## Section 5

The $\phi$-factors used for bearing stresses in Table 5.1.1.3-1 were adopted from Section 3.4.5. The value of $\phi = 0.65$ for shear stress on rivets and bolts was determined by the following derivation. It was assumed that the "typical" shear strength values for rivets given in Reference (10) represent mean values. The ratio of the mean to the "minimum expected" values was found to be 1.15. A coefficient of variation of 0.1 was assumed. It was also assumed that the nominal rivet area is equal to the mean, with a coefficient of variation of 0.1. The mean shear capacity of a rivet is thus

$$\bar{R} = \bar{A}\bar{F}_{su} = 1.0 \times 1.15\, A_n F_{sun} \quad (32)$$

and

$$V_R = \sqrt{V_A^2 + V_{F_{su}}^2} = \sqrt{0.1^2 + 0.1^2} = 0.14 \quad (33)$$

With these statistics a calibration was performed using Eq. 1, and for a $D/L = 0.2$ it was found that ASD design gave $\beta = 3.9$. The LRFD design with $\phi = 0.65$ gave $\beta = 4.0$.

## Section 7

The factored limit state shear stress for fillet welds (Table 7.2-2) is based on a value of $\phi = 0.65$. Following is the reasoning used in arriving at this value:

The mean shear strength of a fillet weld is equal to

$$\bar{R} = \bar{\tau}_u\ \bar{A} \quad (34)$$

where $\bar{\tau}_u$ is the mean shear strength and $\bar{A}$ is the weld throat area. the following data were obtained from Reference (11):

| Filler Alloy | $\bar{\tau}_u / F_w$ | $V_{\tau_u}$ | Orientation of Weld |
|---|---|---|---|
| 1100 | 1.62 | 0.18 | longitudinal |
| 1100 | 1.78 | 0.23 | transverse |
| 4043 | 1.45 | 0.17 | longitudinal |

$F_w$ is specified weld strength in tension. Assuming that the mean weld area equals the nominal area, with $V_A = 0.1$, and using the allowable weld stress from Table 7.2-2 in Part I-A for purposes of calibration, the resulting values of the safety index $\beta$ inherent in current fillet weld design varied from 3.9 to 4.9 as the ratio $D/L$ varied from 0.1 to 0.5. A target of $\beta_T = 4.5$ for $D/L = 0.5$ was selected to arrive at $\phi = 0.65$. The ratios of the weld area required for LRFD to that required by ASD are given in Table C7.1.

### Table C-7.1
### RATIO OF FILLET WELD AREAS REQUIRED BY LRFD TO THAT REQUIRED BY THE ALLOWABLE STRESS *SPECIFICATION*

| Filler Alloy | $F_a$ Table 7.2-2 ASD Ksi | $F_W$ Ksi | LRFD/ASD for $\phi = 0.65$ for | | |
|---|---|---|---|---|---|
| | | | D/L = 0.1 | D/L = 0.25 | D/L = 0.5 |
| 1100 | 3.2 | 7.5 | 1.03 | 1.00 | 0.96 |
| 4043 | 5 | 11.5 | 1.05 | 1.02 | 0.98 |
| 5183 | 8 | 18.5 | 1.04 | 1.01 | 0.98 |
| 5356 | 7 | 17 | 0.99 | 0.96 | 0.93 |
| 5556 | 8.5 | 20 | 1.02 | 0.99 | 0.96 |
| 5654 | 5 | 12 | 1.00 | 0.97 | 0.94 |

## Section 8

The test criteria are very similar to those in the ASD *Specification*, except they provide guidance in determining a resistance factor (as opposed to a factor of safety) on the basis of tests (Section 8.3.2).

# REFERENCES


1. Aluminum Association, *Specifications for Aluminum Structures*, Fifth Ed., December, 1986.

2. B. Ellingwood, T.V. Galambos, J.G. MacGregor, C.A. Cornell "Development of a Probability Based Load Criterion for American National Standard A58-Building Code Requirements for Minimum Design Loads in Buildings and Other Structures" National Bureau of Standards, *Special Publication 577*, June 1980.

3. T.V. Galambos, "Load and Resistance Factor Design for Aluminum Structures" *Research Report No. 54*, Civil Engineering Department, Washington University, St. Louis, Mo.

4. J.W. Clark, "Design of Aluminum Structural Members", Ch. 10 in *Structural Engineering Handbook*, ed. E.H. Gaylord and C.N. Gaylord, McGraw-Hill Book Co., New York, 1979.

5. J.C. Chapuis and T.V. Galambos, "Design Criteria for Aluminum Columns and Beam-Columns" *Research Report No. 58*, Civil Engineering Department, Washington University, St. Louis, Mo.

6. B.G. Johnston, Editor, *Guide to Stability Design Criteria for Metal Structures*, Third Ed., John Wiley and Sons, Inc., New York, 1976.

7. A. Bernard, F. Frey, J. Janss, C. Massonnet, "Research on the Behavior and Buckling of Aluminum Bars" (in French), *LABSE Publications*, Vol. 33-I, 1973.

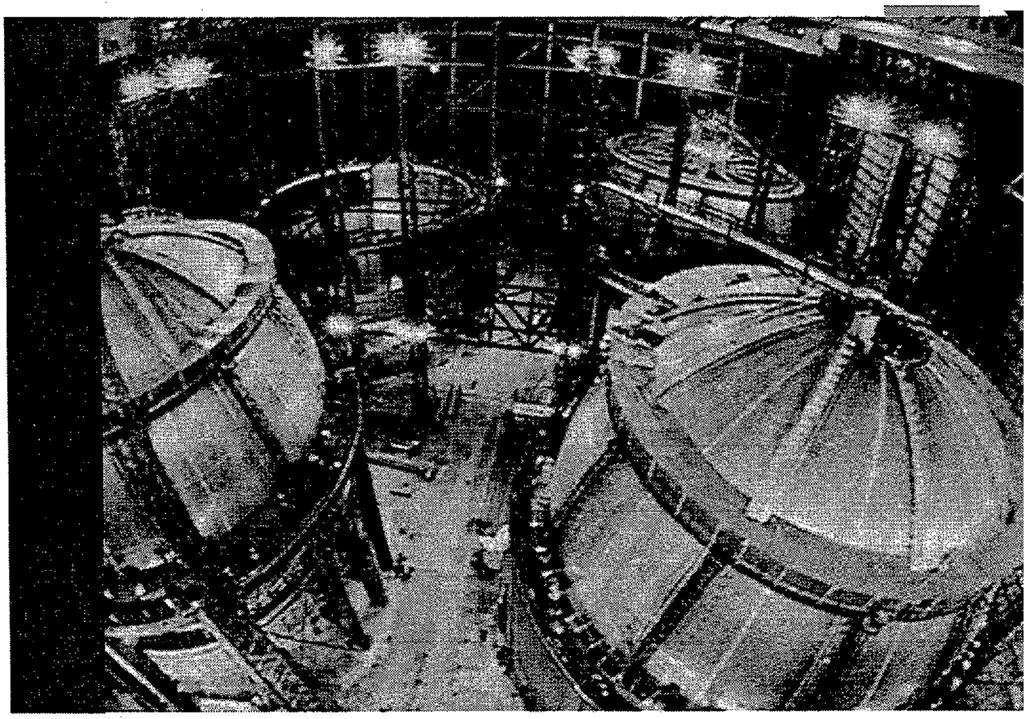
8. R.H. Batterman, G.G. Johnston, "Behavior and Maximum Strength of Metal Columns" *Journal of the Structural Division*, ASCE, Vol. 93, ST2, April 1967.

9. J.W. Clark, "Statistical Aspects of Strength of Aluminum", *ALCOA Report No. 76-74-10*, June 20, 1974.

10. ASCE Task Committee on Lightweight Alloys, "Suggested Specifications for Structures of Aluminum Alloys 6061-T6 and 6062-T6" *Journal of the Structural Division*, ASCE, Vol. 88, ST6, Dec. 1962.

11. F.G. Nelson, R.L. Rolf, "Shear Strengths of Aluminum Alloy Fillet Welds" *Welding Journal Research Supplement*, Feb. 1966.

# DESIGN GUIDE



# PART III

# *Aluminum Design Manual*

# PART III

# Design Guide

The Aluminum Association, Inc.
900 19th Street, NW, Washington, DC 20006

Second Edition, January 2000

# III
# Design Guide

## TABLE OF CONTENTS


**1.0 Introduction .......... 5**

**2.0 Design of Aluminum Structures .......... 6**
2.1 Considerations .......... 6
2.2 References .......... 6
2.2.1 General .......... 7
2.2.2 Fabrication .......... 7
2.2.3 Alloys/Products .......... 7
2.2.4 Aircraft .......... 7
2.2.5 Automotive .......... 7
2.2.6 Bridges/Highway .......... 7
2.2.7 Railroad Cars .......... 7
2.2.8 Ships .......... 7
2.2.9 Storage Tanks/Pressure Vessels/Pipe .......... 7
2.2.10 Other Specifications/Codes .......... 8

**3.0 Member and Component Behavior .......... 9**
3.1 Tension Members .......... 9
3.2 Tension Flange of Beams .......... 11
3.3 Bearing .......... 11
3.4 Compression in Columns .......... 11
3.5 Compression in Beams .......... 12
3.6 Compression in Flat Elements .......... 14
3.6.1 Elements with Constant Thickness .......... 14
3.6.2 Elements with Non-Uniform Thickness .......... 16
3.7 Compression in Tubes and Curved Panels .......... 16
3.8 Shear in Flat Webs .......... 17
3.8.1 Buckling of Stiffened and Unstiffened Webs .......... 17
3.8.2 Tension Field Webs .......... 17
3.8.3 Corrugated Webs .......... 18
3.9 Shear in Tubes and Curved Panels .......... 18
3.10 Combined Stresses/Loading .......... 18
3.11 Stiffeners for Flat Plates .......... 19
3.12 Pipe Bursting Pressure .......... 19

**4.0 Fatigue .......... 20**

**5.0 Joints and Joining .......... 22**
5.1 Mechanical Joints .......... 22
5.2 Welded Joints .......... 23
5.2.1 Welding Fabrication .......... 23
5.2.2 Design of Welded Joints .......... 23
5.3 Adhesive Bonded Joints .......... 27
5.3.1 Advantages and Disadvantages .......... 27
5.3.2 Adhesive Selection .......... 27
5.3.3 Types of Adhesives .......... 27
5.3.4 Aluminum Surface Pretreatments .......... 27
5.3.5 Joint Design .......... 28
5.3.6 Current Adhesive Applications .......... 29

**6.0 Sandwich Panels and Beams .......... 30**

**7.0 Extrusion Design .......... 31**
7.1 Replacement of Fabrications with Extrusions .......... 31
7.2 Design Parameters .......... 33
7.3 Design Guidelines .......... 38
7.4 Design for Assembly .......... 40

**8.0 Prevention of Corrosion .......... 42**

**9.0 Fire Protection .......... 44**

**10.0 References .......... 45**

# 1.0 Introduction

This part of the design handbook provides general, non-mandatory information that may be of interest to a designer of aluminum products of any type. Included are references to the strength formulas given in *Part IA, Allowable Stress Design Specification (Part IB, LRFD Specification,* has similar equations). These formulas are applicable to the design of all types of products; such as building, bridges, ships, railroad cars, automobiles, trucks, highway structures and machinery. For example, the formulas for a column given in the *Specification* apply equally well to a column for a patio roof, a member in a latticed roof, a strut in a rail car or automobile, a member in a bridge truss, and a stanchion/pillar in a ship. When formulas exist in the *Specification* and are discussed in this part, they are referenced by number (italicized) and thus are not duplicated.

The designer can determine the strength of the part from the formulas given in the *Specification* by setting the factors of safety on appearance, yielding and ultimate strength equal to 1.0. The designer can also incorporate other factors of safety into the formulas for the product commensurate with the uncertainties of the load and member strength and with the importance of the structure, and the safety of the user of the structure. Of course the margins of safety for buildings and bridges are specified in the requirements of *Part IA and IB.*

Also covered in this part are topics that are not currently in the *Specification* but are believed to be of interest to the designer. Commentary of the *Specification*, past handbooks from the aluminum producers and published and unpublished reports are the major resources of this material.

# 2.0 Design of Aluminum Structures

The various parts of this handbook provide most of the information that designers need to properly design aluminum structures. *Part IV Materials*, provides general information about aluminum and alloys, the alloy and temper designation system, and comparative characteristics and applications. *Part V Material Properties*, gives mechanical and physical properties of alloys. *Part VI Section Properties*, has tables of section properties of many shapes and general equations for the calculation of various section properties, including torsional and warping values. *Part VII Design Aids*, has charts and tables containing allowable stresses for various alloys and beam formulas. *Part VIII Illustrative Examples of Design*, provides detailed calculations for the design of many specific components and the location of necessary information provided in the parts of this manual. Some additional general guidance for design is provided in this section along with references to other technical literature that provide additional resource material.

## 2.1 Considerations

*Part IV* discusses attributes of aluminum that allow it to be used as a cost effective material in structures. Most of the applications make use of a favorable life cycle cost; the combined costs of the material and its fabrication into the finished product, erection or installation of the product, operation and maintenance, and disposal or reuse of the material after its useful life in the product. For example, aluminum is the principal material in aerospace structures, primarily because of its high strength to weight ratio. The density of aluminum is about 1/3 that of steel and aluminum alloys have strengths similar to those of constructional steels. The aerospace structures are cost effective because smaller engines and less fuel are needed during service compared to those that would be required for heavier structures. The excellent corrosion resistance of aluminum (see Section 8.0) also is a factor in minimizing maintenance costs. Weights of aluminum structures generally are 1/3 to 1/2 those of steel (see Section 3.0). Light weight and corrosion resistance are also the major factors for the selection of aluminum for trucks, automobiles and railroad cars. Low maintenance and fuel savings are the important issues. Aluminum's corrosion resistance in the environment and its appearance, bare or finished, are the major factors in its use in commercial and residential buildings. Many aluminum structures, such as light poles, overhead sign trusses, latticed roofs, bridges and bridge decks are not painted because of the good corrosion resistance of aluminum. Appearance and light weight are also important in truck and automobile wheels.

Sheet, plate, extrusions, forgings and castings are made of aluminum. Alloys and tempers that possess both good strength and corrosion resistance are available for use in most structures. Aerospace alloys are generally not used for other types of structures because their cost is higher and their corrosion resistance is lower than those of the moderate strength alloys. Examples of the common alloys and tempers used for each product form are given in the following table. A more complete list of commonly used alloys and their properties and applications are given in *Parts IA, IV and V.*

| Product form | Application | Alloys |
|---|---|---|
| Sheet and Plate | Building | 3105-H25, 5052-H34, 3004-H16 |
| | Heavy Duty Structures | 5083-H116, 5086-H116, 5456-H116 6061-T6 |
| Extrusions | Building | 6063-T6 |
| | General Purpose | 6061-T6 |
| Forgings | Wheels | 6061-T6 |
| Castings | General Purpose | 356.0-T6 |
| | High Elongation | A444.0-T4 |

The extrusion process is unique to aluminum (compared to steel), and allows the designer to place the material where it is most effective. Section 7.0 provides details on extrusion design. The extrusion process consists of pushing hot aluminum through a die, likened to pushing tooth paste out of the tube. Cross sections generally must stay constant along the length but they can have detailed cross sections. Often fabrication costs can be lowered by consolidation of parts or the incorporation of aids for assembly by the use of extrusions. Extrusions up to about 30 in. are possible, but the more common ones fit within a circle size of 15 in.

All the common joining methods may be used for attachment of assemblies of aluminum structures; welding, mechanical fastening, adhesive bonding, and a combination of adhesive bonding and one of the other joining methods (see Section 5.0). Welding is done in the shop or in an enclosure because the shielding gas must cover the arc and wind can remove the shield.

Although aluminum has excellent corrosion resistance (see Section 8.0) protection is needed when it is attached to steel, or it is joined by steel bolts, to prevent galvanic action. Painting the parts and galvanizing the bolts is a minimum treatment. Sometimes it is desired to protect an aluminum part from pitting or further oxidation. Clear and decorative finishes can be applied to these cases.

## 2.2 References

There are a number of resources, in addition to this handbook, that are available to the designer of aluminum structures and generally will provide information beyond that covered here. The following lists include many of these resources, some general, some very specific to the application.

### 2.2.1 General


1. Sharp, Maurice L., *Behavior and Design of Aluminum Structures*, McGraw-Hill, Inc., New York, New York, 1993.
2. *Structural Design with Aluminum*, The Aluminum Association, Washington D.C., 1987.
3. Angermayer, Karl, *Structural Aluminum*, CPE Corporation, P.O. Box 8507, Richmond, Va, 1987.
4. Mazzolani, F.M., *Aluminum Alloy Structures*, Pitman, Marshfield, Mass., 1985.


### 2.2.2 Fabrication


1. Minford, J. Dean, *Handbook of Aluminum Bonding Technology and Data*, Marcel Bakker, Inc., New York, New York, 1993.
2. *1997 Structural Welding Code-Aluminum*, ANSI/AWS D1.2, American Welding Society, Miami, Florida.
3. *Welding Aluminum: Theory and Practice*, 3rd ed., The Aluminum Association, Washington D.C., November, 1997.
4. *Forming and Machining Aluminum*, The Aluminum Association, Washington D.C., 1991.


### 2.2.3 Alloys/Products


1. *Aluminum Standards and Data 1997*, The Aluminum Association, Washington D.C., 1997.
2. *Standards for Aluminum Sand and Permanent Mold Castings*, The Aluminum Association, Washington D.C., December, 1992.


### 2.2.4 Aircraft


1. *MIL HDBK 5 (Military Standardization Handbook, Metallic Materials and Elements for Aerospace Vehicle Structures)*, Vol. 1, Chapter 3, Naval Publications and Forms Center, 5801 Tabor Avenue, Philadelphia, PA 19111-5094.


### 2.2.5 Automotive


1. *Data on Aluminum Alloy Properties and Characteristics for Automotive Applications*, The Aluminum Association, Washington D.C., 1982.
2. *Use of Aluminum in Automobiles-Effect of the Energy Dilemma*, T12, The Aluminum Association, Washington D.C. 1980.
3. *Report to the National Academy of Sciences Committee on Fuel Economy in Automotive and Light Trucks*, The Aluminum Association, Washington D.C., 1991.
4. *Design for Aluminum-A Guide for Automotive Engineers*, T8, The Aluminum Association, Washington D.C., 1980.
5. *Guidelines to Resistance Spot Welding Aluminum Automotive Sheet*, T10, The Aluminum Association, Washington D.C., 1982.
6. *Aluminum-the Corrosion Resistant Automotive Material*, T17, The Aluminum Association, Washington D.C. 1987.


### 2.2.6 Bridges/Highway


1. *AASHTO LRFD Bridge Design Specifications*, American Association of State Highway and Transportation Officials, Washington, D.C., 1998.
2. *Guide Specifications for Aluminum Highway Bridges*, American Association of State Highway and Transportation Officials, Washington D.C. 1991.
3. *Standard Specifications for Structural Supports for Highway Signs, Luminaires and Traffic Signals*, American Association of State Highway and Transportation Officials, Washington D.C. 1994.
4. *Ontario Highway Bridge Design Code*, Ministry of Transportation and Communications, Downsview, Ontario, Canada, 1983.


### 2.2.7 Railroad Cars


1. *Specifications for Design, Fabrication and Construction of Freight Cars*, Manual of Standards and Recommended Practices, Section C-Part II, Association of American Railroads, Washington D.C., 1988.
2. *The Repair and Maintenance of Aluminum Railcars*, The Aluminum Association, Washington D.C. 1984.
3. *Aluminum for More Efficient Railroad Cars*, The Aluminum Association, Washington D.C., 1980.


### 2.2.8 Ships


1. *ANSI/AWS D3.7-90 Guide for Aluminum Hull Welding*, American Welding Society, Inc., Miami, Florida, 1990.
2. *Rules for Building and Classing Aluminum Vessels*, American Bureau of Shipping, New York, New York, 1975.


### 2.2.9 Storage Tanks/Pressure Vessels/Pipe


1. *ASME B31.3-1999 Process Piping*, American Society of Mechanical Engineers, New York, New York, 1999.
2. *ASME Boiler and Pressure Vessel Code Section VIII, Rules for Construction of Pressure Vessels*, American Society of Mechanical Engineers, New York, New York, 1998.
3. *ASME/ANSI B96.1-1998, Welded Aluminum-Alloy Storage Tanks*, American Society of Mechanical Engineers, New York, New York, 1998.
4. *API Standard 620, Recommended Rules for Design and Construction of Large, Welded, Low-Pressure*

*Storage Tanks*, Ninth Edition, American Petroleum Institute, Washington D.C., 1996.
5. *API Standard 650, Appendix G, Structurally Supported Dome Roofs*, American Petroleum Institute, Washington, D.C., 1998

### 2.2.10 Other Specifications/Codes

1. *Structural Use of Aluminum Part 1. Code of Practice for Design*, British Standard BS 8118, 1991.
2. *European Recommendations for Aluminum Alloy Structures Fatigue Design.* first edition, 1991.
3. *Strength Design in Aluminum*, Canadian Standards Association, Toronto, Ontario, Canada, 1983.

# 3.0 Member and Component Behavior

The structural design of aluminum components and structures is very similar to that for steel and other metal structures. The primary difference is that properties of the various alloys, some of which are different from those of steel, are incorporated into the equations defining structural behavior. Because many engineers are trained in steel technology to a larger extent than aluminum technology, similarities and differences between aluminum and steel are summarized in Table 3.0-1(1).

Because of the difference in properties (modulus for example) an aluminum design should be different than that for steel in order to use the material effectively. An example is illustrated in Figure 3.0-1; the relative weights of box beams of aluminum and steel with the same bending strength and deflection. The yield strength of the two materials is the same. The weight of the aluminum part is about 50% that of the steel part when its size is about 1.4 times that of steel. Other configurations generally will provide weight savings but less than the optimum. Weights of aluminum structures of 50% that of steel structures have been achieved for bridge girders, automotive frames and other transportation vehicles, in which deflection and fatigue are controlling. For structures controlled by static strength, such as automobile hoods and decklids, and some building panels, weights of aluminum structures of about 1/3 that of steel have been achieved. In all these cases the structures are designed for aluminum, not converted from an existing steel design.

The availability of economical aluminum extrusions allows the designer to consolidate parts normally made by fabrication, thereby saving on joining costs. Also the designer can place the material in the section to optimize the section property governing the design. Various quick attachment schemes can be employed. Section 7.0 gives more details on extrusion design.

The inherent corrosion resistance of aluminum offers positive potential for long life structures that require a minimum of maintenance. Many aluminum structures, i.e. light poles, have performed satisfactorily for decades without painting. Life cycle considerations should be used when comparing the merits of aluminum structures with those of other materials, particularly when the other structures need periodic painting and other maintenance. Life cycle should include the costs of the as-fabricated structure, erection/installation, operation/maintenance and disposal/recycling. Information on corrosion resistance is given in Section 8.0.

The following subsections provide more detailed design information for the components and members covered in the *Specification*. As noted previously other information has been included when available.

## 3.1 Tension Members

The accepted measure of ductility of aluminum alloys is fracture toughness and many of the high strength alloys used for aerospace applications have been evaluated (2). The alloys considered in the *Specification* (non-aerospace applications) are too ductile to be evaluated by fracture mechanics methods. Thus, "ductility" generally is not a design issue for wrought products. The best proof of adequate ductility of alloys is the satisfactory service in buildings, bridges, automobiles, trucks, railroad cars etc. Laboratory fracture tests show that the normalized resistance curves (same fatigue strength) of parts made from one of the alloys, 5456-H116 were higher than those of A36 steel, at temperatures from -200 to +75 degrees F(3). Additional information on ductility/toughness of aluminum alloys has been published (1).

Some practical members, such as angles attached by one leg, have not only the stress concentration at the bolt, but also the non-uniform stresses across the cross section from the eccentricity of the load. For single angles attached to a gusset by one leg the non-uniform stress is accommodated by the use of an area equal to one third of the unattached leg plus the net section of the attached leg. For double angles placed back-to-back the eccentricity is less and two thirds of the unattached legs may be used. Other similar types of members are not covered but their behavior can be estimated based on the information on angles. For example, Tees attached by the flange only to a gusset plate should behave similarly to a single angle attached to a gusset plate by one leg.

The ultimate or yield strength of tensile members with elements of different strength may be estimated by the use of the weighted average method. In this case the weighted average strength is the sum of the quantities, each element area times the element strength, divided by the total area.

Some increase in strength of welded parts can be achieved by either welding in the -T4 temper and aging, or by resolution heat treating and aging after welding. The light pole manufacturers, for example, have justified improved as-welded strength as a result of post weld treatment. Usually ductility of transversely welded structures is reduced by post weld thermal treatment because the width of the zone of lower strength material is decreased (plastic deformation may be confined to a narrow zone). Post weld processes usually are not employed without careful evaluation of strength, ductility and corrosion resistance implications.