residual stress in box joints 126–151, 175–179, 181–194
 - residual stress in plate-to-plate welded joints 76–87, 171–173
 - source code of box joint modeling 181–194
 - source code of heat source 175–179
 - TMCP *see* thermo-mechanical control process
 - toughness properties 11, 12, 12, 18
 - tubular structures *see* box hollow section joints
 - two dimensional numerical modeling of residual stress
 - box joints 125–126
 - finite element modeling of plate-to-plate joints 64–76
 - parametric study of plate-to-plate joints 87–96

U

ultrasonic analysis 25, 105

W

weldability of steel 15–16, 16

weld filler addition processes, numerical modeling 27–28, 66, 67–68, 67, 78–79, 78, 79, 80, 96

welding 12, 13–20

couplings in process 26, 26, 27

flux-cored arc welding 14, 77, 100, 101, 130

heat-affected zone 12, 14, 15, 17–18, 51, 63, 68, 149

heat transfer analysis 22–23, 23, 64, 66, 68–70, 72–73, 132–136, 150

high strength steel compared to mild steel 4

shielded metal arc welding 14, 39, 40, 72, 77

three metallurgical zones 14

welding speed

controlled by welder in flux-cored arc welding 130

grain structure 18–19, 18

numerical modeling of box joints 142, 147–150, 149

numerical modeling of plate-to-plate welded joints 94, 95

variation around box joint sides and corners 130, 131

X

X-ray diffraction method for residual stress investigation 24, 25, 37, 125

Z

zones of transformation in

welding 17–18

see also heat-affected zone

















