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Technical Report ITL-93-2
August 1993

US Army Corps
of Engineers
Waterways Experiment
Station

Computer-Aided Structural Engineering (CASE) Project

Steel Structures for Civil Works, General Considerations for Design and Rehabilitation

by CASE Steel Structures Task Group

Prepared for Headquarters, U.S. Army Corps of Engineers

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Final report

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Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

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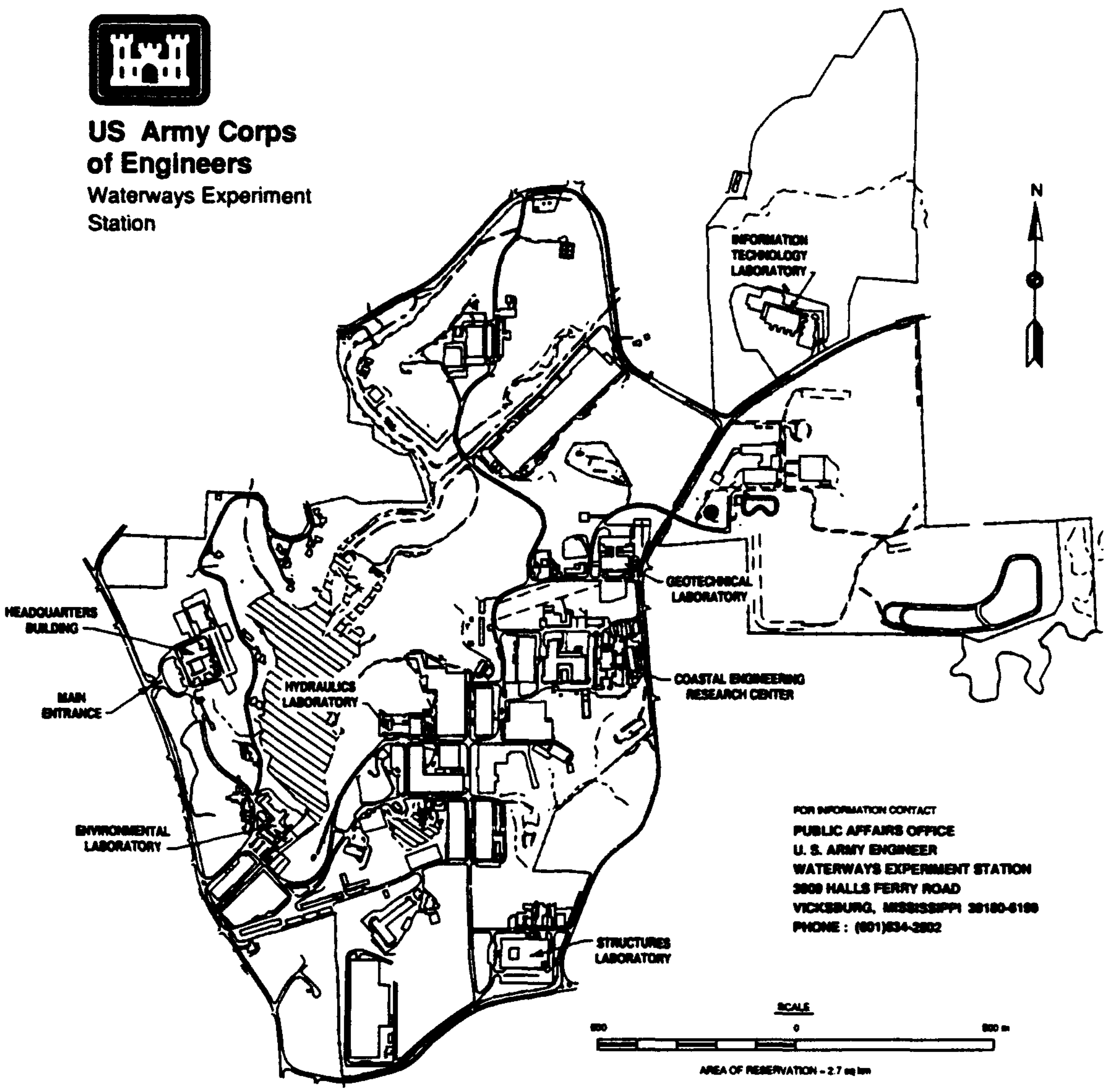

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PREFACE

Corps of Engineers' civil works projects include various types of hydraulic steel structures. The wide range of structure types, combined with their unique environmental and operational characteristics, requires a broad range of knowledge on the part of the designer. This technical report provides background, guidance, and references on many aspects of structural engineering that may be valuable in the design and rehabilitation of hydraulic steel structures on Corps of Engineers' civil works projects. This work was completed by the Computer-Aided Structural Engineering (CASE) Steel Structures Task Group. At the time of preparation of this report members of the CASE Steel Structures Task Group and their Corps of Engineers affiliations were:

Mr. Joseph Hartman, Headquarters (Chairman)
Mr. Don Dressler, Headquarters
Mr. Eugene Ardine, Ohio River Division
Dr. John Jaeger, Jacksonville District
Mr. William Wigner, Jacksonville District
Mr. Thomas Ruf, St. Louis District
Mr. Thomas Wirtz, Rock Island District
Mr. Henry Stewart, North Central Division
Mr. Ray Dewey, Portland District
Mr. Cameron Chasten, Waterways Experiment Station

This report is arranged in ten parts; each part is authored by a member of the CASE Steel Structures Task Group. In Part I, authored by Mr. Joseph Hartman, the scope of the report and Corps of Engineers' design criteria are discussed. In Part II, authored by Mr. Thomas Ruf, guidance for material selection is addressed. Part III, authored by Mr. William Wigner, discusses minimum section or thickness of structural members. Part IV, authored by Mr. William Wigner, covers the design of plate elements. Part V, authored by Mr. Joseph Hartman, is on the design of connections. In Part VI, authored by Mr. Eugene Ardine, considerations for welding are discussed. Fabrication methods and considerations are presented in Part VII, authored by Mr. Henry Stewart. Part VIII, authored by Mr. Thomas Wirtz, includes information on the capabilities and limitations of various nondestructive testing methods. In Part IX, authored by Mr. Thomas Wirtz, various types of corrosion and corrosion protection are addressed. In Part X, authored by Dr. John Jaeger, various cases of distressed hydraulic steel structures are presented. The report was compiled by Mr. Cameron Chasten.

The CASE project is managed by the Information Technology Laboratory (ITL), US Army Engineer Waterways Experiment Station (WES). Mr. Wayne Jones is the CASE Project Manager, and Dr. N. Radhakrishnan is the Director of the ITL.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
feet	0.3048	metres
foot-pounds (force)	1.355818	metre newtons or joules
inches	2.54	centimetres
miles (US statute)	1.609347	kilometres
tons (2,000 pounds, mass)	907.1847	kilograms

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

STEEL STRUCTURES FOR CIVIL WORKS GENERAL CONSIDERATIONS FOR DESIGN AND REHABILITATION

PART 1: INTRODUCTION

Scope

1. Design, repair, or rehabilitation of structural steel elements for civil works projects may require knowledge in a multitude of specialties such as allowable stresses, finite element analysis, material selection, buckling, welding, corrosion, and fatigue. The designer is often a civil engineer specialized in structural design, but with only a brief college exposure to some of the above specialties. This report provides additional background, guidance, and references in many of these specialty areas to enhance the capabilities of design engineers.

2. This report contains general considerations for structural design and repair of hydraulic steel structures on Corps of Engineers' civil works projects. The types of structures covered by this report include gates of all types, bulkheads, trash racks, and appurtenances for these structures, such as embedments and bearings. This report does not include specific information on hydropower turbines, bridges or sheetpiling, except as the general information herein may apply to these items.

3. The topics addressed in this report include material selection, minimum sizes, plate design requirements, connection design, welding, fabrication requirements, nondestructive testing methods, and corrosion protection. Coverage of these topics is not comprehensive; it is more a collection of knowledge and experiences based on design and operation of Corps of Engineers projects.

Design Criteria

4. The major criteria governing steel design for the Corps of Engineers are EM 1110-2-2105 (1993) and specifications by the American Institute of Steel Construction (AISC) (1989, 1986), the American Association of State Highway and Transportation Officials (1989), and the American Welding Society (1992). Guidance applying load and resistance factor design (LRFD) concepts

to civil works criteria for miter gates is contained in EM 1110-2-2105. Various other Engineer Manuals and Engineer Technical Letters have criteria applicable to parts of specific structures. For example, EM 1110-2-2703 (Headquarters, Department of the Army 1984) contains detailed criteria for design of miter gates.

5. Allowable stresses in EM 1110-2-2105 (Headquarters, Department of the Army 1993) are based on AISC but are adjusted lower or higher for structures defined as "dynamically loaded", "hydraulic", or "maintenance closure". Present practice for allowable stress design (ASD) of hydraulic structures is to use AISC allowable stresses, multiplied by a five-sixth reduction factor. The reduction factor is intended to account for uncertainties about loadings and maintenance conditions as discussed in EM 1110-2-2105 (Headquarters, Department to the Army 1993). Other criteria sources are consulted only when AISC or other specific Corps guidance such as American Welding Society (1992), EM 1110-2-2701 (Headquarters, Department of the Army 1962), and EM 1110-2-2702 (Headquarters, Department of the Army 1966) does not provide adequate coverage for a given design situation.

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PART II: MATERIALS

Introduction

References

6. Corps of Engineers guidance for various components of vertical lift gates is given in EM 1110-2-2701 (Headquarters, Department of the Army 1962). Guidance for the selection of material for components of spillway tainter gates is given in EM 1110-2-2702 (Headquarters, Department of the Army 1966). Other types of high strength steel low alloy should be considered in addition to ASTM designation A 441. Guidance for the selection of material for components of lock gates is given in EM 1110-2-2703 (Headquarters, Department of the Army 1984). Guidance for the selection of material for floating mooring bits, line hooks, and check posts is given in ETL 1110-2-247 (Headquarters, Department of the Army 1979). A list of suggested materials for components used in civil works projects can be found in Technical Report CERL-REMR-EM-6 (US Army Corps of Engineers 1989). Guidance for material selection and corrosion mitigation for military construction projects in severely corrosive environments can be found in Technical Report M-88-3 (US Army Corps of Engineers 1988). "Metals Handbook" (1978) contains additional information on material selection.

General

7. The selection of material for components of steel structures for civil works projects requires the consideration of many interrelated factors such as strength, availability, resistance to corrosion, weldability, toughness, hardness, fatigue strength, cost, and compatibility. The relative importance of these factors should be established and weighed to determine which material type is the most appropriate for the component being designed. Experience with existing structures can often be the best guide in selecting a steel appropriate for a given application.

Effects of alloying elements

8. Alloying elements are added to steel to effect changes in the properties of steel. The effects of a particular element may be affected by the presence of other elements, and the effects of a particular element may be beneficial to steel in one respect but detrimental in others.

9. Carbon is the most important single alloying element in steel. It is essential in the formation of several components which can provide a wide

range of mechanical properties and fabrication characteristics. Among steels having comparable microstructures, strength, hardness, and ductile to brittle transition temperature are raised as the carbon content is increased. Increasing the carbon content also increases hardenability.

10. Manganese deoxidizes the melt and facilitates hot working of the steel and improves the machinability of steel. It greatly increases the hardenability of steel.

11. Silicon is one of the principal deoxidizers used in steel making. Chromium is used in low alloy steel to increase its resistance to corrosion, high temperature strength, hardenability, and abrasion resistance in high carbon compositions.

12. Nickel is used in low alloy steel to improve low temperature toughness and to increase hardenability. Nickel is particularly effective when used in combination with chromium and molybdenum in forming an alloy steel that has high strength, toughness, and hardenability.

13. Molybdenum increases the hardenability of steel and is particularly useful in maintaining the hardenability between specified limits. It is unique in the extent to which it increases the high temperature tensile and creep strength of steel.

14. Copper is added to steel primarily to improve its resistance to atmospheric corrosion.

15. Vanadium is generally added to steel to inhibit grain growth during heat treatment. In controlling grain growth, vanadium improves both the strength and toughness of hardened and tempered steel.

16. Niobium lowers the transition temperature and raises the strength of low carbon alloy steel.

17. Titanium increases the effectiveness of boron in increasing the hardenability of the steel.

18. Zirconium and cerium can be used to control the shape of inclusions thereby increasing steel toughness.

19. Boron significantly increases the hardenability of steel.

20. Lead is added to steel to improve its machinability.

21. Aluminum is added to control the grain size during hot working, and heat treatment and is also used to deoxidize steel.

22. Calcium is sometimes used to deoxidize steel.

23. Any of the alloying elements above may appear in steel as a result of their presence in raw materials. As such they would be known as residual

elements. Because of possible undesired effects, their amounts are usually minimized. Several other elements, generally considered to be undesirable impurities, may be introduced into steel; however, for certain purposes they may be deliberately added.

24. Phosphorus increases strength and hardenability of steel but severely decreases ductility and toughness. Phosphorus may be added to improve a steel's machinability or corrosion resistance.

25. Sulfur is very detrimental to the transverse strength and impact resistance of steel, but it affects the longitudinal properties only slightly. It also impairs surface quality and weldability. Sulfur may be added to some steel solely for the improvement in machinability that results.

26. Nitrogen increases the strength, hardness, and machinability of steel, but it decreases the ductility and toughness. It can be used to control the grain size of steel, thereby improving both toughness and strength. Nitrogen can reduce the effect of boron on the hardenability of steel.

27. Oxygen can slightly increase the strength of steel but seriously reduces toughness. Hydrogen can seriously embrittle steel. Tin can render steel to temper embrittlement and hot shortness. Arsenic and antimony also increase susceptibility of a steel to temper embrittlement.

Effects of alloying elements

28. Alloying elements are added to steel to effect changes in the properties of steel. Carbon, manganese, silicon, chromium, nickel, molybdenum, copper, vanadium, niobium, titanium, zirconium and cerium, boron, lead, aluminum, and calcium.

Strength

References

29. A summary of structural steel available in plates, shapes, and bars with their corresponding minimum yield and tensile strengths can be found in Table 1 of "Manual of Steel Construction" (AISC 1989). A summary of steel pipe and structural tubing with corresponding minimum yield and tensile strengths can be found in Table 3 of the previously mentioned manual. Typical mechanical property data for the most commonly used stainless steels can be found in Table 3 of Technical Report CERL-REMR-EM-6 (US Army Corps of Engineers 1989).

General

30. High yield strength steels have proven to be economical where lighter members, resulting from use of higher allowable stresses, are not penalized because of instability, local buckling, or deflection. Two frequent uses are tension members and columns having low slenderness ratios. Two factors should be investigated when considering the use of higher strength steel. The first is increased cost per pound of material which must be compared to the reduced amount of material required resulting from the use of higher strength material. The second factor is that the use of higher strength material will result in smaller members and thus larger deflections which may prevent the structure from meeting serviceability requirements.

Availability

References

31. Section A3.1.a of AISC (1989) lists the standard ASTM specifications for structural steels approved for use in building construction. Section A3.2 lists the standard ASTM specifications for steel castings and forgings. Section A3.3 lists the standard ASTM specification for steel rivets. Section A3.4 lists the standard ASTM specifications for steel bolts, washers, and nuts. Section A3.5 lists the standard ASTM specifications for steel anchor bolts and threaded rods. The availability of structural steel plates, shapes, and bars is shown in Table 1 of AISC (1989). The availability of steel pipe and structural tubing is contained in Table 3 of AISC.

General

32. For a material to be a viable candidate for selection, it must be available in the required quantity within a reasonable time and in the desired form and size with the required tolerances and surface finish. Most steel producers require a minimum quantity (typically several tons) for each item on an order. The designer should check with suppliers for availability and delivery time before specifying materials that are not ordinary (such as stainless steel).

Resistance to Corrosion

33. The usual environments that Corps structures are exposed to are the atmosphere, soil, fresh water, and salt water. The use of stainless steel to

resist corrosion is often prohibited due to the considerable size of Corps metal structures; therefore, most structures require a protective coating for proper service. Coatings for various components are recommended in the Corps guide specification on painting.

34. ASTM A 242 and A 588 are atmospheric corrosion-resistant, high-strength low-alloy steel that can be used in the bare (uncoated) condition under normal atmospheric exposure conditions. Guidelines for specifying weathering steel are given in Modern Steel Construction (1990). Most Corps structures experience severe exposure problems in which these steels do not perform satisfactory in the uncoated condition. However, when either A 242 or A 588 steel is used in the coated condition, the coating life is typically longer than with other carbon steel. Although A 242 and A 588 steel are more expensive than other high-strength, low-alloy steels, the reduction in maintenance resulting from the use of these steel usually offsets their higher initial cost.

35. Corrosion of all carbon steel and many low-alloy steels is most devastating when the metal is subjected to alternately wet and dry conditions plus the presence of chloride salts. Typical service where this occurs is in the splash zone just above mean high tide in partly submerged structures. For this type of highly aggressive environmental condition, the only effective remedy (short of using stainless steel) is the application and continual maintenance of an impervious coating. Sacrificial coatings such as galvanizing give short term protection, but are not as effective for long term exposure as a well maintained impervious coating.

36. Stainless steel is more resistant to rusting than plain carbon and low-alloy steel. They have superior corrosion resistance because they contain relatively large amounts of chromium. Although elements such as copper, aluminum, silicon, nickel, and molybdenum also increase the corrosion resistance of steel, their usefulness in this respect is limited. Stainless steel may be defined as iron based alloys that contain at least 10 percent chromium with or without other elements.

Fabrication details

37. The potential for corrosion can be reduced by proper detailing in the design process. Structures should be designed to assure that all exposed portions of the structure can be painted properly. Drain holes should be provided to prevent the entrapment of water.

Cathodic protection and coatings

38. As an alternative to using material with high natural resistance to corrosion (such as stainless steel), a less corrosion resistant material can be selected and the component can be protected by coating and cathodic protection. However, consideration should be given to accessibility of the component for maintenance of the protection system.

Dissimilar materials in contact

39. Dissimilar metal contact should be avoided when possible due to the possibility of corrosion occurring from galvanic action. The potential for galvanic reaction between dissimilar metals is given in several sources. If contact cannot be avoided, the dissimilar metals should be isolated electrically using proper gaskets or coatings. Contact between aluminum and concrete should also be avoided.

40. Part IX includes discussion of corrosion and corrosion prevention.

Weldability

References

41. Part VI is a discussion of welding. Welding of iron and steel is also discussed in detail in Metals Handbook (American Society for Metals 1978). Technical Report CERL-REMR-EM-6 (US Army Corps of Engineers 1989) gives a thorough discussion of welding of stainless steel.

General

42. The term "weldability" encompasses all aspects of the suitability of a metal for reliable welding under specified conditions. A metal may have good weldability under one set of conditions and very poor weldability under another. For example, successful arc welding of carbon steel may require specific weld joint designs and filler metals, preheating and postheating, and careful control of heat input during welding. If these requirements are met, high-reliability arc welds can be obtained; otherwise, cracking or other defects are probable.

43. A good approximation of the weldability of a material can be estimated from its composition. The most significant alloying element affecting weldability is carbon. The affects of other elements can be estimated by equating them to an additional amount of carbon. The total alloy content has the same affect on weldability as an equivalent amount of carbon. Several empirical formulas have been devised for carbon equivalent. The formula used

by the International Institute of Welding for judging the risk of underbead cracking (also called cold cracking) is as follows:

$$\text{Carbon Equivalent (\%)} = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

44. In general, steel with low carbon equivalent values have high weldability. A carbon equivalent less than or equal to 0.45 percent generally indicates good weldability. However, other factors such as section thickness and joint constraint are also important in selecting steels for welding and in planning welding procedures.

Carbon and low alloy

45. With proper welding procedures all steel listed in AISC (1989) is suitable for welded fabrication.

Stainless steels

46. Stainless steels may be defined as iron-based alloys that contain at least 10 percent chromium. Other iron-based alloys with as little as 4 percent chromium are sometimes referred to as stainless steel, but this discussion is limited to those containing at least 10 percent chromium (all the steel referred to in CERL-REMR-EM-6 (US Army Corps of Engineers 1989) fall in this category). These alloys generally contain alloys in addition to chromium, such as nickel, molybdenum, copper, and manganese, which are added to improve a desirable mechanical property. Generally these elements do not adversely affect weldability. Other elements, such as carbon, silicon, niobium, and titanium can enhance properties in properly controlled amounts or can be detrimental if their presence is uncontrolled. The third group of alloying elements, including sulfur, phosphorus, and selenium are considered to be detrimental to the weldability of stainless steel even though they may improve some other characteristic of the alloy, such as machinability. Most stainless steel that do not contain amounts above 0.03 percent sulfur, phosphorus, and selenium is considered to be weldable.

47. All stainless steels can be readily arc welded by any common welding process. Procedures and precautions appropriate for the various types are important if optimum corrosion resistance and mechanical properties are to be attained in the completed assembly. Corrosion resistance can be impaired by carbide precipitation. Welding of stainless steels produces "sensitized"

areas in heat affected weld zones; these areas are susceptible to intergranular corrosion. The use of low carbon (e.g., Type 304L or 316L) or stabilized (e.g., Type 321 or 347) grades of austenitic stainless steel can prevent corrosion of welds in stainless steel structures.

Toughness

References

48. Section A3.1c of AISC (1989) gives recommendations for toughness requirements for heavy shapes. The chapter titled "Notch Toughness of Steels," of Metals Handbook gives further discussion of this topic.

General

49. Toughness is defined as the ability of a metal to absorb energy and deform plastically before fracturing. The amount of energy absorbed during deformation and fracture is a measure of the toughness of a metal.

50. Experience with various steel structures such as bridges, storage tanks, pressure vessels, and gas pipe lines have established notch toughness as an important parameter for selecting the material to be used. There are several factors that have commonly been found in brittle fractures in the past, typically in structures experiencing impulsive loading at low temperatures. These are stress risers (resulting from a design feature or fabrication defect), low ambient temperature (often in the range of 40 °F), and brittle fracture even though the material possessed adequate ductility at room temperature.

51. In applications where notch toughness is considered important, a supplemental requirement for a minimum Charpy V-notch test value (e.g. 25 ft-lb at 70 °F) should be specified. The test procedures are discussed in detail in ASTM E 23. Toughness becomes a more significant factor in selecting a material at low service temperature and/or low inspection frequency.

Hardness

References

52. Hardness values for stainless steel used in civil works structures are given in Table 3 of CERL-REMR-EM-6 (1989).

General

53. Hardness is a material property useful for estimating the wear resistance of materials and estimating the approximate strength of steels. It is probably the most significant factor in controlling wear of steel. Generally, there is reduction of toughness with increased hardness. The surfaces of steel parts are often hardened to improve the wear resistance or fatigue resistance of the part. A shallow hardened case (0.005 to 0.025 in.) provides a part with good wear resistance in applications involving light to moderate loading. For applications involving heavy or impact-type loading, or abrasive or erosive wear, case depth must be increased to a depth as great as 0.25 in.

54. Compressive residual stresses develop as a result of surface hardening. These stresses effectively increase the fatigue strength of parts subject to bending or torsional fatigue.

55. Examples where hardness should be specified are pintles, pintle bushings, lift gate bearing plates, and reaction plates.

56. When specifying the hardness of parts in contact, the part which can be considered to be sacrificial should be specified to have a lower hardness value.

Galling

57. Adhesive wear is caused by metal to metal contact (under heavy pressure and without lubrication), resultant welding, and breaking of those welds. When this happens on a large scale, it is known as galling, and the metal is smeared and severe surface damage results. Galling tests have been used to evaluate various stainless steel under nonlubricated conditions. CERL-REMR-EM-6 (1989) identifies which stainless steel combinations are susceptible to galling. Galling can occur between bolts and nuts and sometimes prevents removing the nut and bolts without damaging the threads. Galling can be prevented by specifying a hardness difference of 10 (Brinell Hardness) for the bolt and nut material. Alternatively an antiseizing compound can be applied to the parts.

Resistance to Fatigue

References

58. Appendix K of AISC (1989) discusses the design of connections for fatigue considerations.

General

59. Fatigue is defined as the progressive localized permanent structural change that occurs in a material subjected to repeated or fluctuating strains at nominal stresses having maximum values much less than the tensile strength of the material. Fatigue may result in cracks or failure after a sufficient number of fluctuations. The process of fatigue consists of three stages:

a. Initial fatigue damage leading to crack initiation.

b. Crack propagation to critical size at which the remaining section becomes unable to carry the imposed loads.

c. Sudden failure of the cross section.

Prevention of fatigue failure

60. Material selection does not drastically affect fatigue life, although there is a slight increase in fatigue resistance with increased yield strength. However, fatigue failure can be considerably reduced by careful attention to design details and manufacturing processes. The most effective and economical methods of improving fatigue strength consist of the following:

a. Eliminating stress risers by streamlining parts.

b. Avoiding sharp surface tears resulting from punching, stamping, and shearing.

c. Preventing surface discontinuities during processing or heat treatment.

d. Improving the details of fabrication and fastening procedures.

Cost

General

61. The cost of material is generally not the largest part of the total cost of a component. However, cost differences can be used to evaluate different materials which are all suitable for use in the component being designed.

Reduction in maintenance costs

62. The selection of the proper material can reduce maintenance costs by eliminating or minimizing corrosion.

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PART III: MINIMUM SECTION

Introduction

63. In order to produce an efficient, economical design for a steel structure, efforts should be made in the design process to minimize the size of steel members. Thickness of steel sections (such as plates) or parts of steel sections (e.g., the web or flanges of steel beams) are based primarily on strength requirements, although other factors influence the selection of a material thickness. These factors may include allowances for corrosion, damage, severity of exposure, and fabrication and erection.

64. In general, good structural design is usually associated with economical structural design. For this reason, minimizing the amount of structural steel during the design process is of major concern to the design engineer. Contract documents almost always contain weights of major steel structures (e.g., gate and hoist drawings show total weight of gates for proper sizing of operating equipment), and contractors use this as a major factor in preparing the bid price for those items.

Design Criteria

65. General design procedure is to size steel members on the basis of strength and stability requirements and then to add allowances for other requirements as deemed applicable by the design engineer. In the case of hydraulic gates, appropriate Corps guidance (see references) details design procedures and criteria for specific structures.

66. In some applications, Corps criteria establish a minimum thickness for members even though structural analysis would permit a lesser value. Part of the reason for setting minimum thicknesses for the flanges and webs of beams is to offset a loss of section due to corrosion that might lead to a change in member designation (i.e., from a compact to a noncompact section). This in turn might introduce buckling problems for unstiffened elements. A minimum thickness specified by Corps criteria for plates is generally aimed at preventing perforation due to pitting corrosion and avoiding problems with welding thin metals. These minimum thicknesses vary between structures and applications. Appropriate engineer manuals (EM's) should be consulted prior to design.

Design Procedure

67. Design of steel structures is rarely a closed form procedure which yields an optimal design. In most cases, the design engineer will execute the following three-step design process to arrive at a solution based on strength requirements.

Conceptualization of structure and layout of members

68. The design engineer begins by developing a framework of primary and secondary structural members, determining joint fixity, and defining load combinations.

Analysis of structure

69. The structure, as developed above, is then analyzed using an appropriate method of analysis. Forces on individual members are identified.

Sizing of members

70. Member sizes are then selected based on specifications of the AISC Manual and allowable stresses specified in EM 1110-2-2105 (Headquarters, Department of the Army 1993). From the computed forces (i.e., shears, moments, axial, torsional, or combinations of these) members are selected which meet adequate section requirements.

71. The design engineer may decide at this time to revise the framing layout and reanalyze the structure in order to either minimize the amount of steel required or to simplify fabrication.

Other Allowances

72. The procedure outlined in Paragraph 67 regards strength requirements only. Although strength is of primary concern when determining the minimum thickness of a member, other factors need to be considered which impact the thickness of members for permanent structures as discussed below. Temporary steel structures, such as temporary construction bracing or scaffolding, are usually exempt from these extra allowances due to their brief time in service.

Corrosion

73. In most cases, steel structures on civil works projects are protected from corrosion by an adequate coating system. Periodic maintenance on a regular basis ensures its continued integrity. Design of structures should

include the addition of features (e.g. bulkheads, needle beams, removable gate assemblies) that will facilitate periodic maintenance.

74. The use of an applied coating system should be used whenever possible; however, in some (rare) circumstances, application of a coating to a steel structure or periodic maintenance will not be possible. Increasing the thickness of unprotected steel members as a design approach to account for expected corrosion should be used with caution as corrosion of normal grade steel does not develop in a uniform fashion and cannot be expected to terminate at a predetermined depth. In these instances where corrosion will be unavoidable, the design engineer may specify weathering steel (conforming to ASTM A 588) in lieu of normal grade steel. These special grade steels form a tightly adherent oxide on the surface when exposed to the atmosphere to prevent further corrosion with a negligible loss in member section. However, strict adherence to industry guidelines must be observed in the use of these materials. Cases have been documented (Nickerson 1990) where improper use of weathering steel has resulted in similar or even greater corrosion rates than what would have been obtained through the use of painted, normal grade steel.

Damage

75. Steel structures are often exposed to potential damage from vessel contact and mechanical wear. A loss of section, deformation, or cracking may result in steel members that cannot adequately resist these loads. Steel structures exposed to potential vessel contact should be analyzed to resist appropriate impact forces. Steel sections are frequently increased in expectation of wear. Engineer manuals address this condition, where appropriate. One such example is spillway tainter gates where the hoist cable contacts the skin plate. EM 1110-2-2702 (Headquarters, Department of the Army 1966) specifies that the skin plate thickness in this area be increased to compensate for this bearing force. While the magnitude of these external forces are sometimes difficult to compute, the design engineer should recognize their presence and make appropriate increases to member thicknesses.

Severity of exposure

76. Steel structures on civil works projects are oftentimes exposed to adverse weather conditions. Ice loading on gates is a common occurrence in northern climates. Most EM's (see EM 1110-2-2701 (1962), EM 1110-2-2702 (1966), and EM 1110-2-2703 (1984)) address the need to analyze structures under special loading conditions as these.

Fabrication and erection

77. In addition to analyzing steel structures for in-service load cases, the design engineer must also investigate the stability and condition of the structure during fabrication, transportation, erection, and servicing. Gates, for example, are fabricated while in several different positions other than the final vertical position. Handling during and after fabrication can often introduce residual stress in the members. Provisions of the fabrication plan and shop drawings should be reviewed by the design engineer for consistency with member design. Members to be galvanized should have adequate section prior to the galvanization process.

Stiffness

78. Not only are steel members required to have adequate section properties to meet strength requirements, they must also provide enough stiffness to prevent excessive deflections which would interfere with the normal operation of the structure. Torsional deflection of miter gate leafs influences the design of the diagonals; stiffness of the members plays a major role in this analysis (EM 1110-2-2703). For this reason, the design engineer must be concerned with other requirements for increased stiffness in addition to strength.

Shape Availability

79. There are two factors concerning shape availability which the design engineer must recognize when designing to minimize member thickness.

Steel mills produce shapes with established sections

80. A shape which exactly meets the requirements of the structural analysis may not be available; rather, the design engineer may be constrained to select a shape which best meets the requirements by using a built-up section to enhance the sectional properties of a smaller member, or by fabricating a specific section from plate elements or other shapes.

Fabricators may have a limited inventory of steel shapes

81. Most fabricators will have the most commonly used sections on hand, but not all which are indicated as available in the AISC Manual (1989). The design engineer should consult with cost engineers and fabricators in the immediate area of the project site to determine shape availability.

Specifying shapes which provide a minimum amount of weight but are unavailable may not be the most cost effective if they have to be ordered and shipped in lieu of using adequate sections already available.

Fabrication Costs

82. Discretion should be exercised by the design engineer when attempting to optimize the design of a steel structure by using a large variety of different member thicknesses (e.g., fabricating a beam with a compression flange that has been thickened in the vicinity of a maximum moment with thinner flanges in other areas). The savings recognized by a decrease in material could be offset by an increase in fabrication costs.

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PART IV: DESIGN OF PLATE ELEMENTS

Introduction

83. Plate elements are used in a variety of situations on Corps structures. The most common uses are skin plates for hydraulic gates (tainter, vertical lift, and miter) and flange stiffeners. Plate elements act as part of primary load resisting members and as secondary, load transfer members. Analysis of plate elements, in most cases, cannot be performed using conventional beam theory. Finite element analysis or plate theory is necessary in order to accurately analyze the state of stress under design loading. Application of plate theory is usually selected over finite element analysis due to lower costs. Although plate theory is a relatively more complex subject than beam theory (American Association of State Highway and Transportation Officials 1989), charts and monographs have been developed which simplify the analysis process (Paragraph 87). Part IV covers procedures for the design of plate elements on the basis of stress only. Other considerations may impact the final design section dimensions and properties.

Uses of Plate Elements

84. As mentioned in Paragraph 83, skin plates on hydraulic gates and some flange stiffeners are members which need to be treated as plate elements. When used as skin plates, plate elements act compositely with girder flanges. Bending stresses are generally the most critical stresses on skin plates, and stiffeners are subjected to a combination of forces (axial and/or bending) which may necessitate the investigation of buckling possibilities. Shear stresses can also be critical in the webs of some members as in the top girder of miter gates.

Design Criteria

85. Design of steel plate elements for use as skin plates on gate structures is governed by Corps guidance (para. 2-1.c, of EM 1110-2-2703 (1984)). Allowable stresses are defined in EM 1110-2-2105 (Headquarters, Department of the Army 1993).

86. Design of stiffeners is usually not as involved or complicated as the design of skin plates. Stiffener design is covered in AISC (1989) and American Association of State Highway and Transportation Officials (1989).

Analysis of Stresses

87. Proper design of a plate element requires a realistic determination of the state of stress in the element using plate theory. Complex plate theory, as documented in "Theory of Plates and Shells" by Timoshenko (1940), has been simplified to a point where the design engineer can withdraw necessary formulae frcm derived tables. Common configurations of plate elements in regards to shape, size, fixity, and loading combinations are documented in "Theory of Plates and Shells" (Timoshenko 1940) and "Formulas for Stress and Stain" (Roark and Young 1975).

Design of Skin Plates

88. When skin plates are used in gate structures, they are fastened to a framing of hcrizontal and vertical members with continuous welds as shown in Figure 1. The reason for using continuous welds is based partly on strength requirements but mostly to form an impenetrable barrier to moisture. Continuous welding will inhibit corrosion from forming between the framing member and the skin plate and improve fatigue behavior. At the same time, continuous welding of the skin plate to flanges of beams or girders creates a biaxial bending condition on the edges of fixed plate elements as discussed below.

Skin plate stresses

89. Examining the case of a skin plate, continuously welded to a framework of horizontal and vertical members, as shown in Figure 1 and 2, the plate must be designed to withstand the stresses listed below.

90. Skin plate action as an effective part of the girder flange. Because of the continuous, welded connection, the skin plate is an effective part of the compression flange of the girder. The effective width is specified in section B5.1.c of the AISC Manual and is shown graphically in Figure 3. Compressive stresses are developed across the effective width of the skin plate from two possible sources.

a. Bending of the girder.

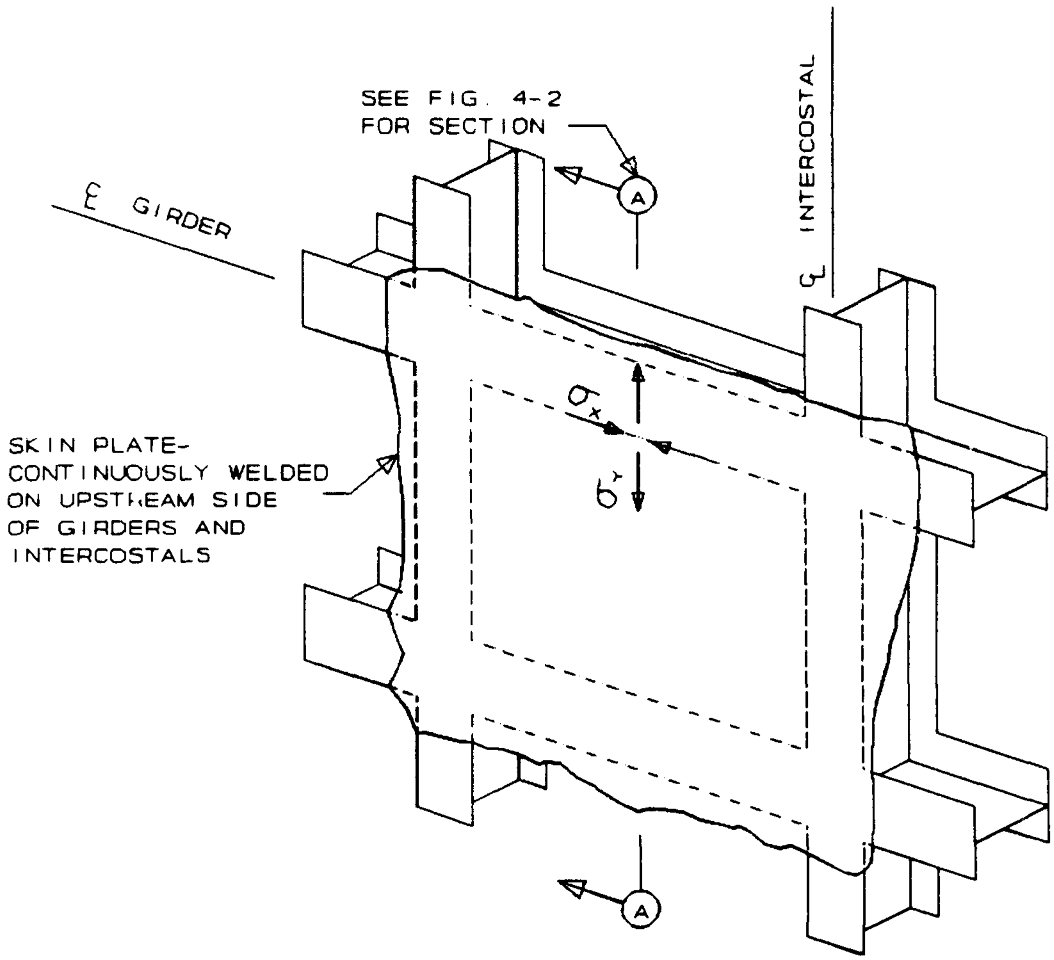

Figure 1. Biaxial stresses at midpoint of horizontal girder

b. Axial (compressive) forces transmitted along the girder and effective width of the skin plate.

91. The combination of these stresses produce a horizontal stress, shown in Figure 1 as σ_X.

92. Direct skin plate bending. Rectangular skin plate panels are analyzed as plate elements fixed on all four sides. Paragraph 2-1.c.1 of EM 1110-2703 defines the locations of fixity to be assumed in reference to the girders and intercostals. Hydrostatic loading on the panel is in the form of a uniformly varying load which increases with depth. For analysis reasons, the load can be simplified by assuming a uniform load with a value equal to the hydrostatic pressure at midheight of the panel. Timoshenko (1940) tabulates values for the moments at the center of the edges and the center of the

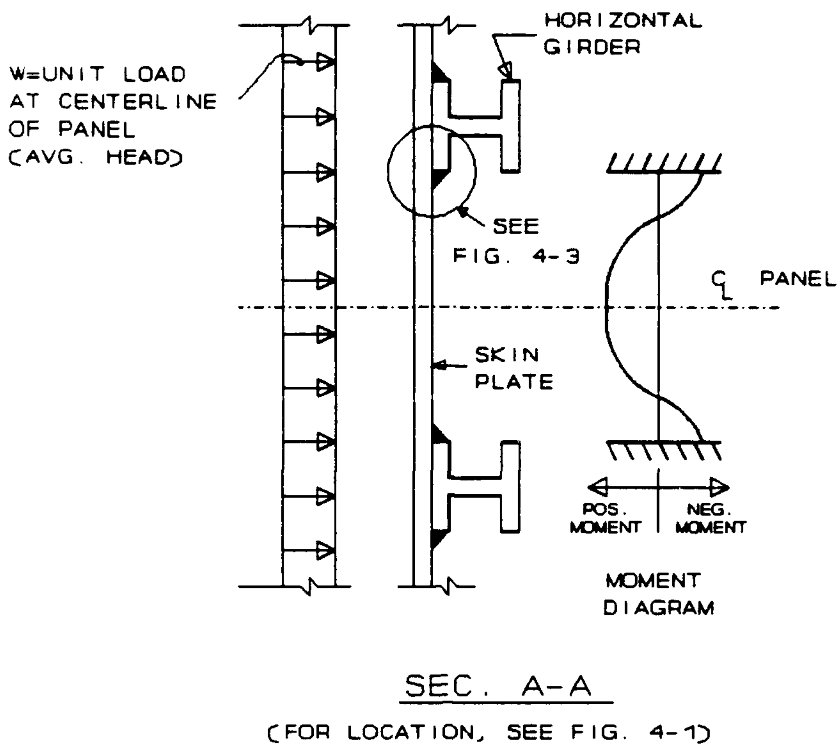

Figure 2. Bending moments along vertical section at center of panel

panel due to a uniform loading condition for panel shapes of different aspect ratios. Dividing these moment values by the section modulus for a unit width of the plate ($t^2/6$) yields the bending stress at these locations. However, the problem with using tabulated values is that results can only be obtained for certain aspect ratios. Equations have been developed to calculate the bending stress at the midpoints of the edges of panels for any combination of panel width and height. These equations are documented in paragraph 2-1.c.1 of EM 1110-2-2703, and they provide the bending stress at the center of the long and short edges of the panel.

93. Depending on the panel orientation in regards to the long and short edges, the appropriate stress is obtained at the horizontal girder. This is shown in Figure 1 as σ_Y. Figure 3 illustrates the stress condition in the plate due to the bending stress, σ_Y. At the edge of the girder flange, where the biaxial stress condition exists, tension is produced on the upstream face of the plate, and compression is produced in the plate next to the girder flange. This is due to the negative moment developed at the edge (see moment

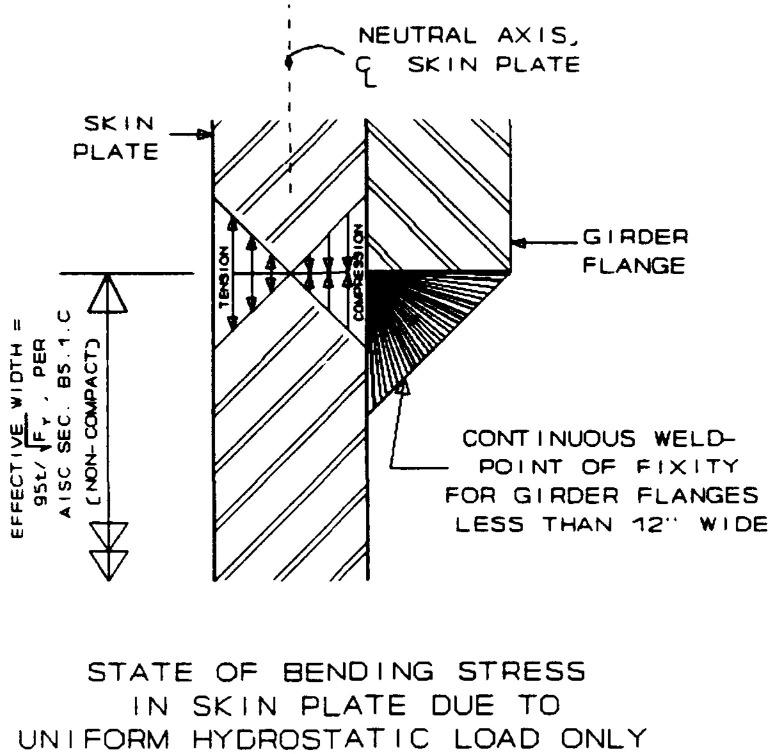

Figure 3. Stresses due to bending in skin plate at edge of girder

diagram, Figure 2). Sign convention is important; while the magnitude of the bending stress and tensile stress is equal to σ_Y, tensile stresses are the most critical in this condition when σ_X is a compressive stress.

Combined stress (Huber-Mises equation)

94. After obtaining the biaxial stresses σ_X and σ_Y, the combined stress σ_C is obtained from the Huber-Mises (or von Mises) yield equation

$$\sigma_c^2 = \sigma_X^2 - \sigma_X\sigma_Y + \sigma_y^2 \tag{1}$$

95. The combined stress, σ_C, must be less than $0.75F_Y$, where F_Y is the yield strength of the steel. The Huber-Mises equation is of the form of an ellipse and represents a failure envelope. Combined stress values falling within the ellipse indicate the material is behaving elastically. Combined stress values falling on the ellipse indicate a stress condition where the

steel is yielding. Figure 4 is a plot of the Huber-Mises yield criterion reduced by a factor of safety.

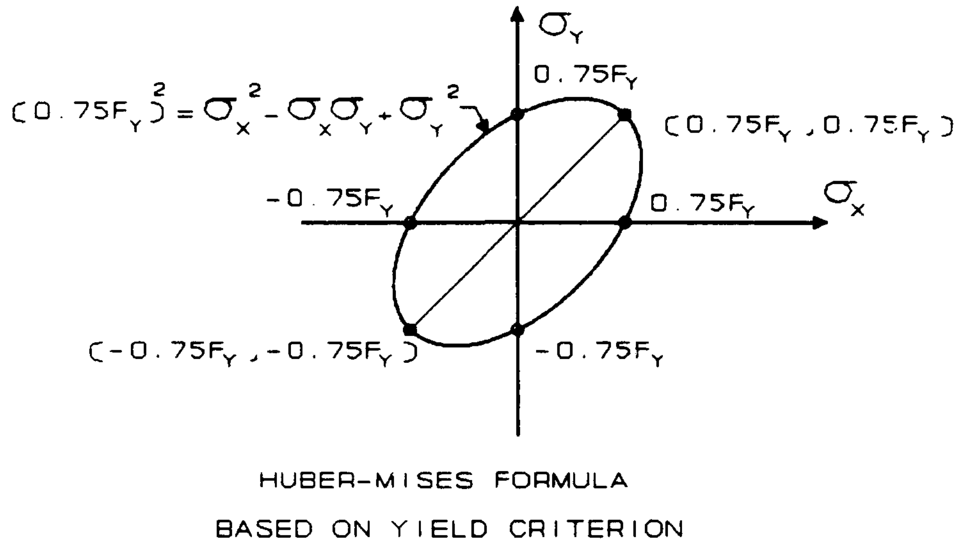

Figure 4. Huber-Mises combined stress failure envelope

96. As discussed, when σ_X is a compressive (positive) stress, the most critical state of stress for σ_Y is tension (negative). This can be seen in Figure 4 in the Huber-Mises ellipse where the failure envelope can accommodate a higher compressive stress value for σ_Y when σ_X is compressive. The design procedure presented below is appropriate for design of skin plates subject to a biaxial stress condition (combination of σ_x and σ_y). However, in the LRFD method for miter gates (EM 1110-2-2105), additional design criteria including serviceability deflection limits and consideration of fatigue are specified. With these additional criteria, and since minor local yielding will not inhibit the ability of the skin plate to form a damming surface, EM 1110-2-2105 requires consideration of only σ_y in the design of miter gate skin plates using the LRFD method.

Design procedure

97. Because of the biaxial stress condition developed in skin plates, arrival at a skin plate thickness is not a closed form solution. The design engineer must begin by assuming an initial thickness, computing the combined stress (σ_C), and verifying that it is less than $0.75F_Y$. Paragraph 89 discussed the condition that exists at the midpoint of the panel at the girder flange. In most cases, the most critical stress combination will occur at

that point. However, in order to perform a complete analysis, two other locations where biaxial stress conditions exist require examination.

Midpoint of the panel at the intercostal

98. This location is shown in Figure 5. The design engineer should verify through analysis as to the proper sign convention (tension or compression) of σ_Y.

99. Center of the panel. This condition, as shown in Figure 6, is one in which both stresses, σ_X and σ_Y, are produced by bending stresses in the plate only. Table 30 of "Theory of Plates and Shells" (Timoshenko 1940) provides values for the moments in both directions at the center of the panel. These stresses, due to bending of the skin plate only, are typically higher than the bending stresses produced at the edges.

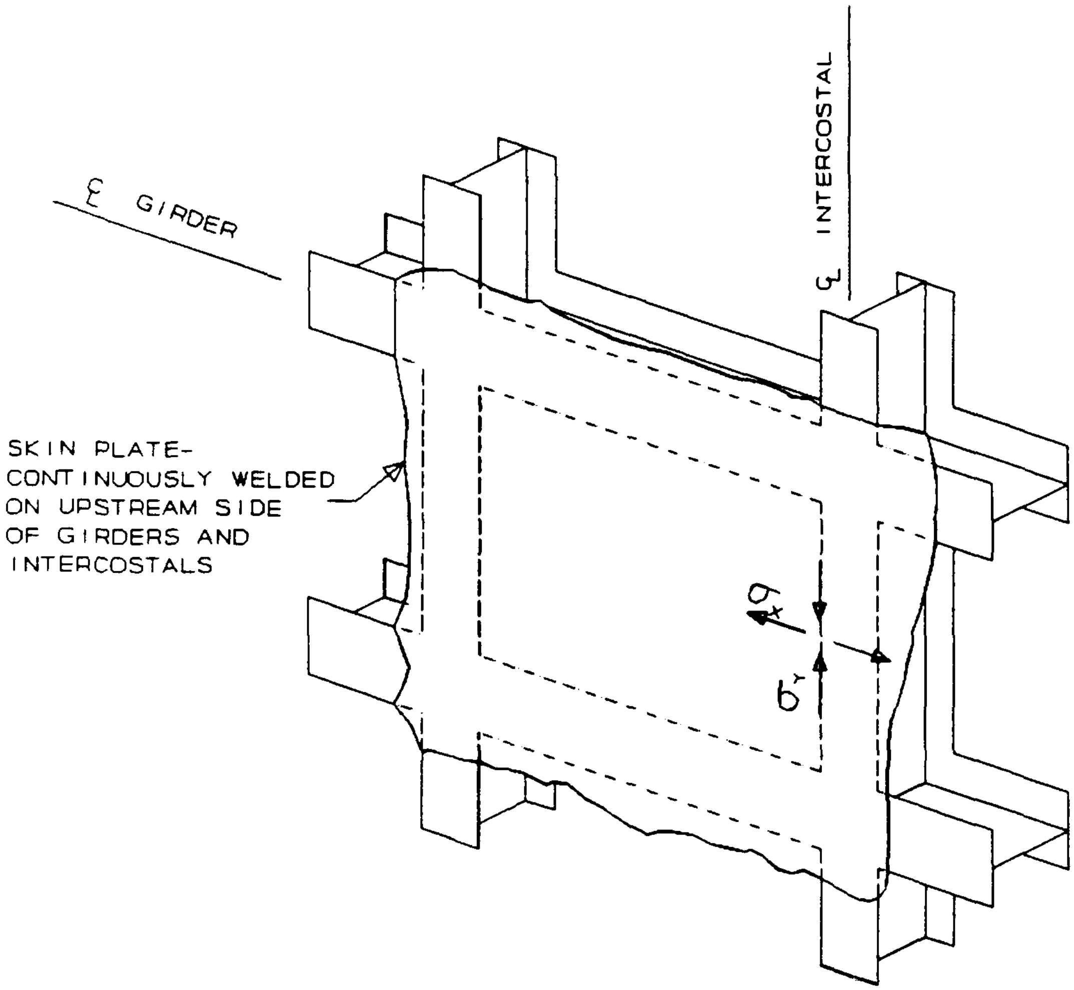

Figure 5. Biaxial stresses at midpoint of vertical intercostal

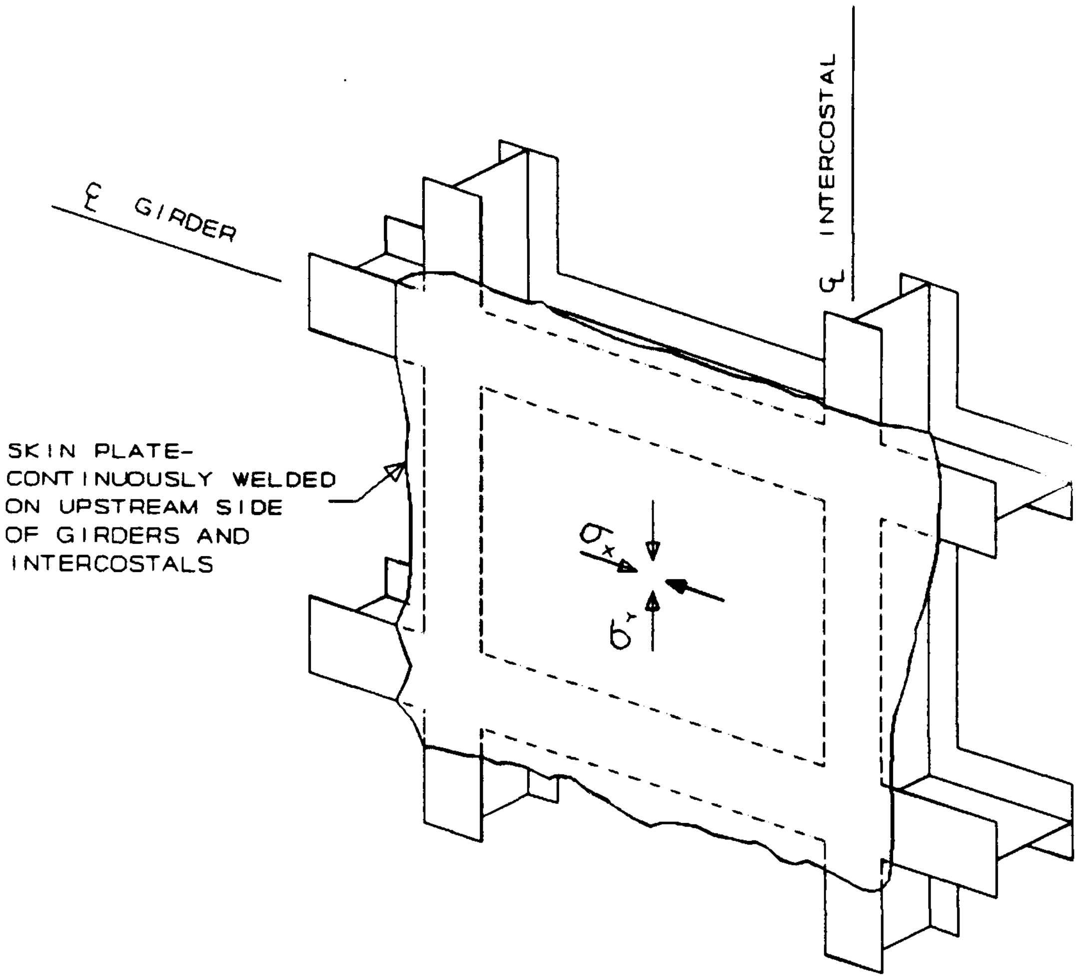

Figure 6. Biaxial stresses at center of skin plate panel

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PART V: CONNECTION DESIGN

Introduction

100. Structural design is often viewed as selection of members to resist applied loads, and connections between members sometimes receive only secondary attention. Yet, most structural failures occur because of inadequate connection design, not because of inadequate member size. The purpose of connections is to transfer forces between the connected members. The forces might consist of any combination of axial or shear loads and bending or torsional moments. Connections may also provide required stiffness to limit relative movement between members. There are numerous ways to satisfy these requirements.

101. Textbooks which address connection design for steel structures Blodgett (1966) do so for typical building construction. Even the AISC specification has "for buildings" in its title. Joints for building frames are usually shop welded and field bolted. Members are often at right angles, and connection types and details are fairly standard. Detailed design of building connections is often left to the fabricator. Connections are protected from the weather, and strength is the major design criteria. Connections in hydraulic structures, however, are subject to different conditions. Exposure may be to weather or to salt or fresh water. Flowing water may induce vibrations. Barge impact may severely stress the structure. Though many connection design principles are equally applicable to buildings and civil works structures, the above factors do lead to some unique requirements for the civil works structures.

102. This section includes brief discussions of some of the more important considerations in selecting connection types, and some of the potential pitfalls in connection design. Detailed design methods for connections are not within the scope of this section. Such detailed methods and additional discussion of many of the following topics are included in many textbooks. AISC (1984) is an especially useful book for connection design. Due to typical member sizes, types of connections, and loadings, many of the features of civil works steel structures have more in common with bridges or heavy mechanical elements than with building frames. Therefore, AASHTO may be a useful reference for some aspects of design as may various texts on machine design.

Stress Concentrations

103. Members of uniform cross section usually have uniform stress distribution. However, any notch, hole, bend, or joint will disrupt the uniform stress field and cause stress concentrations. A simple round hole in a uniform tension member will increase the local stress at the hole to three times the nominal average stress. Sharper discontinuities can produce much higher stress concentration factors.

104. Such stress concentrations are often ignored during design with no resulting decrease in load-carrying capacity. This is because most steels are ductile, thus able to redistribute localized high stresses to adjacent material. So, when should stress concentrations not be ignored?

105. High stress concentrations occur at sharp discontinuities, especially cracks, and at large changes in cross section, such as at points where cover plates terminate. They may also occur at welds where the backing bars have not been removed. For ductile materials even these higher concentrations may not lead to failure. Problems are most likely to occur when the steel material is high strength, brittle, or lacks toughness, or when cyclic loads or barge impact may cause crack initiation and growth. Unfortunately, high strength steel is usually more brittle or less tough. Note that the heat affected zone adjacent to welds or flame cuts is likely to combine low toughness, stress concentrations, and residual stresses. The reduction of toughness due to welds or flame cut heating is more pronounced in thick members.

106. Designers and field inspectors should always be aware of potential problems due to stress concentrations and should give special attention to any combination of sharp discontinuities with nonductile material or with cyclic loading. Low carbon steels such as ASTM A 36 are usually considered ductile, but even these may be nonductile for thicknesses greater than 1.5 in. Where such adverse conditions exist, the conditions should be modified or a fracture or fatigue analysis should be performed, and additional inspection may be necessary. Modifications may consist of smoothing the discontinuity, providing a tougher material, or reducing stresses by increasing the member size. Fracture analysis may be used to determine the size or type of defect which will be acceptable during the inspection program. Barsom and Rolfe (1987) include additional discussion and analysis methods for fracture and fatigue. American Welding Society (1992) shows recommended geometry to minimize stress concentrations at transitions between members of different thicknesses or

widths. One set of recommendations is for members subject to static loads, and another set is for dynamic loads.

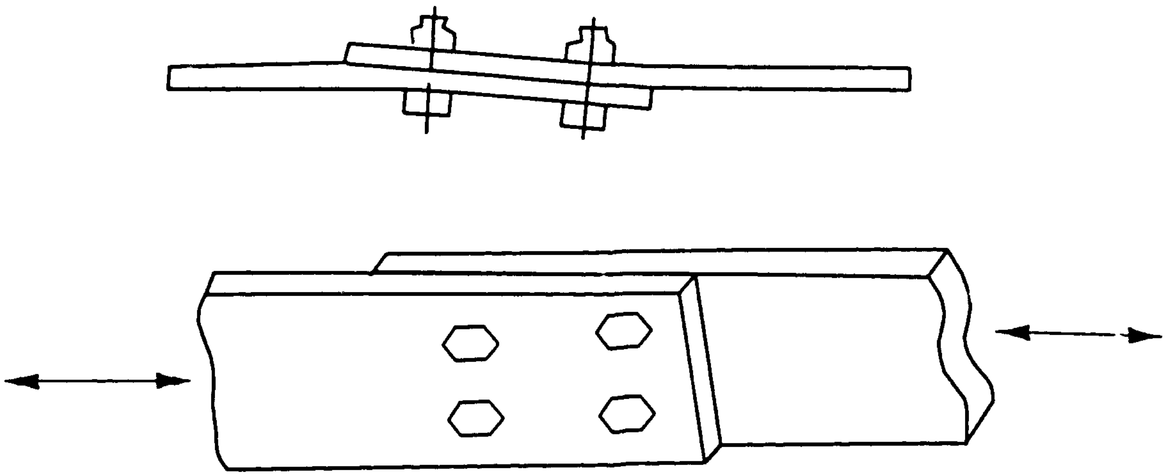
Eccentricity

107. Loads eccentric from member centroids cause bending moments. This concept is easily recognized and accommodated by all structural designers. Eccentricities at connections are not always as obvious and the effects may not be as clear. Connection eccentricities can significantly increase local stresses or individual fastener loads above the average stress or fastener load. Such local increases can cause fracture of critical elements in a connection if the elements are not ductile enough to permit redistribution of loads.

108. For bolted connections, eccentricities can be accounted for in the design by an ultimate strength method or by a vector analysis based on elastic theory. The elastic method is conservative but does not take advantage of fastener ductility and redistribution between fasteners. The ultimate strength method provides a more uniform safety factor with respect to the ultimate capacity of the fastener group, and is the method used for fastener group capacities as shown in the AISC Manual. The two design methods are illustrated in AISC (1984).

109. There is a similar choice between ultimate and elastic design methods for eccentrically loaded weld patterns. Historically, the elastic method has been used. However, several tables in the AISC Manual are based on ultimate test results but are limited to specific weld patterns and loading conditions. The elastic design method is shown in AISC (1984), and Tide (1980) explains some research and the analytical technique for an ultimate strength method.

110. For connection of single angles and similar members, the centroid of the connection pattern need not be aligned with the centroid of the member for static loads (see section J1.9 of AISC (1984)). Where the centroids of connected members do not all pass through a common point, the eccentricity will induce a moment at the joint (see Figure 7). This moment should be distributed among the connected members based on relative stiffness. In some cases, a properly designed eccentric connection is more economical and may perform better than a concentric connection which requires poorly shaped elements such as long gusset plates (see Glass 1990).



a. Tension splice

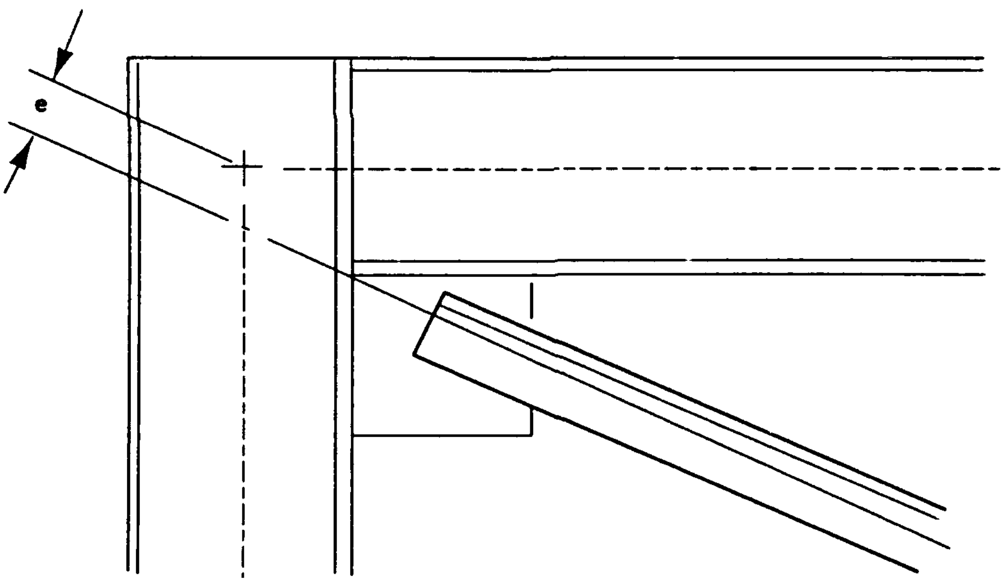


Figure 7. Eccentric connections

Imposed Restraints (Fixity)

111. There are two basic types of imposed restraints; resistance to expansion and contraction, and resistance to relative movement in connections. Usually, expansion/contraction restraints are not severe since magnitudes are small and many structures expand and contract as a unit, thus causing no internal stresses. Where expansion/contraction is significant, it is usually recognized and included in the design (e.g., using elastomeric bearings for bridges).

112. The other imposed restraint is for rotation. Designers often make the assumption that a connection is pinned, that it carries no moment, and that the connected elements are free to rotate relative to each other. This assumption removes a degree of indeterminance, thus simplifying the analysis. However, it is an idealized assumption that is more realistic for machinery design than for structural design. In real structures "pinned" connections may produce significant restraint to rotation between elements. For example, "seal welds" will effectively fix an assumed pin connection but may not provide the strength necessary to resist the imposed moment due to such fixity.

113. The difference between assumption and reality is that a moment will actually be transferred through the connection, but will be ignored in the analysis and design. For ductile connections this moment may not significantly reduce the ultimate safety of the connection, just as a moment does not reduce the shear capacity of a steel beam. Potential problems may arise when connected members could have large relative rotation, or when connection details are not ductile. This may cause very high stresses at any corners or notches, resulting in potential cracking. Designers should be cautious about using pinned assumptions for design of fully welded connections.

Bolted Versus Welded Joints

114. There is no universal rule governing selection of connection type or the relative economy of welded versus bolted joints. For buildings, steel connections made in the shop are often welded while those made in the field are usually bolted. Use of rivets has largely been replaced by high strength bolts due to the high labor costs and extreme noise associated with rivets. Therefore, skilled riveters may be difficult to find. The main reasons for

the use of field bolting are the simplicity of bolting and the relative difficulty of field inspection of welds, compared to verification of adequate bolt installation.

115. Bolted connections are much less common on hydraulic structures than on buildings or bridges. However, experience with older structures with riveted joints has been satisfactory; specifically, corrosion has not occurred within the joints even though rivets themselves may have corroded. On new designs, substitution of tightly bolted joints for riveted joints should produce acceptable performance, providing that the bolt itself is protected from corrosion. During rehabilitation of several older projects, replacement of existing rivets with high strength bolts has produced acceptable results to date, but the existing members must be protected from damage during removal of the rivets.

116. Thick plates (over 1.5 in.) and jumbo rolled shapes often exhibit low toughness away from the rolled surfaces. (The importance of toughness is discussed later in the report.) Welding operations can superimpose stress concentrations and high residual stresses on these low toughness areas, thus increasing the chance for crack initiation. Therefore, connections for such members should be bolted rather than welded, or the welded connections should be very carefully designed and detailed.

Welded Joints

117. PART VI contains a more detailed discussion of welding considerations. One of the sections which may be of special importance for welded joints is that on imposed restraints. The welding process itself leads to internal restraints during the heating and cooling of the welded parts. This may be aggravated by external restraints on the connected members. Such restraints may produce high residual stresses at locations of stress concentration which may contribute to cracking in brittle materials. The designer should be aware of this potential problem when configuring the connections. Figures 8.2 and 9.4 from American Welding Society (1992) require fillet welds to be interrupted at corners of certain joints, and certain other weld geometry requirements are included. Welding process design can also help minimize residual stresses.

118. Another potential problem in welded joints is lamellar tearing. The rolling process causes flattening and spreading of the grain structure and

any imperfections, thus producing lower strength and ductility in the through-thickness direction. This effect is usually significant for thicknesses greater than 1.5 in., and if necessary, the production process can be modified to reduce this weakening effect. Residual stresses due to weld shrinkage during cooling can cause separation between the grain layers. This separation can also be caused by externally applied forces which produce through-thickness tension. The potential for lamellar tearing can be reduced by joint detailing to minimize through-thickness tension or by use of improved welding design. Additional information on lamellar tearing is included in AISC (1984) and Building Structural Design Handbook (White and Salman 1987) and in many other reference.

119. There is another common way that weld configuration can be used to minimize potential problems. It is safer to load welds in longitudinal shear rather than in transverse shear or tension. This helps control stress concentrations, and orients tensile stresses away from probable crack opening directions.

120. Connection details on hydraulic structures often consist of full penetration welds or large continuous fillet welds. Such welds usually provide much greater strength than necessary. The reasons for using such welds seem to be a desire for water-tight joints, concern for corrosion within the joint, and the simplicity of design when large amounts of weld are provided. However, such extensive welding is expensive and may cause higher shrinkage stresses or greater imposed constraints. Partial penetration welds or intermittent fillet welds may be better choices for joints where the resulting stress concentrations will not cause problems. Intermittent welds may be appropriate where corrosion conditions are not critical, (e.g., bulkheads stored on land), however, they can decrease fatigue life. American Welding Society (1992) requires continuous fillet welds along the length of cover plates for dynamically loaded members.

Bolted Joints

121. Sources of information for bolted joints are AISC (1984), Guide to Design Criteria for Bolted and Riveted Joints (1987), and American Society for Civil Engineers (ASCE) (1985). The latter specification includes requirements for bolt tightening. These requirements depend on whether the joint is "slip critical." Most bolts in nonslip critical joints need only be snug tight.

Full tightening is required for cyclic loads, bolts in oversize holes, and certain other conditions. The effects of coatings on slip resistance are significant. For slip critical joints one should avoid the use of organic zinc-rich paints; hot-dip galvanized surfaces must be roughened by hand wire brushing; metalizing, vinyl coatings, or zinc-silicate paint should be acceptable. For hydraulic structures, tightened bolts may also be necessary to improve water tightness or corrosion resistance of the joint. The designer must clearly indicate which bolts require full tightening.

Prying is a potential cause of bolt failure. It can cause much higher loads than expected for a given bolt. Prying can lift one side of the nut or head, causing high stresses due to increased tension and bolt bending. Prying can be eliminated by using bolts in shear rather than in tension, or it can be reduced by adjusting the joint configuration. Additional discussion of prying is discussed by Kulak, Fisher, and Struik (1987) and in Section 4 of AISC (1984).

122. Bolts are more susceptible to brittle fractures when the bolt material has high hardness and strength. For typical hydraulic structures A325 bolts should perform acceptably, whether galvanized or uncoated. Uncoated A490 bolts should also perform acceptably; however, use of galvanized A490 bolts should be avoided due to the possibility of hydrogen stress cracking (see Kulak, Fisher, and Struik 1987).

Connection Design Responsibility

123. Responsibility for design of connections has been debated within and among the design, construction, and legal professions for a long time. This question comes to the fore especially after highly publicized failures such as the walkway collapse at the Hyatt Regency Hotel in Kansas City. As yet, there is no universal, clear definition of levels of responsibility, though several organizations are currently trying to resolve this issue.

124. A common practice in building construction is to leave design of simple connection details for the steel fabricator. When this is done the designer must clearly define connection requirements to the fabricator. There is always a potential for incomplete understanding between the structural designer and the connection detailer.

125. In design of Corps hydraulic structures, steel connections should be fully detailed by the design engineer, though some noncritical connections

may be left to the fabricator to detail. Even for fully detailed connections, there are additional decisions required of the fabricator. For example, weld process selection and edge preparation are usually left to the fabricator. For welded connections the size and length of the weld must be shown and the type and extent of required inspection should be stated. The weld inspection requirements should be thought through by the designer and should be defined on the drawings and in the specifications. The designer should also review the weld processes and shop drawings. Similar review by the designer is required for bolted connections. The contract submittal register should include all documents needed for such review.

Fatigue and Fracture

126. The subject of fatigue and fracture can be complex, and detailed analyses require specialized knowledge. However, design engineers should be aware of the basic concepts to be able to minimize potential problems. An excellent source of detailed information on metal fatigue and fracture is by Barsom and Rolfe (1987).

127. Fatigue is the term for formation and growth of a crack due to repeated fluctuating loads. Fatigue behavior is governed mainly by stress range, number of load cycles, and specific local details which cause stress concentrations. In general, material yield stress or ultimate strength properties have minor effects on fatigue life. Fatigue life can be extended mainly by using fatigue resistant details and by keeping the stress range low. Appendix K of AISC (1989) should be used to select proper details and determine the allowable fatigue stress range.

128. Certain materials in specific environments can exhibit significantly reduced life due to corrosion fatigue. Simply operating in water (especially salt water) rather than air can greatly reduce the fatigue life of many metals, though this effect is more pronounced for higher numbers of load cycles. Corrosion-fatigue life can be extended by various coatings and by cathodic protection. More information on corrosion fatigue is given by Barson and Rolfe (1987) and Gilbert (1956).

129. Fatigue life consists of crack initiation and crack propagation (growth) periods. Usually the expected life to crack initiation is long, and the life during crack propagation is short. As the stress range increases, initiation life becomes smaller in relation to propagation life. Severe

overloads can even initiate cracks during a single loading cycle, thus eliminating a major part of the expected life of a structure. An example of this might be a barge impact on a gate, which causes a small crack at some stress concentration point. Subsequent load cycles may then cause the crack to grow quickly, causing premature failure of the component.

130. Fracture is the sudden growth of a crack (referred to as unstable propagation within the fracture mechanics field), usually causing failure of a component. Fracture behavior is governed mainly by nominal stress level, geometry of existing crack or discontinuity, and material toughness. Toughness is the ability of a material to resist crack propagation, to absorb energy without rupturing. Toughness is a measure of resistance to sudden fracture, not resistance to fatigue cracking. In fracture mechanics this property may be refined to a consideration of "notch toughness" since fractures usually occur at locations of extreme stress concentrations such as at crack tips.

131. Toughness is a measurable property and the required toughness should be part of a material specification when necessary. The expected service temperature for a structure can be a critical factor in determining toughness requirements since many steels exhibit a transition from ductile to brittle failure at common ambient temperatures. The potential for brittle failures should always be minimized.

132. Toughness of a steel can be modified by heat treatments. The heat input due to welding can reduce toughness properties in the heat affected zone (HAZ). The HAZ is the area of unmelted parent material adjacent to the weld which is sufficiently heated by the welding so that its material properties are affected. This area may be of special importance in thick members since these usually have lower initial toughness and are subject to greater heat input during welding. Unfortunately, stress concentrations often overlap the HAZ of welds, thus combining the bad effects of high stress and low toughness. This is a probable location for crack initiation and ultimate fracture. Additional information on stress concentrations was discussed earlier.

Field Splices

133. Large steel structures are often delivered to a construction site in pieces because of size restrictions during shipping. Field splicing is then necessary to form the completed structure. Sometimes large structures are completely assembled in the shop to check alignment tolerances; they are then match marked, disassembled for shipping, and reassembled in the field. Usually, complicated field connections should be held to a minimum because of the greater efficiency and quality control available in the fabrication shop. When field splices are unavoidable, there are several considerations which may improve the quality of the completed structure.

134. Field quality control is easier for bolted rather than welded connections. Inspections of bolted connections may be simpler. However, requirements for strength, stiffness, or water tightness may lead to selection of a welded field splice. Splice locations are important, they should be located in areas of simple, uncongested geometry and in areas of low or moderate stress. If possible, splices should be staggered to avoid a continuous weakened plane. When splice locations are critical, they should be shown on the drawings. Just as for other connections, either splice details or design forces must be shown on the drawings.

135. Before determining the need for splices or splice locations, the designer should investigate any size or weight limitations imposed by transportation methods. Such limits on road, rail, or water transport can be found in applicable transportation codes and standards, but these may vary regionally.

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PART VI: WELDING

Introduction

136. The use of welds for the assembly of a member and for connections between members is common in the fabrication and erection of civil work steel structures. A welded built up member is designed to resist the external forces acting on the weldment with the type of welds used to form the desired shape selected for the proper transfer of the internal stresses between the various components. Providing the proper welded connections in the assembly of the component parts is an integral part in obtaining a safe and economical structure. Design guidance on welding is given in steel design textbooks by Blodgett (1966) and Cary (1979), ASSHTO standard specifications, and ANSI/AWS codes, and guidance on loads and allowable stresses applicable to a specific structure or type of structure can be obtained from the appropriate engineering manuals, engineering technical letters, and AISC manuals (see references at the end of PART I).

137. Improper and inadequate welding or weld detailing can lead to failure and very expensive repairs and substantial cost to industry when a civil works structure such as a lock is either restricted or closed to traffic. Weld failures can be avoided or minimized when proper attention to all of the critical features are considered in the weld design.

138. The design of each weldment and connection should consider the proper, efficient, and economical use of both the base metal and weld material. After a designer chooses the base metal based on strength or other properties, the type of weld best suited for the transfer of the stresses within the total assembly should be selected.

139. This section addresses the selection of the weld type, size and detail, welding procedure and process, nondestructive examination of critical welds, and touch on other items such as the metallurgical considerations and effects of heat. Fabrication and nondestructive testing (NDT) are covered in PARTS VII and VIII, respectively.

General

140. The basic design principals and methods for the design of weldments and connections are adequately covered in steel design and welding

design books (Blodgett 1966), and will not be included in this section. The design and detailing of welded connections can be accomplished by following guidance provided in AISC ASD and LRFD Manuals of Steel Construction.

141. The extent of welding required should be clearly shown on the shop drawings. Complete information about location, type, size, and extent of all welds and nondestructive testing should be shown or noted on the shop drawings. Symbols for welding and nondestructive examination shall conform to the latest edition of ANSI/AWS A2.4-86 (ANSI/ANS 1986).

142. A report on computer programs evaluated by the CASE Steel Structures Task Group which could be useful aids in the design of weldments on civil works projects will be made available for field office use.

Weld Type

143. The common types of welds used in civil work structures are the fillet, plug or slot, and groove. The primary usages of the various types of welds are fillet weld to transfer shear and moment, the plug or slot weld to transfer shear, and the groove weld to transfer tension, shear, and moment. The designer should carefully review the functional aspect of the weld application and determine the type of weld best suited for the joint or connection. The horizontal shear transfer in a beam between the web and flange plates is suitably accomplished with fillet welds while splicing of girder flanges is best accomplished with a groove weld.

144. The selection of the type of groove weld, either full or partial penetration, should be based on the finished joint being adequate to provide for the transfer of stress. ANSI/AWS D1.1-92 (1992) contains guidance on the use of fillet welds to reinforce groove welds in corner and T-joints for statically and dynamically loaded structures. In either load case, the maximum size of fillet weld reinforcement is limited to 3/8 in. A partial joint penetration groove weld shall not be used where design criteria indicate cyclic loading could produce fatigue failure or would be subjected to tension normal to its longitudinal axis. When appropriate, the use of a partial joint penetration groove weld is recommended. Weld and joint selection should try to minimize distortion, reduce heat input, keep the heat effected zone small, and eliminate the need for special provisions (i.e. preheat and postheat).

Weld Size

145. The effective weld areas, lengths, and throats to be used by the designer are defined in ANSI/AWS D1.1-92 (1992). Design and code requirements should be followed when designating weld size. The selection of the size of the weld should be determined after considering strength requirements, joint details, and parts to be joined.

146. A recommended minimum size of fillet weld is based on plate thicknesses as per code (i.e., Table 2.2 of ANSI/AWS D1.1-92). The fillet weld size in the table is theoretical and was determined based on providing a sufficient weld heat input to the plate to give a desired rate of cooling. The use of a fillet weld size too small for plate thickness size could lead to cracking during cooling. Seal welds, when considered necessary, must be sized based on adjoining parts.

147. Full penetration groove welds are used when development of the full strength of the member is required. When two members of different thicknesses are joined, the smaller member will determine the weld size. Requirements for transition of thickness and widths in butt joints are contained in D1.1-90, Chapters 8 and 9. Partial penetration welds are allowed and should be used when development of the full strength of the member is not required. Some typical applications for partial penetration welds are field splices in columns and built-up boxed members. For minimum size of partial joint penetration groove welds, see Table 2.3 of ANSI/AWS D1-1-92 (1992). For prequalified full and partial penetration groove welds, see Chapter 2, Figures 2.4 and 2.5 of ANSI/AWS D1.1-92.

148. Distortion control requirements due to welding, metallurgical changes due to large weld deposits and heat input, and the economy of the joint should always be considered when selecting the type of groove weld. In selecting the groove weld joint detail, one should consider using the shape which will require the least amount of weld material whenever practical. J and U welds may be more economical than V and bevel welds in many applications. In either case, a welding sequence which limits severe one-sided distortion may be necessary on some weldments in order to obtain the straightness requirement given in various Corps of Engineers (CE) civil works guide specifications.

Weld Details

149. Weld details are covered at length in ANSI/AWS D1.1-92, Part C (ANSI/AWS 1992). These include joint qualification and details of fillet, plug and slot, and full and partial penetration groove welds. The use of a backing bar on one sided groove welding is required whenever back gouging of the root pass is not obtainable. Without this provision the structural welding code considers this to be a partial penetration groove weld due to the uncertainty of the competency of the root pass.

150. The ANSI/AWS standard weld symbols should be used on the shop drawings to convey the intent of the designer for the assembly of the weldment. For groove welds, the drawings must show by proper symbol designation whether a complete or partial penetration is required.

151. Complete detailing of the groove weld joint, such as angle, root opening and land, is usually left to the fabricator. The welding provisions of the specifications should require submittal of these details for review and approval. This will enable the fabricator the latitude to select the weld processes and weld procedures suitable to his plant's operation and capability.

Welding Procedures and Processes

152. Joint welding procedures used in civil work structures' assemblies shall either be prequalified or qualified by test. All prequalified joint welding procedures to be used shall be prepared by the manufacturer, fabricator, or contractor as a written prequalified welding procedure specification, and shall be submitted for review and approval. Details for prequalified joints for fillet welds, complete joint penetration groove welds, and partial joint penetration groove welds can be found in ANSI/AWS D1.1-92, Table 2.2 and Figures 2.4 and 2.5, respectively. Qualification requirements for welds requiring qualification by test can be found in ANSI/AWS D1.1-92, Section 5.

153. Welding procedures which conform in all respects to the provisions of ANSI/AWS D1.1-92, Section 2, Design of Welded Connections, Section 3, Workmanship, and Section 4, Technique, are considered prequalified. Changes in the amperage (wire feed speed), voltage, travel speed, or shielding gas flow rate, beyond those specified on the welding procedure specification, are

considered essential changes and shall require submittal of a new or revised welding procedure specification.

154. The use of a prequalified joint welding procedure as contained in ANSI/AWS D1.1 or others previously qualified by test procedures is not intended as a substitute for engineering judgment in determining the suitability of these joint procedures to a welding assembly or connection. Built up assembles containing many welds in close proximity to each other is a unique situation in which the total effect of welding may be different than considered in the qualification of the welds addressed above. In cases where an assembly is a critical component of a structure, the designer should consider mechanical testing and/or thermal mechanical finite element analysis of the assembly.

155. The procedures using the shielded metal arc welding(SMAW), submerged arc welding(SAW), gas metal arc welding(GMAW) (except short circuiting transfer), and flux cored arc welding (FCAW) processes which conform to applicable provision of ANSI/AWS D1.1-92, Sections 2,3,4,8,9 and 10 are prequalified without performing procedure qualification tests for the process. Other welding processes such as electroslag(ESW) and electrogas(EGW) welding may be used provided they are qualified by applicable test as prescribed in ANSI/AWS D1.1-92 (1992), Section 5.2 and are acceptable for use for the particular application and are approved by the design engineer. Welding of quenched and tempered steels with ESW and EGW is prohibited since the high heat input associated with them causes serious deterioration of the mechanical properties of the heat affected zone. The use of ESW and EGW should be approached with caution since the advantage of low residual stress and possible cost savings may be outweighed by the disadvantage of poor toughness in the finished joint.

Metallurgical Considerations

156. A weld joint should ideally have uniform strength, ductility, notch toughness, fatigue strength, and corrosion resistance throughout the weld and adjacent material. Due to the extreme heat and the mixing during the welding process, this is not achievable. With the solidification of the molten pool and the formation of a heat affected zone that occurs during or immediately following the welding operation, hot cracking, heat-affected zone cracking, and hydrogen-induced cracking can occur. In addition, hardening and

the susceptibility of the hardened structure to cracking are increased when base metals are used which have a high carbon equivalent or high alloy content.

157. The possibility for hot cracking to occur is affected by assembly restraints, weld shape, heat input and material composition. The susceptibility of the heat affected zone cracking is influenced by the thickness of the base metal, the type of weld, the composition of the base material, the welding process and filler metal type, the energy input, and the preheat temperature and cooling rate. The probability of hydrogen-induced cracking is minimized on CE projects by specifying the use of low hydrogen electrodes. Conformance to requirements on storage and use of the low hydrogen electrodes is an integral part in their effectiveness. Coverage on the individual items with their effect and control is beyond the scope of this chapter, but information can be found in a welding technology Cary's book (1979).

Effects of Heat

158. The effect of heat on a weldment can be minimized by controlling the rate of heating, the maximum temperature attained, the length of time at that temperature, and the rate of cooling. Preheat and interpass temperature, heat input control for quenched and tempered steel, and stress relief heat treatment are important factors which must be considered. Guidance for these can be found in ANSI/AWS D1.1-92, Section 4, Technique, Part A ANSI/AWS D1.1-92 (1992). Table 4.3 in the above referenced section specifies minimum temperatures which are considered adequate to prevent cracking in most cases.

159. When extreme heat is generated during the welding process, the following detrimental effects can occur: (1) differential shrinkage stresses from localized heating causes high residual stresses which may lead to warpage distortion; (2) a reduction of ductility to a degree of hardening in the heat-affected zone that leads to cracking; (3) the deterioration of the toughness properties of the joint, primarily in the heat-affected zone; and (4) the loss of strength in the heat-affected zone of certain work hardened, quenched, tempered, and quenched and tempered materials.

Fabrication

160. The designer must be actively involved in the quality assurance aspect of the welding fabrication process. The review of the fabricator's details and verification of the adequacy of the written welding procedure qualification specifications should be followed by inspection of actual fabrication. These inspections should be scheduled and performed when critical weldments are being assembled both in the shop and in the field.

161. Some of the items the designer should look for during inspections are weld size, proper joint configuration, welding position, welding procedure, welding machine settings, restrictive jig arrangements, and required preheat and postheat treatment.

162. Fabrication is covered in detail in PART VIII.

Nondestructive Examination

163. The methods of nondestructive testing required should be determined by the designer and included in the contract specifications. The type of nondestructive examination (NDE) system to be used should be determined considering joint design, material thickness, and accessibility to the joint. The specifications or drawings must clearly indicate which joints require 100 percent NDE, which joints require random inspection, and which methods are to be used for each joint. For random inspection, the drawings must indicate the location, number of joints, and minimum incremental length of weld which will be inspected. Radiographic examination is expensive and requires special safety precautions; therefore, designation of 100 percent examination should be called for only when absolutely necessary. Ultrasonic examination of fillet welds and partial penetration welds should be used with caution because interpretation can be difficult.

164. Joints not inspected by liquid penetrate, magnetic particle, radiographic, or ultrasonic methods should be subject to visual inspection. Joints critical to the structure should be determined and should be inspected more closely than noncritical joints. Radiographic and ultrasonic testing should be used on critical groove welds since discontinuities can be detected throughout the entire joint cross section while magnetic particle and liquid penetrate detect discontinuities primarily near or at the surface.

165. Welds shall be unacceptable if shown to have defects prohibited by ANSI/AWS D1.1, Subsections 8.15 and 9.25, as applicable, or possess any degree of incomplete fusion, inadequate penetration, or undercutting. The designer should be aware of what defects will be considered acceptable under the guidance provide.

166. The designer should review each structure to ascertain which welds are critical to the overall integrity of the structure. The soundness of large welds in highly stressed members (i.e., diagonals on miter gates) is of prime concern in the proper functioning of this type of structure. Welds in members subject to cyclic load with little redundancy in load paths and difficult to assemble are generally chosen for closer inspection. In many cases, the selection of NDT requirements (method and extent) must be based on engineering judgement or past experience.

167. Examples of general areas where weld joints for various components of a navigation structure are selected for NDT are listed below; there can be similar areas on structural components on reservoirs and flood control structures.

a. Miter gates. Top anchorage, anchorage linkage, gudgeon hood, girder flange and web plate slices, quion and miter post web and flanges, skin plate splices, diagonal gusset plates and diagonals.

b. Culvert valves. End frame at valve body and trunnion and pickup assembly.

c. Culvert bulkhead. Skin plate splices, pickup assembly, and dogging plates.

d. Tainter gates. Trunnion yokes, trunnion plates to hubs, girder flange and web plate splices, skin plate splices, gate pickup assembly, strut side frame to girder flanges, and webs and trunnion plates.

References

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PART VII: FABRICATION

Introduction

168. To simplify the design and keep the cost of fabrication low, gate components should be readily available in the form of simple rolled sections and geometric shapes. The fabrication of gates frequently involves the use of thick sections and complex welded connections. Therefore, any consideration of fabrication methods is greatly dependent on the weldability of the steel. Furthermore, the use of welded connections offers the designer more freedom to be innovative in his design concept, whereby he is not bound to the use of standard sections but may build up cross sections that he feels to be most advantageous in transmitting the design loads from one member to another. Structural parts such as gate arms, horizontal framing beams, lifting eyes, stiffeners, wheel supports, and guide lugs are attached to the gate skin plate by welding (welded to ensure optimum leak-proof design). The most widely used industrial welding method is arc welding. Residual stresses in a weld and in the adjoining areas cannot be avoided and are quite complex. If the weld residual stress is superposed on the stress due to external loads and the resultant stress exceeds the yield point of the material, local plastic yielding will result in redistribution of the stress in ductile materials. Welded connections are sometimes subject to lamellar tearing (separation within the steel caused by strains induced by shrinkage of hot metal as it cools) which becomes more serious when using thicker steel sections or where movement between members is restrained. The designer should closely check the shop fabrication drawings for structural connections with probable high restraint conditions and for tight fit-up weldments which may result in the critical restraint of members. In the case of highly restrained, heavily welded joints, it is advisable to call for ultrasonic testing after completion of the welding. These topics are further discussed in the following sections.

Shop Fabrication Versus Field Fabrication

169. The amount of field fabrication work which can be specified depends on equipment size and accessibility to the work site. The design engineer should discuss and coordinate this with the fabricators and construction personnel before preparation of the shop drawings is started. Where gate

size allows transportation by road/rail/waterway to the site in one piece, all fabrication should be completed in the workshop under a controlled environment. Shop assembly is more conducive toward a better finished product especially where close tolerances are specified. The advantages of shop fabrication become more pronounced when heavy sections with greater steel thickness require handling. Regardless of the welding process, the use of good joint fitup and proper end preparation are of extreme importance along with a clear understanding of the applicable codes and specifications used. If the gate size warrants the gate be sectionalized, then individual match-marked sections should be assembled together and welded in the field with provision for good quality control to prevent distortion and excessive shrinkage. Welding sequence and finished tolerances are a direct function of measurement control which must be checked at regular intervals, especially after each major strength weld has been completed and allowed to cool. Shop assembly and inspection, where called for in the specifications, should be performed in the presence of a Government inspector.

170. Inspectors should have free access for the inspection of material and workmanship in the mill and shop. Inspectors should reject any material or work that does not meet the requirements of the plans and specifications. If a dispute should arise, the final decision will rest with the engineer.

Designer's Role in the Fabrication Process

171. Before a decision is made on whether to sectionalize or to fabricate an item as one piece, the designer should investigate any restraints imposed by size limitations on transportation handling and erection which can be found in applicable transportation codes and standards. Size limitations may vary throughout the United States.

172. To form the basis of an acceptance criteria, it is essential to indicate key control measurements under the quality assurance program, such as limits and tolerances that will be permitted in the critical dimensions of items as defined in the codes, standards, drawings, and specifications.

173. Consideration should be given to splice locations for field welding if the gate is to be sectionalized. It is recommended that splice points on a large gate be staggered symmetrically about the vertical and horizontal center lines of the gate, and that the splices be adequate enough to develop the full strength required by the stresses at the point of splice. The

locations, size and quantity of temporary supports, bracing and lifting eyes for the gate/gate components during shipment, handling, and field assembly should be clearly shown on the drawings so as to avoid deformation and injury. In addition to this, the designer should check the splice locations shown on the shop drawings for conformity to the plans and specifications. Machined surfaces should be protected by the application of grease and/or a suitable protective covering, and should be so specified in the design documents.

174. The designer should ensure that the minimum spacing of gate horizontal beams provides sufficient clearance and access through the rear flanges for fabrication, painting, and maintenance purposes. A thickness of skin plate should be selected so as to provide the beam spacing required while simultaneously satisfying the allowable plate effective width and unit stress requirements. The beam spacing may be increased progressively towards the top as the water pressure gradient decreases.

175. Edges of steel plate should be ground and beveled in accordance with good workshop practice. Flame cutting of structural steel should conform to the requirements of the applicable specifications. Care should be exercised when it becomes necessary to cut holes in a finished product (e.g., drain holes cut into webs of horizontal beams). Preparation methods may involve either machining operations or the use of flame cutting procedures. Since flame cutting produces excessive localized heating which can be harmful to the materials involved and a flame cut hole causes unwanted stress concentrations, the designer should specify the method of edge preparation required. Particular care should be given to the method of fabrication and fitup of stiffeners on the gate skinplates that are intended to carry static and dynamic loadings. Such stiffeners should have a close bearing against the flanges through which they receive their loading and should extend approximately to the edge of the flange plates.

176. Pins and rollers should be accurately machined to the dimension shown on the shop drawings. Pins and rollers more than 9 in. in diameter should be forged and annealed for increased strength and ductility and to remove unwanted stresses resulting from the machining process (Oberg and Jones 1962). Pins and rollers that are 9 in. or less in diameter may be specified as either forged and annealed if only a few are required, or cold-finished carbon steel shafting if a large quantity is to be made and the required size of raw material is available.

177. All holes for bolting should be either punched or drilled, and contact surfaces of metal should be clean and free of burrs before assembly. During the installation process, bolt fasteners should be protected from dirt and moisture. The designer should specify the preferred method of bolt tightening, either by the use of a calibrated torque wrench, by the turn-of-nut method, or by direct tension indicator tightening (load indicator washers). Although the last mentioned method is not yet covered by an American Society for Testing and Materials (ASTM) specification, it is the single device known which is directly dependent upon the tension load in a bolt and is recognized by AISC.

Welding Versus Casings Versus Forgings

178. Welding offers many advantages because it lends flexibility to structural design and facilitates lightweight construction. By permitting the use of standard rolled shapes, costs are cut by reducing material, machining, and finishing requirements. Welding is used not only for fabrication but also for repair and maintenance purposes. When designing for welding, individual components can be considered separately for design analysis, and then joined to form the entire assembly. Factors requiring consideration during design, which may change the ease of weldability are material thickness, type of treatment (hot or cold), material properties, and accessibility. When only a few parts are to be manufactured, welding is generally more economical than casting. Also, weldments are usually lighter in weight than castings.

179. Sand casting is the oldest and most versatile method of forming metals. Sand casting is a basic low-cost process which lends itself to economical production in large quantities. Practically no limit is placed on the size, shape, or complexity of the part required to be produced. The casting is made by pouring molten metal into sand molds. A pattern, constructed of metal or wood is used to form the cavity into which the molten metal is poured. To design an easily produced, low-cost casting, the designer should envisage how the metal will enter the mold and how solidification will proceed. Steel castings are the most difficult of all materials to produce because they have the highest melting temperature. This high temperature aggravates all casting problems. A complicated part should be designed in two or more simple castings and then assembled by fasteners or by welding. All sections should be designed with a uniform thickness which would be generally

at the minimum thickness necessary to obtain the required strength and stiffness. The use of rib stiffeners as a means of reducing section thickness is especially desirable. One of the difficulties of the sand casting process is that the mold can be used only one time as it must be destroyed in order to remove the casting from it. If a number of castings are to be made, metal molds should be considered. However, metal molds are not suitable for large castings or for materials having a high melting point. Metal mold or centrifugal die castings have a cost advantage in that the cast surfaces are normally smooth and accurate so that little if any machining is required. Design flexibility is also an added advantage.

180. Operating strut pin bearing collars, pintle sockets, and pintle shoes are normally fabricated of cast steel, utilizing mild-strength to medium-strength carbon steel castings. For items that are subjected to higher stresses than medium-strength castings capable of carrying (such as the miter guide roller and pintle balls) high-strength, low-alloy steel castings should be used (Headquarters, Department of the Army 1984).

181. Forging is the hot working of metal by hammers, presses, or forging machines. The hot working process produces a refined-grain structure which results in increased strength and ductility. Compared with castings, forgings have greater strength per weight and greater ductility. Additionally, drop forgings can be made smoother and more accurate than sand castings so that less machining is necessary. However, the initial cost of the forging dies is usually greater than the cost of patterns for castings, although the greater unit strength of forgings rather than the cost may sometimes be the deciding factor between these two processes. Furthermore forgings are advantageous when irregular curves, eccentrics, or recesses are required.

182. Gudgeon pins, operating strut connecting pins, anchor link pins, parts of the anchorage links, and guide roller pins should be made of carbon steel forgings rated for general industrial use. Forgings may be untreated or heat-treated depending on size, intended use, and strength requirements. The pintle ball of most gates is made of an alloy steel forging containing nickel, giving the forging a good allowable bearing value as well as a fair degree of corrosion resistance. Corrosion-resistant weld overlays may also be used on pintle balls in highly corrosive environments (Headquarters, Department of the Army 1984).

Treatment of Gate Steels

183. Proper heat treatment is an essential to a well fabricated gate as are good design and forming and welding procedures. The designer should be familiar with the types of steels commonly used to fabricate gate structures within the Corps, heat treatment requirements, and the fact that elimination of heat treatment where it should have been called for could lead to service failures. Stress relief heat treatment is the practice of heating a work piece to a calculated temperature and holding it at that temperature long enough to reduce residual stresses within the work piece which is then cooled down slowly so as to minimize the development of new residual stresses. The following considerations may be useful generally.

184. ASTM A6/A 6M, A 27/A 27M, and A36/A36M are all low-carbon steels (carbon up to 0.30). Generally preheating is unnecessary unless parts are very thick or welding is to be performed below 32 °F atmospheric temperature. Postheating is usually unnecessary. If carbon content is above 0.20 percent, heat-treatment is adapted to slow the cooling rate and avoid hardness.

185. ASTM A 441 is a low-alloy steel found in existing projects but is generally not used for new construction. Steels exhibiting low hardenability are welded with relative ease, whereas those of high hardenability require preheating and postheating to prevent cracking of the material due to the high carbon content.

186. ASTM A 572/A 572M High-Strength Low Alloy Columbium-Vanadium Steel and ASTM A 588/A 588M High-Strength Low-Alloy Structural Steel are similar to ASTM A 6 and A-36 Steels described earlier. A welding procedure suitable for the intended grade of steel and service requirements should be utilized.

187. For a cast steel of a good grade with carbon content below 0.25 percent, welding procedures are approximately the same as for wrought steel. With a carbon content above 0.25 percent special procedures are necessary. The problem of overcoming shrinkage in the repair of castings requires special care. Stress relieving is desirable, especially in repair work. For higher carbon and alloy steels, full annealing may be necessary. During the fabrication process, stress relieving is generally specified for but not limited to tainter gate trunnion hub and yoke assemblies to reduce residual stresses caused by heavy welding.

188. Although cast iron has a high carbon content and is a relatively brittle and rigid material, successful welding can be performed if proper

precautions are observed. Adequate preheat temperature must be maintained throughout the welding operation to reduce embrittlement and unequal expansion and contraction stresses during heating and cooling cycles. If the parts being welded are free of restraint, local preheat may be satisfactory, but if the parts are under restraint, the effect of heating and cooling stresses may be difficult to assess. Unless a special preheat program can be devised, the general rule is to uniformly preheat the entire casting.

Galvanizing

189. Galvanizing of gate parts when called for is usually accomplished under a strictly controlled workshop environment. Warpage or other defects to a workpiece as a result of the galvanizing process is the responsibility of the contractor charged with the satisfactory completion of the work according to the specifications. Specifications should contain direction on the type of galvanizing process required and minimum finished coating thickness for the size of workpiece and type of service expected. The designer should familiarize himself on size restrictions for items that he may intend to specify for galvanizing, which are governed by the dimensions of the galvanic kettles used in the process and may vary depending on location and size of the fabricating shop. Kettle lengths range up to 52 ft with widths and depths varying from 3 to 6 ft. In addition, the designer should also be relatively familiar with the different galvanizing processes and their limitations (see Bibliography). Steel selection is of extreme importance since it is imperative that steels are of galvanizable quality. Welds must be cleaned of all residues preferably by grit or sand blasting prior to galvanizing, and this should be so specified in the working documents. Specifications and design should be realistic and clear, and the fabricator should be required to submit a copy of the specifications and a set of shop drawings to the galvanizer.

190. Hot-dip galvanizing is a two-step operation. The steel must first be thoroughly cleaned and decreased using an appropriate pickling system for adherence of the zinc coating. The second step is galvanizing by immersing the prepared steel into a bath of molten zinc metal over a period long enough for the zinc layers to obtain the required thickness to meet the coating weight specification. Upon withdrawal, the galvanized item will normally exhibit bright, nonporous outer layer coating of almost pure zinc. This

process is used for coating exposed structural steel work and for sheet and pipe coatings.

191. In the sheradizing process, the items are thoroughly cleaned by pickling and sandblasting before being placed in a metal drum with zinc dust and heated to a temperature of from 500 to 600 °F depending on size and shape. The drum is rotated to promote even mixing of the contents. The resultant coating is not pure zinc, but an alloy of about 90 percent zinc and 10 percent iron and is highly resistant to corrosion. This process is especially suitable for screws, bolts and nuts, chains, pipe fittings, small castings, and such other items as may be conveniently placed within the drum.

192. The electrolytic or cold process consists of setting up items to be coated as cathodes in an electrolytic bath of soluble zinc salts with the anode being metallic zinc. This process is ideal for the coating of steel wire. The high ductility of the zinc coating is an outstanding feature of such a coating. Ease of control of the uniformity and thickness of the coating is also advantageous.

193. Metal spraying or metallizing process is especially useful for applying thick coatings to limited areas for rebuilding worn or undersized parts (cylinders, shafts, pistons) and as a protective coating. The process is also readily adapted for coating large assembled structures such as bridges, towers, and canal gates. Zinc, aluminum, and cadmium can be spray coated.

194. Practical design, fabricating, and post-galvanizing considerations should include the following:

a. Different types of steel have different pickling and galvanizing characteristics, as the major elements such as carbon and/or silicon can materially affect the techniques employed. ASTM A 36 steel is best suited for galvanizing.

b. Bending, forming, and punching should be done before galvanizing.

c. Castings should be sandblasted prior to galvanizing since normal pickling solutions will not attack foundry sand. Any finish machining required should be done after sandblasting is completed.

d. Hinged and swiveled sections and sections with moving parts should be disassembled before galvanizing and reamed afterwards.

e. Galvanized steel should be handled so as to minimize mechanical damage to the coating due to dropping, bumping, or scraping.

f. Material stored outdoors and subjected to the elements should be stacked so that moisture will drain off and not be entrapped.

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PART VIII: NONDESTRUCTIVE TESTING

195. Often visual inspection of a part or structure is not adequate to accurately determine its integrity, and the use of various types of inspection equipment is required. Generally inspection equipment is used to find discontinuities; however, some techniques are available to measure stress indirectly. NDT is the means by which materials and structures may be inspected for flaws, discontinuities, and various properties without damaging the item. Often the test can be performed while the item or part is still in service. The National Materials Advisory Board Ad Hoc Committee on NDE established six major categories for NDT technique for (1) visual, (2) penetrating radiation, (3) magnetic-electrical, (4) mechanical vibration, (5) thermal, and (6) chemical-electrochemical.

Objective

196. NDT can be used to determine many types of information (Wenk and McMaster 1987). They include:

- a. Presence of flaws and separation (cracks, voids, inclusions, delaminations, etc.).
- b. Structure or malstructure (crystalline structure, grain size, segregation, etc.).
- c. Dimensions and metrology (thickness, diameter, gap size, etc.).
- d. Physical and mechanical properties (conductivity, elastic modulus, etc).
- e. Composition and chemical analysis (alloy identification, impurities, etc.)
- f. Stress and dynamic response (residual stress, crack growth, wear, vibration, etc.).
- g. Signature analysis (image content, frequency spectrum, field configuration, etc.).

Limitations

197. Each nondestructive technique has inherent limitations described in detail by Wenk and McMaster (1987). These limitations include type of flaw, geometric, accessibility, and material.

Flaw limitations

198. NDT applications are generally limited to a specific type of flaw. For example, radiography may reliably reveal porosity, inclusions, lack of penetration in welds, and cracks parallel to the radiation but will not detect small surface cracks and cracks perpendicular to the radiations. Similarly, magnetic particle inspection may reveal surface cracks and discontinuities but may not find deeper ceded flaws.

Geometric limitation

199. Some test are limited to objects of certain geometry. For instance, ultrasonics resonance thickness gaging is limited to walls of plates that are nearly parallel surfaces. A few types of NDT's are applicable only to specimens of exactly identical geometry. Some electromagnetic induction or eddy current test devices can only detect discontinuities in symmetrical rods or bars of given shape and diameter.

Accessibility Limitations

200. Certain NDT's such as radiography and X-ray require access to both sides of the test specimen. Other methods such as magnetic particle, ultrasonic reflection, and liquid penetrant require access to only one side.

201. Some methods utilize portable equipment such as magnetic particle and ultrasonic. These can be used to inspect large items in the field. Others include large testing units on fixed foundations which make field inspection impossible.

Material Limitations

202. Many tests such as magnetic particle inspection are limited to ferromagnetic materials and can not be used for light alloys or nonmagnetic stainless steels alloys.

Description of Specific Type of Inspection Equipment

Magnetic particle inspection

203. This is a method of detecting cracks and other discontinuities in steel and iron by applying a magnetic field perpendicular to the defect and applying magnetic particles over the area. When this is done, the magnetic

particles will adhere to the defect. These particles can be applied in several ways. The piece to be inspected may be magnetized and then covered with magnetic particles or the particles may be applied during magnetization. The magnetic particles may be held in suspension in a fluid that is washed over the defect or the piece may be submerged in the fluid. This is known as the wet method. The particles may be applied by dusting a fine magnetic particle powder over the area in question. This is know as the dry method.

204. When the defect is at the surface, the magnetic field leaks out to the surface and forms small north and south poles that attract the magnetic particles. If the defect is below the surface, less leakage takes place and fewer magnetic particles are attracted.

205. The sensitivity of magnetic-particle inspection is affected by a number of factors, including strength of the magnetizing current, time subjected to magnetization, depth of defect, and time allowed for the indication to form.

206. Any machine parts must be demagnetized after a magnetic-particle inspection since they will attract steel filing and other particles which may cause abrasion to such parts. Avner (1974) describes this method in further detail.

Ultrasonic inspection

207. Ultrasonic inspection utilizes sound waves in the 1 to 5 MHz range to detect discontinuities in a variety of mediums. A transducer is used to produce these sound waves using piezoelectric materials.

208. Two methods are utilized in ultrasonic inspection; the through-transmission and the pulse echo methods. The through-transmission method uses a transmitting transducer on one side of an object being tested and a receiving transducer on the other side. The transmitting transducer sends an ultrasonic wave through the medium where it is received on the other side by the receiving transducer. If there are flaws in the path, a smaller signal is detected at the receiving transducer.

209. Most ultrasonic inspection equipment uses the pulse echo method. This method uses only one transducer which acts as both the receiver and transmitter. When the ultrasonic wave is induced, part of it is reflected back to the transducer which produces a spike on the oscilloscope of the instrument. When the sound wave reaches the other side of the material, it is reflected back where it appears as another spike on the oscilloscope. If there is a crack or flaw in the material, a third spike appears between the

other two spikes. The distance between spikes is a measurement of time needed for the wave to travel to the surface and back. The ultrasonic unit can be calibrated such as the depth of the flaw can readily be measured. Angled transducer can also be used for inspecting plates of metal or when it is suspected that a fault is perpendicular to the surface of the item in question.

210. Ultrasonic inspection is fast, accurate, and dependable. Generally, the device is easy to operate and is portable. Ultrasonic inspection works the best on smooth surfaces and often requires film of oil to ensure good contact between the transducer and the test piece. Rough surfaces deflect the sound waves in many directions which lessen the accuracy of the readings. Also, interpretation of reading requires training. Avner (1974) describes this method in further detail.

Eddy current inspection

211. Eddy current inspection can be conducted on materials which are electrically conductive to detect irregularities and defects. When alternating current passes through a coil, a varying magnetic field is produced. When this coil is placed near a test specimen, eddy currents will be developed, which in turn develop their own magnetic field and convert the signal into a voltage which can be read on a meter or oscilloscope. Flaws in the specimen will alter the magnetic field.

212. Eddy current testing may be used to detect surface and subsurface defects, plate or tubing thickness, and coating thickness. It is generally a quick process and contact with the test piece is not required. However, it is only good for conductive materials and has a limited depth of penetration. A number of variables can affect the results which can lead to false indications. Avner (1974) describes this method in further detail.

Liquid penetrant

213. A liquid penetrant can be used to detect minute defects that are open to the surface. This method may be applied to both magnetic and nonmagnetic materials, its primary application is for nonmagnetic materials. Liquid penetrants are usually light oil-like liquids which are applied to the test material. Capillary action draws the penetrant into the crack. After the penetrant has had time to seep into the defect, the surface is washed and a developing powder is applied which draws the penetrant out of the cracks. The inspector can then visually spot the location of the crack.

214. Some liquid penetrants have fluorescent characteristics which glow under a black light. This aids in the detection of cracks.

215. The advantages of using a liquid penetrant include low cost, simple to use, results being easy to interpret, and no elaborate setup required. However, it is limited to detecting only surface defects and the surface must be clean. Avner (1974) describes this method in further detail.

Radiography

216. Radiography of metals may be carried out by using X-rays or gamma rays. Gamma rays may be obtained from any naturally radioactive material such as radium or cobalt-60. Gamma rays penetrate more than X-rays but are not as sensitive. Radiography of metals is primarily used for inspection of castings and weldments. A radiograph is a shadow picture of a material more or less transparent to radiation. The X-rays darken the film so that regions of lower density which readily permit penetration appear dark on a negative as compared with regions of higher density which absorb more radiation.

217. There are several advantages to using radiographic inspection. The results of the test are often easier to interpret than ultrasonic and eddy current methods and a permanent record is produced. However, trained technicians are needed when using either X-rays or gamma ray radiography because there is a radiation risk involved. Also, the initial cost of radiographic equipment is high. Avner (1974) describes this method in further detail.

Barkhausen noise

218. If a piece of ferromagnetic material is magnetized, it will elongate in the direction of the magnetic field. Conversely, if the same piece is stretched by an applied load, it will be magnetized in the direction of the load. The same occurs with compression, except that the resulting magnetization occurs 90 deg to the direction of compressive load. This is the principle of magnetoelastic interaction.

219. To apply this principle in the measurement of stress in ferromagnetic materials, another phenomenon known as Barkhausen effect is employed. The Barkhausen effect describes the series of abrupt changes or jumps in the magnetic field when the magnetic field is gradually altered. Combining these two phenomena allows a qualitative stress measurement. An increasing tensile stress will be accompanied by an increasing "Barkhausen noise" level and an increasing compressive stress by a decreasing noise level. By measuring this Barkhausen noise, the stress in the specimen can be determined.

Acoustic emissions

220. Acoustic emission is the detected elastic energy which is released when materials undergo deformation and/or fracture. It is a passive

monitoring system which relies on redistribution of stresses within the specimen to provide the excitation function. Once the stresses in the specimen stabilize, the acoustic emission is no longer produced until the stabilized stress level is exceeded. If the stress is stabilized, acoustic emission will not be produced even if the load is removed. When the load is reapplied, no emission occurs until the previous load has been exceeded. Acoustic emission techniques have been used to provide early warning of failure, detecting and locating flaws, and detecting subcritical flaw growth. Spanner (1974) describes this method in further detail.

Strain gages

221. Strain gages measure the strain that takes place when a specimen is loaded. Once the strain is determined in three directions at a point, the principle stresses can be determined. It is important to note that these gages only measure the strain change. To determine the total stress, the strain gages must be attached to the specimen while the actual strain is zero.

Choosing the best test method

222. Of the many types of NDT methods available, there is usually one or a few methods that are best suited for the particular application. Tables 1, 2 and 3 indicate general suitability of NDT tests for metals.

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Table 1

General Suitability Comparison Chart for Nondestructive Tests of Magnetic (or Heavy) Metals*

General Classification of Test Methods	Major Variations in Test Methods		GENERAL: Minute Surface Cracks	GENERAL: Normal Surface Cracks	GENERAL: Internal Cracks	GENERAL: Internal Voids	GENERAL: Thickness	GENERAL: Metallurgical Variations	SHEET AND PLATE: Thickness	SHEET AND PLATE: Laminations	SHEET AND PLATE: Holes	BARS AND TUBES: Seams	BARS AND TUBES: Pipe	BARS AND TUBES: Cupping	BARS AND TUBES: Inclusions
Penetrating radiation tests[4]	film radiography		U	F[2]	F[2]	G	F	F	G[3]	U	G	P	G	G	F
	fluoroscopy[1]		U	U	P	F	U	U	U	U	G	U	U	U	F
	radioisotopes		U	F[2]	F[2]	G	F	F	G[3]	U	G	P	F	F	F
Ultrasonic and sonic tests	contact pulse reflection	normal beam	U	U	G	G	P	P	P	G	G	U	G	G	F
		shear wave	U	P	G	G	U	U	U	F	F	F	U	U	F
		surface wave	U	G	U	U	U	U	U	U	U	F	U	U	U
	immersion pulse reflection	normal beam	U	U	G	G	F	F	F	G	G	U	G	F	G
		angle beam	U	F	G	G	U	U	U	F	F	F	P	U	F
		surface wave	U	F	U	U	U	U	U	U	U	F	U	U	U
	through-transmission		U	U	F	G	U	F	U	G	U	F	G	G	F
	resonance		U	U	P	P	G	U	G	G	P	P	G	P	U
	natural frequency		U	P	U	U	U	U	U	U	U	U	U	U	U
Magnetic particle tests	alternating current (wet method)		G	G	U	U	U	U	U	F	U	G	P	U	F
	alternating current (dry method)		F	G	U	U	U	U	U	F	U	G	U	U	U
	direct current (wet method)		G	G	P	U	U	U	U	G	U	G	P	U	G
	direct current (dry method)		F	G	F	P	U	U	U	G	U	G	U	P	U
Electromagnetic tests	eddy current		F	F	U	U	P	G	P	U	U	F	U	U	U
	magnetic field		P	F	P	P	F	G	F	U	U	G	F	F	P
	leakage field pick-up		F	G	F	U	U	U	U	U	P	G	U	P	P
	direct current conduction		F	F	P	P	F	P	F	P	P	F	U	P	U
Liquid penetrant tests[5]	visible dye penetrants		F	G	U	U	U	U	U	F	P	G	F	U	U
	fluorescent dye penetrants		G	G	U	U	U	U	U	F	P	G	F	U	U
	filtered particles		U	U	U	U	U	U	U	U	U	U	U	U	U
Other	electrified particles		U	U	U	U	U	U	U	U	U	U	U	U	U

General Classification of Test Methods	Major Variations in Test Methods		CASTINGS: Cold Shuts	CASTINGS: Surface Cracks	CASTINGS: Internal Shrinkage	CASTINGS: Holes (Porosity)	CASTINGS: Core Shift	FORGINGS: Laps	FORGINGS: Inclusions	FORGINGS: Internal Bursts	FORGINGS: Internal Flakes	FORGINGS: Cracks and Tears	WELDS: Shrinkage Cracks	WELDS: Slag Inclusions	WELDS: Lack of Fusion	WELDS: Porosity	WELDS: Lack of Penetration	PROCESSING: Heat Treat Cracks	PROCESSING: Grinding Cracks	SERVICE: Fatigue Cracks (Heat Cracks)	SERVICE: Stress Corrosion	SERVICE: Blistering	SERVICE: Thinning	SERVICE: Corrosion Pits
Penetrating radiation tests[4]	film radiography		G	F[2]	G	G	G	F	F	F	F	F[2]	G[2]	G	G	G	G	P	U	P	F	P	F	G
	fluoroscopy[1]		F	U	F	F	F	U	U	U	U	U	F[2]	F	F	F	F	U	U	U	U	U	P	P
	radioisotopes		G	F[2]	G	G	G	U	U	G	U	F[2]	G[2]	G	G	G	G	U	U	P	P	P	F	P
Ultrasonic and sonic tests	contact pulse reflection	normal beam	F	U	F	F	F	F	G	G	G	P	F	F	F	F	P	U	U	U	U	U	U	P
		shear wave	F	P	F	F	U	P	F	G	F	F	F	F	F	P	F	F	U	F	U	U	U	P
		surface wave	P	U	U	U	U	P	U	U	U	F	F	U	U	U	U	F	U	F	F	U	U	U
	immersion pulse reflection	normal beam	F	U	P	F	P	P	G	G	F	F	F	F	F	F	F	U	U	U	U	U	U	U
		angle beam	F	P	P	F	U	U	F	G	F	G	F	F	F	F	F	F	U	F	U	U	U	U
		surface wave	U	P	U	U	U	P	U	U	U	U	P	U	U	U	U	F	F	F	P	U	U	U
	through-transmission		F	U	F	F	U	U	G	G	G	U	P	F	G	F	U	U	U	U	P	F	U	U
	resonance		U	U	U	P	G	U	U	U	U	U	P	U	U	U	U	U	U	U	U	G	G	F
	natural frequency		U	P	P	U	U	U	U	U	U	P	U	U	U	U	U	U	U	U	U	U	U	U
Magnetic particle tests	alternating current (wet method)		G	G	U	U	U	G	F	U	U	G	G	U	F	U	U	G	G	G	G	F	U	U
	alternating current (dry method)		G	G	U	U	U	G	F	U	U	G	G	U	F	U	U	G	G	F	F	U	U	P
	direct current (wet method)		G	G	P	U	U	G	G	F	F	G	G	P	F	U	U	G	G	G	G	U	U	U
	direct current (dry method)		G	G	F	P	U	G	F	F	F	G	G	G	G	F	F	G	G	F	F	U	U	P
Electromagnetic tests	eddy current		P	F	P	U	P	P	U	U	U	P	F	P	F	U	P	G	F	F	U	U	F	U
	magnetic field		P	F	P	P	P	P	P	F	P	P	P	P	P	U	P	G	F	F	U	U	P	U
	leakage field pick-up		P	F	U	P	U	F	P	P	P	F	G	F	F	U	F	G	F	G	U	U	U	U
	direct current conduction		U	F	U	U	P	F	U	U	U	F	F	U	P	U	U	F	F	F	F	U	F	U
Liquid penetrant tests[5]	visible dye penetrants		F	G	U	G	U	F	U	U	U	G	G	U	U	U	U	G	G	G	G	U	U	F
	fluorescent dye penetrants		F	G	U	G	U	F	U	U	U	G	G	U	U	F	U	G	G	G	G	U	U	F
	filtered particles		U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
Other	electrified particles		U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U

[G] GOOD [F] FAIR [P] POOR [U] UNSUITABLE
1 Fluoroscopy only suitable for thin sections
2 May be good if beam is parallel to crack
3 Special thickness gages are available
4 Size of discontinuities found depends on thickness of section
5 Discontinuities must be open to a surface to be located with penetrants

* From Wenk and McMaster (1987).

Table 2

<u>General Suitability Comparison Chart for Nondestructive Tests of Magnetic (or Light) Metals*</u>

			GENERAL						SHEET AND PLATE			BARS AND TUBES				CASTINGS					FORGINGS					WELDS					PROCESSING		SERVICE				
General Classification of Test Methods	Major Variations in Test Methods		Minute Surface Cracks	Normal Surface Cracks	Internal Cracks	Internal Voids	Thickness	Metallurgical Variations	Thickness	Laminations	Holes	Seams	Pipe	Cupping	Inclusions	Cold Shuts	Surface Cracks	Internal Shrinkage	Holes (Porosity)	Core Shift	Laps	Inclusions	Internal Bursts	Internal Flakes	Cracks and Tears	Shrinkage Cracks	Slag Inclusions	Lack of Fusion	Porosity	Lack of Penetration	Heat Treat Cracks	Grinding Cracks	Fatigue Cracks (Heat Cracks)	Stress Corrosion	Blistering	Thinning	Corrosion Pits
Penetrating radiation tests[4]	film radiography		U	F[2]	F[2]	G	F	F	G[3]	U	G	P	G	G	F	G	F[2]	G	G	G	F	F	G	F	F[2]	G[2]	G	G	G	G	U	U	F[2]	F	P	F	G
	fluoroscopy[1]		U	F[2]	F[2]	G	F	P	U	U	G	P	F	F	F	F	F[2]	G	G	G	P	F	F	U	F[2]	G[2]	F	F	F	F	U	U	U	U	U	P	P
	radioisotopes		U	F[2]	F[2]	G	F	F	G[3]	U	G	P	G	G	F	G	F[2]	G	G	G	F	F	G	U	F[2]	G[2]	G	G	G	G	U	U	P[2]	P	P	F	P
Ultrasonic and sonic tests	contact pulse reflection	normal beam	U	U	G	G	F	F	F	F	U	U	G	G	F	F	U	F	F	G	F	F	G	G	F	U	F	U	F	U	U	U	U[2]	U	F	F	P
		shear wave	U	U	G	G	P	P	U	F	F	F	F	P	F	F	F	U	F	U	F	F	G	G	F	F	F	F	P	F	F	P	F	U	U	U	P
		surface wave	U	F	U	U	U	U	U	U	U	F	U	U	U	U	F	U	U	U	F	U	U	U	F	P	U	U	U	P	F	F	F	F	U	U	F
	immersion pulse reflection	normal beam	U	F	G	G	F	G	F	G	F	F	G	P	G	F	U	F	F	F	F	G	G	G	G	F	G	F	F	P	P	U	P	U	F	F	P
		angle beam	U	F	G	G	P	P	P	F	F	F	P	U	P	F	U	U	U	U	P	F	G	F	F	F	F	G	F	F	P	U	P	U	U	U	P
		surface wave	U	F	U	U	U	U	U	U	U	F	U	U	U	U	F	U	U	U	F	U	U	U	F	P	U	U	U	P	F	F	F	U	U	U	U
	through-transmission		U	U	F	G	U	F	U	G	U	F	G	G	F	F	U	F	F	U	U	G	G	G	U	P	F	G	F	U	U	U	U	P	F	U	U
	resonance		U	U	P	P	G	U	G	G	U	U	G	P	U	U	U	U	P	G	U	U	U	U	U	P	U	U	U	U	U	U	U	U	G	G	F
	natural frequency		U	P	U	U	U	U	U	U	U	U	U	U	U	U	P	P	U	U	U	U	U	U	P	U	U	U	U	U	U	U	U	U	U	U	U
Magnetic particle tests	alternating current (wet method)		U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
	alternating current (dry method)		U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
	direct current (wet method)		U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
	direct current (dry method)		U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
Electromagnetic tests	eddy current		F	G	F	P	G	G	F	U	U	G	P	P	F	G	G	P	P	P	G	P	U	U	F	F	P	P	U	U	G	G	G	P	U	F	U
	magnetic field		U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
	leakage field pick-up		U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
	direct current conduction		F	F	P	P	F	P	F	P	P	F	U	P	U	U	F	U	U	P	F	U	U	U	F	F	U	P	U	U	F	F	F	F	U	F	U
Liquid penetrant tests[5]	visible dye penetrants		G	G	U	U	U	U	U	F	P	G	F	U	U	F	G	U	G	U	F	U	U	U	G	G	U	G	F	U	G	G	G	P	U	U	U
	fluorescent dye penetrants		G	G	U	U	U	U	U	F	P	G	F	U	U	F	G	U	G	U	F	U	U	U	G	G	U	G	F	U	G	G	G	P	U	U	U
	filtered particles		U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U
Other	electrified particles		U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U	U

[G] GOOD [F] FAIR [P] POOR [U] UNSUITABLE
1 Fluoroscopy of light metals much better than of heavy metals (Figure 5)
2 Provided beam is parallel to the cracks
3 Special thickness gages are available
4 Size of discontinuity found depends on thickness of section
5 Discontinuities must be open to a surface to be located with penetrants.

* From Wenk and McMaster (1987).

Table 3

General Suitability Comparison Chart for Nondestructive Tests of Other Materials*

General Classification of Test Methods	Major Variations in Test Methods		Glass	Glazed Ware	Porous Materials	Plastics	Internal Assemblies	Coating Thickness	Lack of Bond
Penetrating radiation tests[2]	film radiography		U	U	U	G	G	F	F
	fluoroscopy[1]		U	U	U	G	G	U	U
	radioisotopes		U	U	U	F	G	F	U
Ultrasonic and sonic tests	contact pulse reflection	normal beam	F	U	U	F	U	U	F
		shear wave	F	U	U	F	U	U	F
		surface wave	P	U	U	P	U	U	U
	immersion pulse reflection	*normal beam*	F	U	U	F	U	U	F
		angle beam	F	U	U	F	U	U	F
		surface wave	U	U	U	U	U	U	U
	through-transmission		G	U	U	G	U	U	G
	resonance		G	U	U	G	U	U	G
	natural frequency		U	G	G	U	U	U	U
Magnetic particle tests	alternating current (wet method)		U	U	U	U	U	U	U
	alternating current (dry method)		U	U	U	U	U	U	U
	direct current (wet method)		U	U	U	U	U	U	U
	direct current (dry method)		U	U	U	U	U	U	U
Electromagnetic tests	eddy current		U	U	U	U	U	F	U
	magnetic field		U	U	U	U	U	U	U
	leakage field pick-up		U	U	U	U	U	U	U
	direct current conduction		U	U	U	U	U	U	U
Liquid penetrant tests[3]	visible dye penetrants		G	G	U	G	U	U	U
	fluorescent dye penetrants		G	G	U	G	U	U	U
	filtered particles		U	G	G	U	U	U	U
Other	electrified particles		G	G	U	F	U	U	U

[G] GOOD [F] FAIR [P] POOR [U] UNSUITABLE

1. Fluoroscopy of light metals much better than of heavy metals (Figure 5)

2. Size of discontinuity found depends on thickness of section.

3. Discontinuities must be open to a surface to be located with penetrants.

* From Wenk and McMaster (1987).

PART IX: CORROSION

Introduction

223. Corrosion is often defined as the deterioration of a material, usually a metal or alloy, because of a reaction with its environment. Unprotected steel exposed to a wide variety of environments has a natural tendency to revert back to its oxide; the process by which this occurs is corrosion. Conservatively estimated, approximately 10 percent of the 119,000,000 tons of steel produced in the United States each year is used to replace corroded steel (National Association of Corrosion Engineers 1983).

224. Corrosion occurs by an electrochemical process. The phenomenon is similar to that which takes place when a carbon-zinc "dry" cell generates a current. The four things that are needed are an anode (negative electrode), a cathode (positive electrode), an electrolyte (corrosive environment), and a metallic circuit connecting the anode to the cathode.

225. Dissolution of metal occurs at the anode where the corrosion current enters the electrolyte and flows to the cathode.

Types of Corrosion

General corrosion

226. General corrosion is sometimes referred to as uniform attack. When this form of corrosion occurs, anodic dissolution is uniformly distributed over the entire metallic surface. The corrosion rate is nearly constant at all locations. Microscopic anodes and cathodes which are continuously changing their electromagnetic behavior from anode to cathode and cathode to anode are believed to provide the corrosion cells for uniform attack. There are several methods used to prevent general corrosion (Headquarters, Department of the Army 1980):

a. Selection of more corrosion resistant metals.

b. Protective coatings.

c. Use of nonmetallic materials.

d. Treatment of environment.

e. Cathodic protection.

Galvanic corrosion

227. This occurs when two electrochemically-dissimilar metals or alloys are metallically connected and exposed to a corrosive environment. The less noble material (anode) suffers attack, and the more noble material (cathode) is cathodically protected by the galvanic current. The larger the potential differences of the two metals the greater the galvanic current generated and therefore the greater the corrosion at the anode.

228. For a given galvanic current, a large anodic area is most desirable. Commonly referred to as the "area effect", large cathode-to-anode area ratios usually aggravate the galvanic corrosion problem.

229. Distance between cathode and anode is also important. The greater the distance between the two, the less corrosion is likely due to greater resistance of the circuit. Prevention of galvanic corrosion can be accomplished by:

a. Material selection.

b. Avoiding large cathode to anode ratios.

c. Breaking metallic current by use of isolators.

d. Use of inhibitors.

e. Cathodic protection.

f. Use of protective coatings to both metals.

Concentration cell corrosion

230. This type of corrosion occurs because of differences in the environment. Sometimes called crevice corrosion, it commonly occurs in localized areas where small volumes of stagnant solution exist in such places as in sharp corners, spot welds, lap joints, fasteners, flanged fittings, couplings, and threaded joints. It is known that areas on a surface in contact with electrolyte having a high oxygen content will generally be cathodic relative to those areas where less oxygen is present. This is commonly described as the "oxygen-concentration cell". Some of the methods used to reduce concentration cell corrosion damage include:

a. Using butt welds instead of rivets and bolts.

b. Caulking, welding, and soldering existing lap joints.

c. Removing deposits from materials.

d. Using cathodic protection.

e. Using protective coatings.

f. Providing drainage.

Pitting corrosion

231. This is a randomly occurring, highly localized form of attack on a metal surface. It is characterized by corrosion pits which are deeper than they are wide. Pitting corrosion is similar to concentration cell corrosion in many ways; however, crevices, deposits, or threaded joints are not requisites for pit initiation. Methods to mitigate pitting attack include:

a. Cathouic protection.

b. Material selection.

c. Protective coatings.

Intergranular corrosion

232. Intergranular corrosion is a localized attack which occurs at the grain boundaries of an alloy. Although a number of alloys are susceptible to intergranular attack, most of the problems involve austenitic stainless steels and the 2xxx and 7xxx series aluminum alloys. Welding, stress-relief annealing, improper heat treating, or overheating are services that generally establish the microscopic compositional inhomogeneities which make a material susceptible to intergranular corrosion. When this happens in austenitic stainless steels, chromium combines with carbon at the grain boundaries to form zones immediately adjacent to the boundaries. Since a stainless steel corrosion resistance is proportional to the chromium content, theses zones are then susceptible to corrosion. Methods to prevent intergranualar corrosion include:

a. Material selection.

b. Proper heat treatment and welding procedures.

Stress corrosion cracking

233. This phenomenon occurs when many alloys are subject to static, surface tensile stress and exposed to certain corrosive environments. Cracks are initiated and propagated by the combined effect of a surface tensile stress and the environment. Often the tensile stress involved is much less than the yield strength of the material, and the environment is one in which the material exhibits good resistance to general corrosion. In addition, stress corrosion cracking is brittle in macroscopic appearance even though it may occur in a highly ductile material. Table 4 shows conditions where stress-corrosion cracking may likely occur.

Table 4

Some of the Alloy/Susceptible Environment Combinations

Where Stress-Corrosion Cracking Can Occur

Alloy System	Environment	Type of Cracking
Mild Steel	OH^- NO_{3-}	Intergranular Intergranular
Alpha Brass (70 Cu - 30 Zn)	NH_{4+}	Transgranular high Ph; intergranular in neutral solutions
Austenic Stainless Steel	Cl^-	Transgranular
2XXX - Series Al Alloys	Cl^-	Adjacent to grain boundaries.
7XXX - Series Al Alloys	Cl^-	Intergranular
Cu-P Alloys	NH_{4+}	Intergranular
Titanium Alloys*	Cl^-	Transgranular or intergranular
Mg-Al Alloys	Cl^-	Intergranular; sometimes transgranular
Beta Brass	Cl^- NH_{4+}	Transgranular Intergranular
Martensitic Low-Alloy Steel	Cl^-	Along prior-austenite grain boundaries
18 Ni Maraging Steel	Cl^-	Along prior-austenite grain boundaries

* Includes Ti-8Al-1Mo-1V, Ti-6Al-4V, and Ti-5Al-2.5 Sn alloys.

Coatings

General information

234. Coatings are the first (and often only) line of defense against corrosion. Even the most sophisticated cathodic protection system relies on a coating to be partially effective.

235. For any paint system to be effective, good surface preparation is needed. For hydraulic structures, this often requires sand blasting to near white metal.

236. Coatings can be applied in the field or in the shop. Often it is preferable to apply coatings in the shop because of better quality control and less negative environmental impact. Using different colors for different paint layers aids in the inspection of the paint application. It enables the inspector to immediately determine which layer is being painted and if each layer is receiving enough or too much coverage.

The basic ingredients

237. In general, the three basic ingredients in paint are solvent binder, and pigment. Solvents or thinners are used to make application easier by lowering the viscosity. After application, the solvent usually evaporates into the atmosphere. Common solvents include alcohols which can be environmentally hazardous. Binders are the glue that holds everything together. Common binders include drying oils such as linseed, fish, tung, and soya; and resins include alkyd, phenolic, acrylic, epoxy, urethane, chlorinated rubber, silicone, shellac, and vinyl. Pigment is used for color, corrosion resistance, filler, ultraviolet radiation absorption, hardness, and abrasion resistance.

Coating selection for various exposures

238. Atmospheric exposure. This exposure category applies to items exposed to atmospheric conditions including rain, snow, and sunlight. Under these conditions, alkyd enamel and aluminum based paints are generally specified.

239. Industrial/corrosive exposure. This category does not apply to most lock and dam structures but may exist in heavily industrialized areas where the water may be highly polluted. For most cases vinyl paints will work best but chemical analysis of the air or water may be needed to determine the best paint system.

240. Fresh water immersion. This exposure category would apply to items that occasionally immersed in fresh water as well as those items which are routinely or continuously immersed. Generally vinyl paints perform the best under these conditions.

241. Salt water/brackish water. This exposure category applies to items which are immersed in salt water. Under this condition, coal tar epoxy paint systems are often used. Vinyl paint systems work for chloride concentrations less than 1,000 ppm chloride.

242. Salt spray. Under salt spray conditions, salt concentrations can be high because the water will evaporate off of the steel leaving the salt

behind. For this reason, vinyls do not perform well. Instead, coal tar epoxy and alkyd enamel paint systems are generally used.

Cathodic Protection

General

243. This is a method used to force all parts of the structure to be a cathode. Cathodic protection is achieved by applying a direct current to the structure from some outside source such as a rectifier or sacrificial anode.

Sacrificial anodes

244. This method involves attaching anodes to the structure to produce a galvanic current. Typically the anode is made of magnesium or zinc. The use of sacrificial anodes has the following advantages and disadvantages.

a. Advantages

(1) No external power required.

(2) No regulation required.

(3) Easy to install.

b. Disadvantages

(1) Limited driving potential.

(2) Lower and limited current output.

(3) Installation can be expensive.

(4) May require many large anodes.

(5) Can be ineffective in highly resistive environments.

Impressed current

245. This method involves attaching an anode and a direct current power source to the structure. A current is then forced through this circuit. Two type of anodes are typically used, graphite rods and ceramic shapes. The ceramic anode is a relatively new product. It is lighter, more durable, and has a variety of shapes. The use of the impressed current method has advantages and disadvantages.

a. Impressed current advantages

(1) Use fewer anodes.

(2) Adds less weight to gates.

(3) Can produce high driving potentials.

(4) Can produce high current.

(5) Very versatile.

b. Disadvantages

(1) Continuously draws power.

(2) Can be expensive.

(3) If installed wrong, it can accelerate corrosion.

(4) Must be monitored.

Galvanization

246. Galvanization involves placing a thin layer of zinc on steel. The zinc protects the steel in two ways. When zinc is exposed to air and moisture, it forms an oxide which tightly adheres t the surface and protects the underlying metal. If the zinc and zinc oxide are scrapped off the steel, the zinc will act as a sacrificial anode and protect the steel. The zinc can be applied by several different processes which include the following.

Hot dip galvanizing

247. This involves the dipping of iron or steel into a bath of molten zinc to achieve a uniform zinc coat.

Electrogalvanizing

248. Zinc can be electrodeposited from aqueous cyanide sulfate or chloride solutions. However, the deposition of zinc is generally not uniform and tends to concentrate on projection and ignores recesses.

Sherardizing

249. This process is limited to relatively small parts. This is a simple process where iron is heated and tumbled with metallic zinc dust. This provides an excellent base for painting.

Metallizing

250. Molten zinc particles can be sprayed on suitably prepared steel surfaces by using a metallic wire or a powder spray gun. The advantage of this process is that there are no limits of the size of work. The disadvantages are high cost, need for special surface preparation, and difficulty of avoiding thin spots.

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PART X: PERFORMANCE IN SERVICE

Introduction

251. The existing high level of performance that hydraulic steel structures (HSS) currently provide has resulted from several factors. One of these factors has been that service performance has always been incorporated into the general design consideration for HSS. In keeping with that tradition and goal of continuously trying to improve the quality of performance in service, the following information is provided in the form of brief case histories.

Failure of Top Anchorage on Lock and Dam 26 Miter Gate

Description

252. Lock and Dam 26 was located on the Mississippi River at Alton, Il. The project included a 600-ft main lock and a 300-ft auxiliary lock, both of which contained vertically framed miter gates spanning 110 ft wide chambers. The downstream leaves were 45 ft high. The vertical girders were 48-1/4 in. deep with 72-1/2 in. deep upper and 48-1/4 in. deep lower horizontal girders. This project has recently been replaced by the Melvin Price Lock and Dam located approximately 2 miles downstream.

Conditions

253. A failure of the embedded gate anchorage at the top of the lock wall occurred on July 13, 1989 and is shown in Photo 1. The chamber was at tailwater elevation when the failure occurred. The anchorage fracture occurred through the 7-in.-diam gudgeon pin hole where the minimum edge distance was 2.5 in. Since the top anchorage is a tension nonredundant member, the leaf suddenly fell to the concrete sill where it remained vertical. The embedded top anchorage was composed of a two 12-ft channels and two 1/2-in. thick plates assembled as shown in Figure 8. The anchorage material was structural steel while the strut was cast steel utilizing class B Med. material.

254. In an effort to place the lock back into operation as quickly as possible repairs were completed by operation and maintenance personnel prior to consultation with engineering division. The top anchorage repair consisted of butting and welding a new channel section to the remaining embedded channel

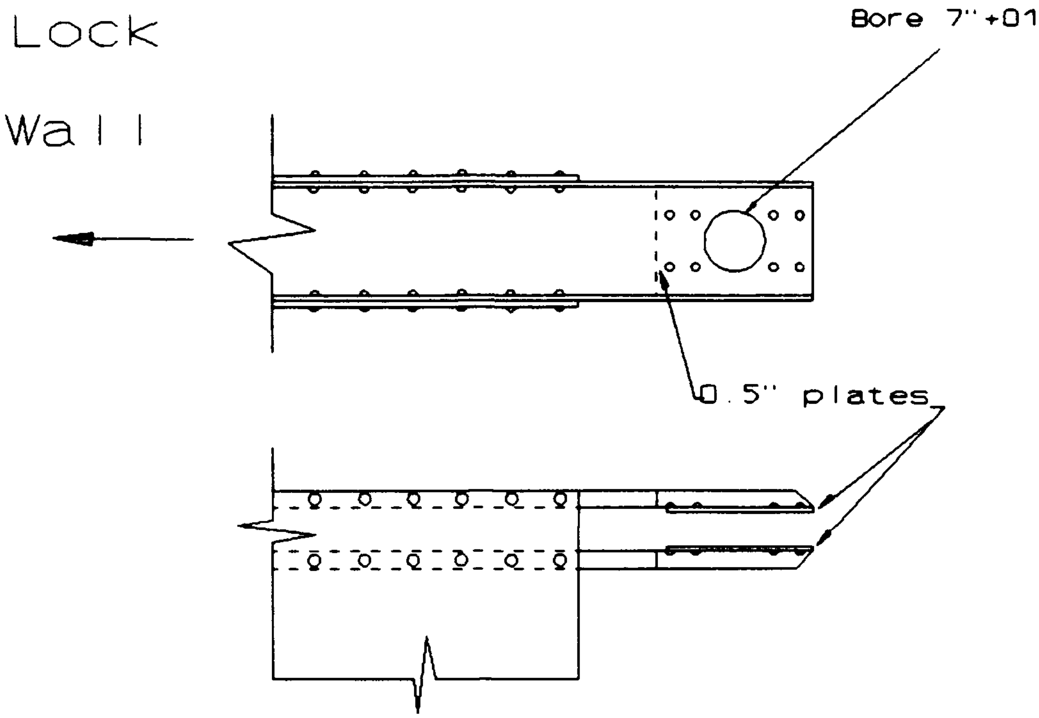

Figure 8. Lock and Dam 26 miter gate embedded top anchorage

anchorage and bolting a 1-in.-thick cover plate to the outside face of the channel web (see Photo 2). The type of bolts and base material used for the repairs is unknown and the failed surfaces were disposed of before an engineering assessment could be made of the fractured surface. The stress magnitude and distribution in the anchorage is unknown.

255. Two additional projects are known to contain a total of 16 similar top anchorage assemblies. These projects are not scheduled or budgeted to be replaced in the near future. In addition the geometry of the anchorage connection promotes ponding of water, and scaling and pitting have been observed at these remaining sites.

Design considerations

256. It should be recognized that the miter gate top anchorage is a tension nonredundant member and as such consideration should be given to specifying a minimum toughness requirement. This consideration should be extended to repair procedures when they become necessary. The possibility for impact loading should be considered. Toeing the top channel upward promotes ponding and pitting which may minimize cross sectional area and increase the stress concentration already created by the large hole itself. Detailed NDT

inspection procedures should be developed to inspect the anchorages at established service intervals. An allowable discontinuity size should be established where closure of the lock would be mandatory until adequate repairs are performed. Repair procedures developed and approved prior to a failure would provide timely information when necessary. The use of unknown material in making structural repairs is risky at best.

Distress of Spare Miter Gate at Lock and Dam 26

Description

257. As a result of a barge accident on 12 September 1989 in which a tow collided with the permanent gate at the downstream end of the main lock at Lock and Dam 26, a spare gate was assembled and temporarily installed. The spare gate consisted of five welded modular sections that were stacked vertically and field bolted together as shown in Figure 9. The spare gate was fabricated in 1969 and had previously been installed several times. On 27 October 1989 it was observed that the downstream flanges on three of the vertical girders cracked. The gate did not experience any hydrostatic loading greater than what was considered in the design.

Conditions

258. It is suspected that the failure occurred just prior to discovery of the cracks. Temperatures ranged between 30 and 90°F during this period. All three girders experienced similar crack profiles as shown in Photos 3, 4, and 5. It is speculated that the cracking originated on the downstream face of the 1.5 in. vertical girder flange in the HAZ at the toe of the transverse fillet weld where the 1-in.-thick attachment for the field bolted connection was located. The crack then propagated through the 1.5-in.-thick flange and into the web. Subsequent to the cracking the downstream face of the girder flanges were approximately 0.5 in. out of vertical alignment.

259. To expedite repairs, operation and maintenance personnel developed repair procedures without consultation with engineering division. The flange repair consisted of gouging the flanges along the crack length and filling the opening with weld metal then fillet welding two 3/4 in. by 1 in. by 8 in. bars across the crack (see Photo 6). The material specifications for the bars are unknown. The web repair consisted of filling the crack opening with weld metal.

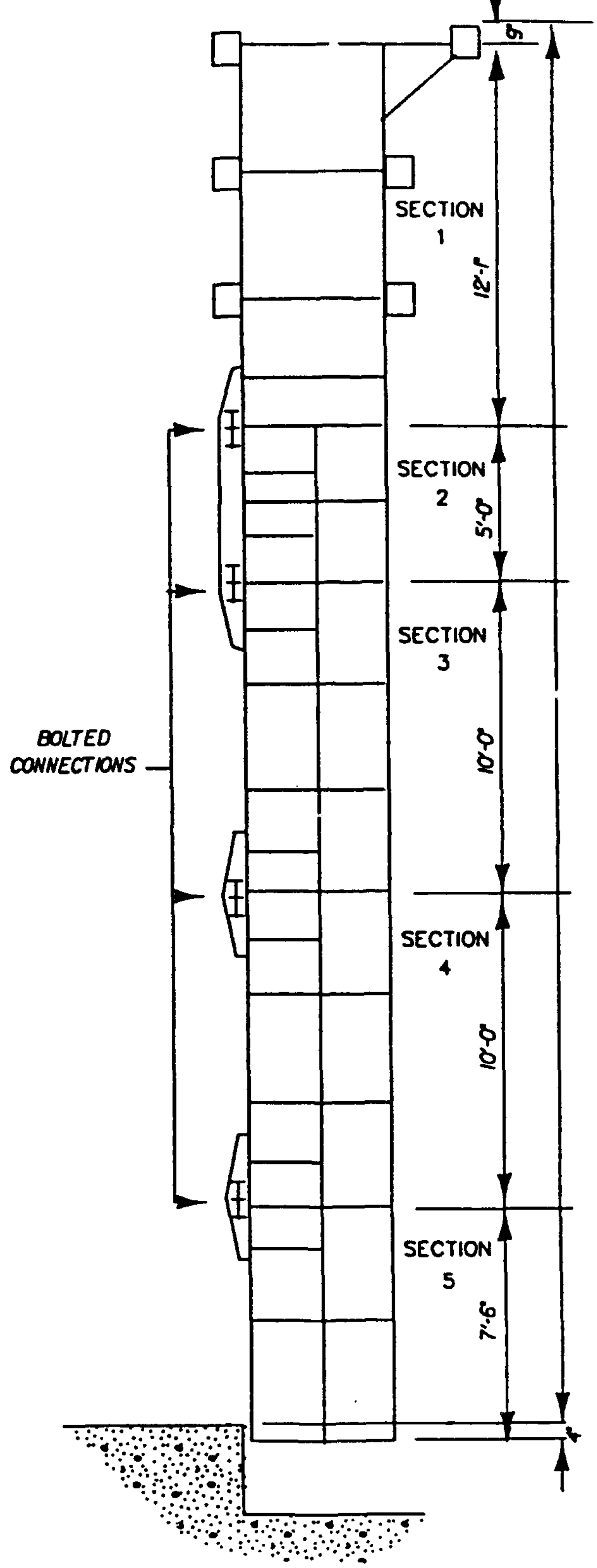

Figure 9. Spare miter gate assembly

Design considerations

260. The intersection of the 1-in.-thick plate on the attachment and the 1.5-in.-thick downstream flange creates a stress concentration and is considered a category E for fatigue.

261. The use of high fatigue categories were possible. Recent research (Chang and Lawrence 1983) has indicated that fatigue life can be increased by peening the weld. If the weld will be NDT, then the peening should be performed after the NDT work is completed. The development of an inspection interval and procedure should be considered for high fatigue category details. Consideration should be given to the number of cycles and stress range that will occur.

262. The repair that was performed increased the size of the stress concentration. The two small bars on the flange were not sufficient to transfer load across the repair and tend to be more detrimental to future serviceability. Repair procedures should be developed that will enhance the gate performance. Consideration should be given to developing repair procedures in advance such that timely repairs can be made in the future.

Tainter Gate Trunnion Girder Anchorage Assembly

Description

263. During initial fabrication of the tainter gate trunnion yoke for the right side of gate 2 at the Melvin Price Lock and Dam a discontinuity was located in the base material. The anchorage assembly is bolted to the dam trunnion girder and functions as the primary pin connection to transfer loads from the tainter gate struts to the dam trunnion girder. The assembly is composed of 4 and 3-3/4-in.-thick plates as shown in Figure 10. The plate material is ASTM-A572-50 and was inspected according to ASTM-A435 using ultrisonic testing at the mill.

Conditions

264. The welded tee connection between the yoke plates and the base plate is shown schematically in Figure 11. This connection required ultrasonic inspection of the groove welds. After the 4-in.-thick connection was welded and the ultrasonic inspection was being performed, it was determined that a 1-in. planar discontinuity existed in the base metal of the base plate approximately near the center of the tee connection as shown in Figure 11. Since this discontinuity could be contained in a 2-in.-diam circle, it was

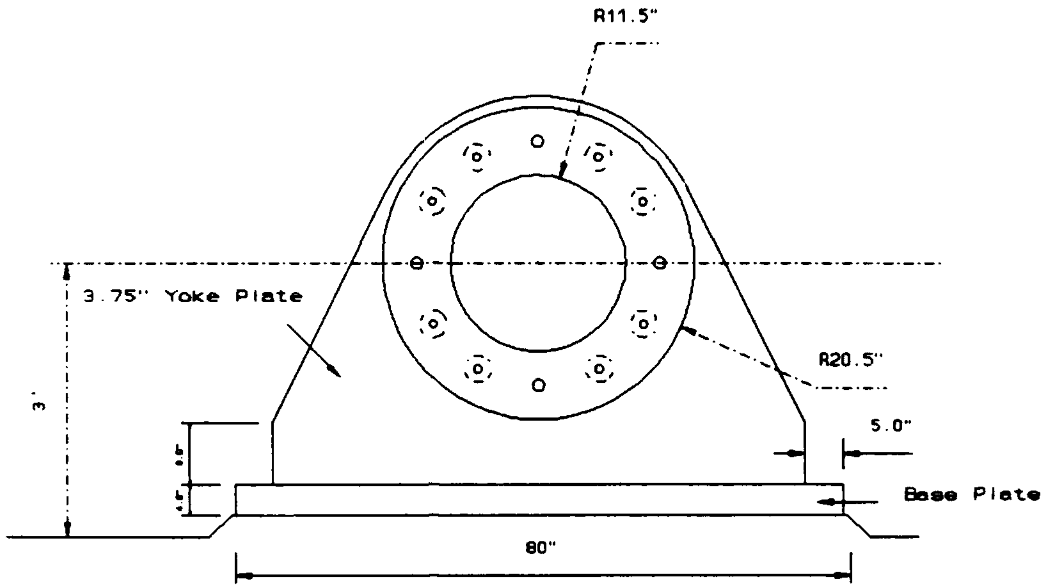

Figure 10. Tainter gate trunnion girder anchorage assembly

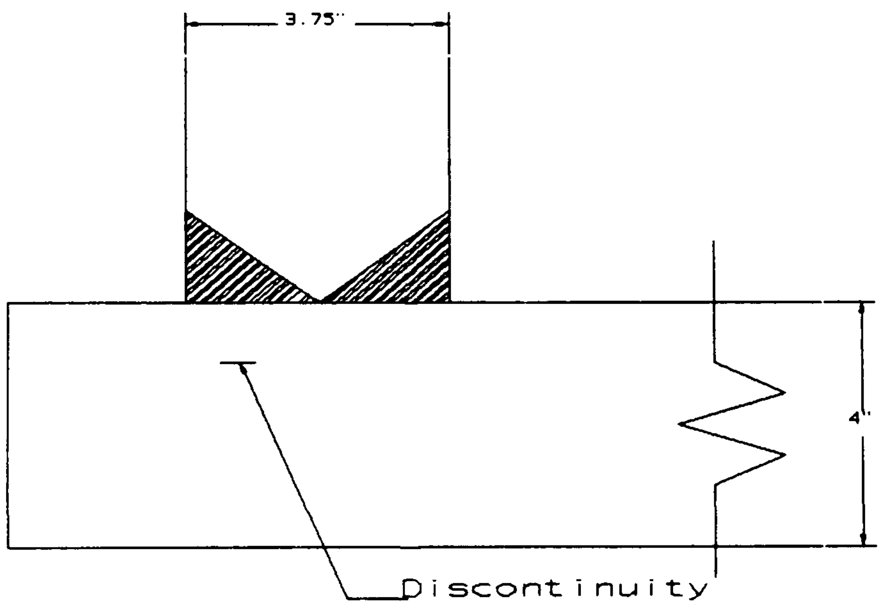

Figure 11. Anchorage assembly discontinuity

within the acceptable criteria of ASTM-A435 for the base metal. It was decided during fabrication, however, to gouge down to the discontinuity and repair the excavation with weld metal.

Design considerations

265. The cost of this repair could be considerably reduced by performing ultrasonic testing on 100% of the 4 in. wide surface of the base metal at the intersection of the tee connection prior to welding. Consideration should also be given to the significance that a 2 in. diameter circular discontinuity (ASTM-A435) could have on the serviceability of the trunnion yoke. Generally as plate thickness increases toughness decreases and for 4 in. thick plate its possible that the toughness is low. The influence from the tensile residual stress created from welding should also be considered. Consideration should be given to the selection of materials with higher toughness and through thickness properties such as ASTM-A610.

Tainter Gate Hitch at Melvin Price Lock and Dam

Description

266. Two tainter gate hitches at the Melvin Price Lock and Dam experienced cracking during fabrication. The tainter gate hitches were fabricated from 1.5-in. to 2-in.-thick ASTM-A36 material. The hitches are located at the bottom of the tainter gate and provide the connection between the lifting cables and the tainter gate. The hitches are primarily 3 ft by 5 ft by 2 ft welded boxes that are stiffened by several 1.5-in.-thick plates as shown in Figure 12. During fabrication a 6-in. by 3-in.-deep edge crack developed near the center of a 1.5-in.-thick plate. The crack occurred several hours after welding had been completed. As a precautionary matter, previously welded hitches were retested to determine if any delayed cracking had developed. A crack was identified in one additional hitch.

Conditions

267. The tainter gate hitch assembly was fabricated according to AWS D1.0. The fabrication sequence consisted of welding several plates into a box assembly. As the plates were added the constraint or rigidity of the box increased. The residual stress created from weld metal shrinkage became significant enough in the through plate thickness direction to cause lamellar tearing of the 1.5-in.-thick plates. The accumulated effect of this residual stress was time dependent. It was possible for one hitch to be completed and

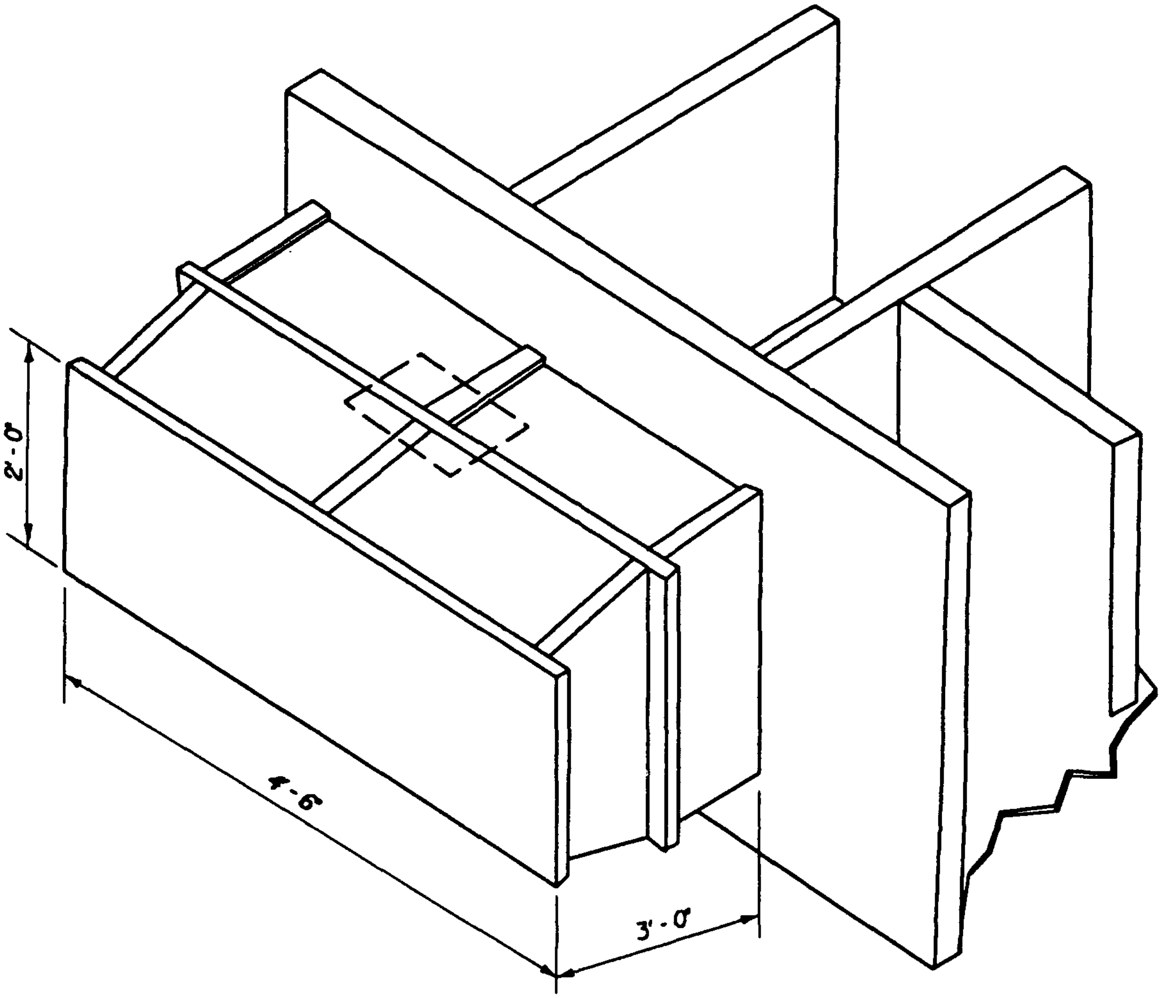

Figure 12. Tainter gate hitch connection

pass ultrasonic inspection prior to sufficient time being elapsed for a crack to develop.

Design considerations

268. When possible, joint details should be selected such that residual stress in the through thickness direction is minimized. When lamellar tearing and effects from welding residual stress are a concern, thermal mechanical finite element modeling can be used to analyze the problem (Jaeger, in preparation). The residual stress and potential for cracking can be minimized by modifying the welding procedures. The finite element analysis can be used as a tool to investigate what influence joint geometry, welding process, welding parameters, and weld sequence have on the residual stress magnitude and distribution in the through plate thickness. In addition, minimum toughness

requirements should be considered for the hitch since it is a critical non-redundant tension member. Low hydrogen welding procedures should be considered.

Cracked Lift Gate at Lock and Dam 27

Description

269. The upstream leaf of the upstream lift gate in the main and auxiliary lock chambers at Lock 27 was reported cracked on 1 March 1990. The cracks were observed coincidentally while the lock was dewatered for concrete repair. Each leaf consists of 6 horizontal tapered girders that span the 110 ft chamber. The girders are 8 ft 2 in. deep at the center of the chamber with a 7/16-in.-thick web. The gate was originally fabricated in 1953 for 8.2-ft head while supported on chains and 21.2-ft head while supported on rests. In 1960 the hydraulic criteria was increased to 17.3 ft for gate supported on chains, and 23.0 ft for the gate supported on rests. Cover plates were added to the downstream flanges, and the diagonal angle bracing was increased to account for the increased loading. The leaf is completely submerged during normal operation. A detailed inspection of the main lock chamber leaf identified over 100 cracks. Some of these cracks are identified by yellow in Photo 7. One of the most significant cracks extends approximately 3 ft into the web of a main horizontal girder.

Conditions

270. The gates were fabricated with a carbon steel material; however an in depth search was unable to locate a copy of this material specification. Review of the original design indicated that improper loading assumptions were made and omission of load cases existed. In addition, it was determined that the limit switches were incorrectly stopping the gate and causing excessive vertical hydrostatic loads. It was also determined by field inspection that the majority of the original welds would not satisfy current AWS criteria for weld surface profiles. The framing details for the vertical bracing on the downstream face of the leaf resulted in additional stress being developed from eccentric joints. Additionally, there was a reported barge impact to the top of the leaf in 1986.

271. Testing was performed to evaluate the strength, toughness (i.e. charpy V-notch) and weldability of the base metal. The results of these tests indicated that the material closely satisfied the yield strength and

elongation requirements for ASTM-A36 material. The carbon equivalents for the various members cracked ranged from 0.35 to 0.38. The charpy values were low ranging from 5 ft-lb at 32°F to 15 ft-lb at 70°F.

272. Repair procedures were developed by engineering division; however, to expedite the repair those procedures were not adhered to by field personnel. In addition, it was later determined that structural welds were being performed by welders who were not qualified according to AWS requirements.

Design considerations

273. Special attention should be given to eccentric connections and assumptions made for the degree of fixity at the end of a welded member. Consideration should be given to malfunctioning limit switches and the additional loads that could be created should a malfunction develop. Dewatering should be performed to inspect HSS that are submerged during a significant portion of there life. When evaluating existing HSS fabricated during the early 1950's consideration should be given to the possibility that low toughness exists and the ability of the material to resist crack propagation may be limited. Written repair procedures should be developed by engineering division and enforced. Only qualified welders should be allowed to perform welding repairs.

Failure of Cofferdam Sheet Pile Cell 68 a Melvin Price Lock and Dam

Description

274. Sheet pile 55 in cell 68 suddenly failed while construction activity was being performed on top of the cell. The crack was initiated at the top of the sheet pile where a partial flame cut existed in the web.

Construction

275. Construction of the cofferdam began on February 14, 1985 (2nd stage cofferdam) and was nearing completion on December 9, 1985 when sheet 55 in cell 68 suddenly failed. The cell was composed of PS32 and PSX32 sheet piles. The cell was approximately 63 ft in diameter and 50 ft high above the river bottom. A stability berm was necessary on the inside of the cofferdam. To construct the berm, sand was being off loaded from a barge on the outside of the cofferdam and stock piled on top of the cofferdam. Then a front end loader was used to move the sand from the top of the cofferdam to the inside area where the berm was to be located. The cell failed while the front end loader was performing these construction activities at the top of the cell

near the inward edge of the sheet piles. The crack in the sheet pile initiated at the top of the 3/8-in.-thick web where a partial flame cut existed and propagated approximately 40 ft downward. There were no flame cutting procedures on record. The ambient temperature at the time of failure was near freezing. Charpy test results indicated that the material had a transition temperature near 50°F.

Design considerations

276. Partially cutting the sheet pile into its web and stopping creates a notch or stress riser where a crack could easily initiate. In addition, the surface roughness or notches along the flame cut edge itself exceeded that specified by ANSI-B46.1. Flame cutting was being performed during cold weather without preheating; consequently a brittle martensitic structure existed along the flame cut edge. Once the crack was initiated at the partial cut, the material had little ability to resist propagation, especially considering that the ambient temperature at the time of the failure was below the transition temperature. Preheating should be considered in flame cutting procedures along with grinding flame cut surfaces on cellular cofferdams. Consideration should be given to restricting construction equipment from coming in contact with sheet piles. Specifying minimum toughness requirements or carbon equivalent should be considered. Steel sheet piling for use in cellular cofferdams should be considered as critical nonredundant tension members.

Summary

277. In general, most of the problems which are addressed here are a result of not using the most suitable detailing or quality control during construction. A common factor with each of these distressed hydraulic steel structures is that there are no formal documenting or reporting procedures that are required. Consideration for this would allow accumulation of data that can be used to improve future analysis, design, and repairs.

References

Chang, S. T., and Lawrence, F. V. 1983. "Improvement of Weld Fatigue Resistance," University of Illinois Report UILU-ENG 83-3602, Urbana, IL.

Tsai, C. L., Kim, D. S., Shim, Y. L., Feng, Z., Lee, S., and Jaeger, J. 1992. "Determination of Residual Stress and Effects in Thick-Section Weldments for Hydraulic Structures", Technical Report ITL-92-8, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Photo 1. Embedded gate anchorage failure

Photo 2. Embedded gate anchorage repair

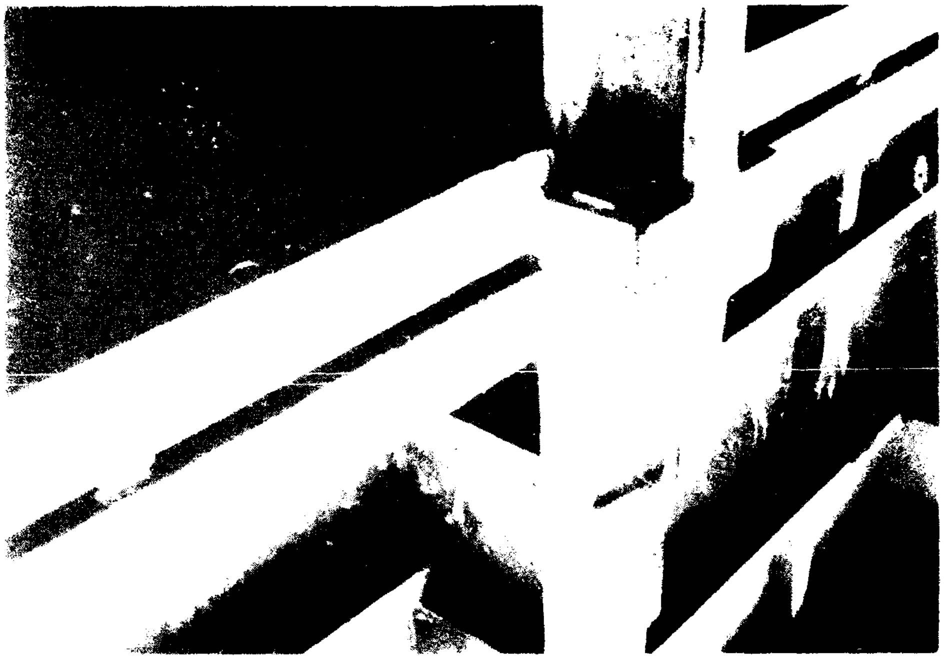

Photo 3. Vertical girder crack profile

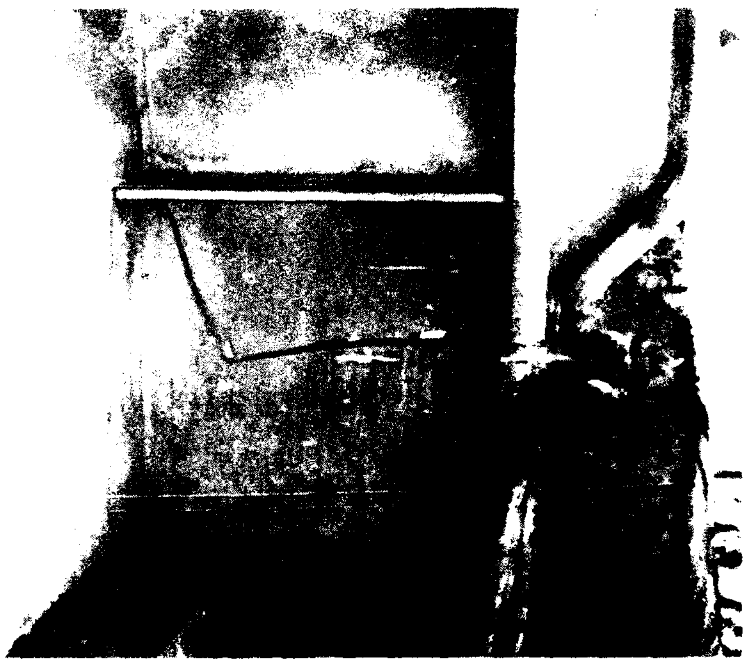

Photo 4. Vertical girder crack profile

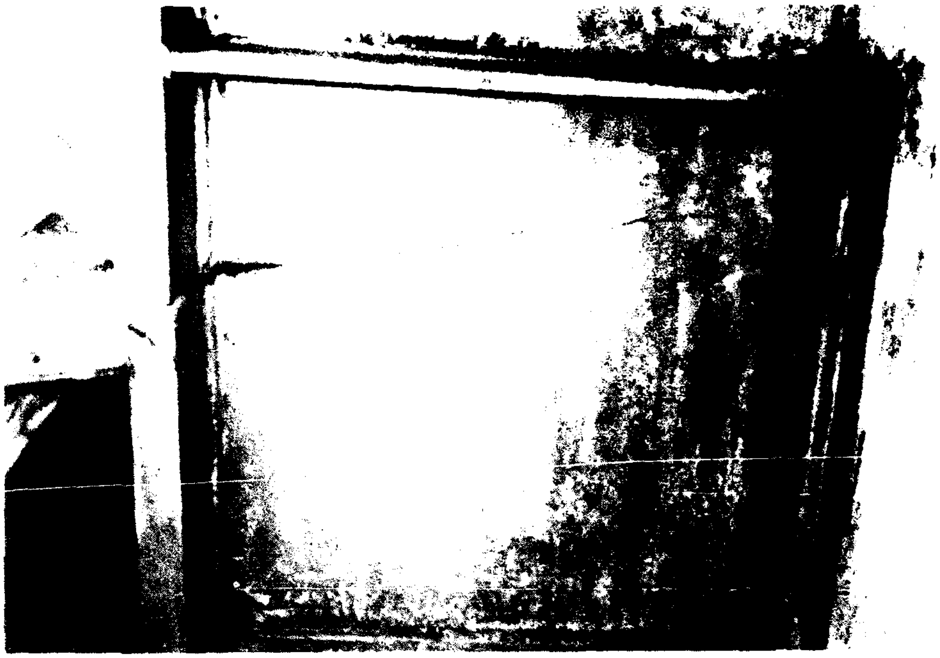

Photo 5. Vertical girder crack profile

Photo 6. Vertical girder field repair

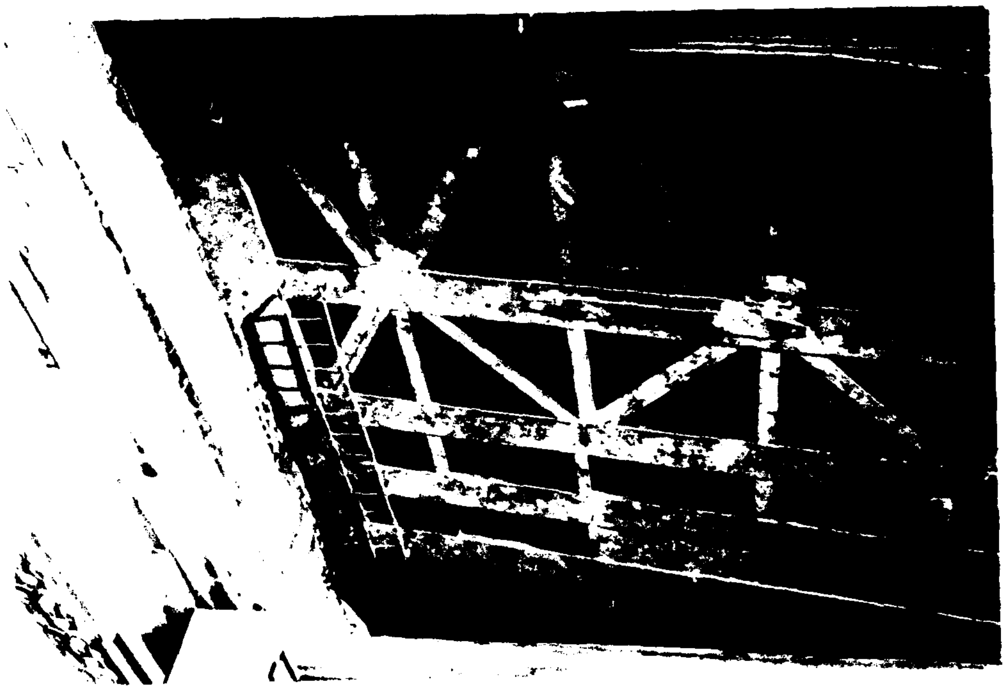

Photo 7. Lock and Dam 27 lift gate cracking

APPENDIX A: CASE PROJECT REPORTS

WATERWAYS EXPERIMENT STATION REPORTS PUBLISHED UNDER THE COMPUTER-AIDED STRUCTURAL ENGINEERING (CASE) PROJECT

	Title	Date
Technical Report K-78-1	List of Computer Programs for Computer-Aided Structural Engineering	Feb 1978
Instruction Report O-79-2	User's Guide: Computer Program with Interactive Graphics for Analysis of Plane Frame Structures (CFRAME)	Mar 1979
Technical Report K-80-1	Survey of Bridge-Oriented Design Software	Jan 1980
Technical Report K-80-2	Evaluation of Computer Programs for the Design/Analysis of Highway and Railway Bridges	Jan 1980
Instruction Report K-80-1	User's Guide: Computer Program for Design/Review of Curvilinear Conduits/Culverts (CURCON)	Feb 1980
Instruction Report K-80-3	A Three-Dimensional Finite Element Data Edit Program	Mar 1980
Instruction Report K-80-4	A Three-Dimensional Stability Analysis/Design Program (3DSAD)	
	Report 1: General Geometry Module	Jun 1980
	Report 3: General Analysis Module (CGAM)	Jun 1982
	Report 4: Special-Purpose Modules for Dams (CDAMS)	Aug 1983
Instruction Report K-80-6	Basic User's Guide: Computer Program for Design and Analysis of Inverted-T Retaining Walls and Floodwalls (TWDA)	Dec 1980
Instruction Report K-80-7	User's Reference Manual: Computer Program for Design and Analysis of Inverted-T Retaining Walls and Floodwalls (TWDA)	Dec 1980
Technical Report K-80-4	Documentation of Finite Element Analyses	
	Report 1: Longview Outlet Works Conduit	Dec 1980
	Report 2: Anchored Wall Monolith, Bay Springs Lock	Dec 1980
Technical Report K-80-5	Basic Pile Group Behavior	Dec 1980
Instruction Report K-81-2	User's Guide: Computer Program for Design and Analysis of Sheet Pile Walls by Classical Methods (CSHTWAL)	
	Report 1: Computational Processes	Feb 1981
	Report 2: Interactive Graphics Options	Mar 1981
Instruction Report K-81-3	Validation Report: Computer Program for Design and Analysis of Inverted-T Retaining Walls and Floodwalls (TWDA)	Feb 1981
Instruction Report K-81-4	User's Guide: Computer Program for Design and Analysis of Cast-in-Place Tunnel Linings (NEWTUN)	Mar 1981
Instruction Report K-81-6	User's Guide: Computer Program for Optimum Nonlinear Dynamic Design of Reinforced Concrete Slabs Under Blast Loading (CBARCS)	Mar 1981
Instruction Report K-81-7	User's Guide: Computer Program for Design or Investigation of Orthogonal Culverts (CORTCUL)	Mar 1981
Instruction Report K-81-9	User's Guide: Computer Program for Three-Dimensional Analysis of Building Systems (CTABS80)	Aug 1981
Technical Report K-81-2	Theoretical Basis for CTABS80: A Computer Program for Three-Dimensional Analysis of Building Systems	Sep 1981
Instruction Report K-82-6	User's Guide: Computer Program for Analysis of Beam-Column Structures with Nonlinear Supports (CBEAMC)	Jun 1982

(Continued)

WATERWAYS EXPERIMENT STATION REPORTS PUBLISHED UNDER THE COMPUTER-AIDED STRUCTURAL ENGINEERING (CASE) PROJECT

(Continued)

	Title	Date
Instruction Report K-82-7	User's Guide: Computer Program for Bearing Capacity Analysis of Shallow Foundations (CBEAR)	Jun 1982
Instruction Report K-83-1	User's Guide: Computer Program with Interactive Graphics for Analysis of Plane Frame Structures (CFRAME)	Jan 1983
Instruction Report K-83-2	User's Guide: Computer Program for Generation of Engineering Geometry (SKETCH)	Jun 1983
Instruction Report K-83-5	User's Guide: Computer Program to Calculate Shear, Moment, and Thrust (CSMT) from Stress Results of a Two-Dimensional Finite Element Analysis	Jul 1983
Technical Report K-83-1	Basic Pile Group Behavior	Sep 1983
Technical Report K-83-3	Reference Manual: Computer Graphics Program for Generation of Engineering Geometry (SKETCH)	Sep 1983
Technical Report K-83-4	Case Study of Six Major General-Purpose Finite Element Programs	Oct 1983
Instruction Report K-84-2	User's Guide: Computer Program for Optimum Dynamic Design of Nonlinear Metal Plates Under Blast Loading (CSDOOR)	Jan 1984
Instruction Report K-84-7	User's Guide: Computer Program for Determining Induced Stresses and Consolidation Settlements (CSETT)	Aug 1984
Instruction Report K-84-8	Seepage Analysis of Confined Flow Problems by the Method of Fragments (CFRAG)	Sep 1984
Instruction Report K-84-11	User's Guide for Computer Program CGFAG, Concrete General Flexure Analysis with Graphics	Sep 1984
Technical Report K-84-3	Computer-Aided Drafting and Design for Corps Structural Engineers	Oct 1984
Technical Report ATC-86-5	Decision Logic Table Formulation of ACI 318-77, Building Code Requirements for Reinforced Concrete for Automated Constraint Processing, Volumes I and II	Jun 1986
Technical Report ITL-87-2	A Case Committee Study of Finite Element Analysis of Concrete Flat Slabs	Jan 1987
Instruction Report ITL-87-1	User's Guide: Computer Program for Two-Dimensional Analysis of U-Frame Structures (CUFRAM)	Apr 1987
Instruction Report ITL-87-2	User's Guide: For Concrete Strength Investigation and Design (CASTR) in Accordance with ACI 318-83	May 1987
Technical Report ITL-87-6	Finite-Element Method Package for Solving Steady-State Seepage Problems	May 1987
Instruction Report ITL-87-3	User's Guide: A Three Dimensional Stability Analysis/Design Program (3DSAD) Module	Jun 1987
	Report 1: Revision 1: General Geometry	Jun 1987
	Report 2: General Loads Module	Sep 1989
	Report 6: Free-Body Module	Sep 1989

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WATERWAYS EXPERIMENT STATION REPORTS PUBLISHED UNDER THE COMPUTER-AIDED STRUCTURAL ENGINEERING (CASE) PROJECT

(Continued)

	Title	Date
Instruction Report ITL-87-4	User's Guide: 2-D Frame Analysis Link Program (LINK2D)	Jun 1987
Technical Report ITL-87-4	Finite Element Studies of a Horizontally Framed Miter Gate Report 1: Initial and Refined Finite Element Models (Phases A, B, and C), Volumes I and II Report 2: Simplified Frame Model (Phase D) Report 3: Alternate Configuration Miter Gate Finite Element Studies–Open Section Report 4: Alternate Configuration Miter Gate Finite Element Studies–Closed Sections Report 5: Alternate Configuration Miter Gate Finite Element Studies–Additional Closed Sections Report 6: Elastic Buckling of Girders in Horizontally Framed Miter Gates Report 7: Application and Summary	Aug 1987
Instruction Report GL-87-1	User's Guide: UTEXAS2 Slope-Stability Package; Volume I, User's Manual	Aug 1987
Instruction Report ITL-87-5	Sliding Stability of Concrete Structures (CSLIDE)	Oct 1987
Instruction Report ITL-87-6	Criteria Specifications for and Validation of a Computer Program for the Design or Investigation of Horizontally Framed Miter Gates (CMITER)	Dec 1987
Technical Report ITL-87-8	Procedure for Static Analysis of Gravity Dams Using the Finite Element Method – Phase 1a	Jan 1988
Instruction Report ITL-88-1	User's Guide: Computer Program for Analysis of Planar Grid Structures (CGRID)	Feb 1988
Technical Report ITL-88-1	Development of Design Formulas for Ribbed Mat Foundations on Expansive Soils	Apr 1988
Technical Report ITL-88-2	User's Guide: Pile Group Graphics Display (CPGG) Post-processor to CPGA Program	Apr 1988
Instruction Report ITL-88-2	User's Guide for Design and Investigation of Horizontally Framed Miter Gates (CMITER)	Jun 1988
Instruction Report ITL-88-4	User's Guide for Revised Computer Program to Calculate Shear, Moment, and Thrust (CSMT)	Sep 1988
Instruction Report GL-87-1	User's Guide: UTEXAS2 Slope-Stability Package; Volume II, Theory	Feb 1989
Technical Report ITL-89-3	User's Guide: Pile Group Analysis (CPGA) Computer Group	Jul 1989
Technical Report ITL-89-4	CBASIN–Structural Design of Saint Anthony Falls Stilling Basins According to Corps of Engineers Criteria for Hydraulic Structures; Computer Program X0098	Aug 1989

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WATERWAYS EXPERIMENT STATION REPORTS PUBLISHED UNDER THE COMPUTER-AIDED STRUCTURAL ENGINEERING (CASE) PROJECT

(Continued)

	Title	Date
Technical Report ITL-89-5	CCHAN–Structural Design of Rectangular Channels According to Corps of Engineers Criteria for Hydraulic Structures; Computer Program X0097	Aug 1989
Technical Report ITL-89-6	The Response-Spectrum Dynamic Analysis of Gravity Dams Using the Finite Element Method; Phase II	Aug 1989
Contract Report ITL-89-1	State of the Art on Expert Systems Applications in Design, Construction, and Maintenance of Structures	Sep 1989
Instruction Report ITL-90-1	User's Guide: Computer Program for Design and Analysis of Sheet Pile Walls by Classical Methods (CWALSHT)	Feb 1990
Technical Report ITL-90-3	Investigation and Design of U-Frame Structures Using Program CUFRBC Volume A: *Program Criteria and Documentation* Volume B: User's Guide for Basins Volume C: User's Guide for Channels	May 1990
Instruction Report ITL-90-6	User's Guide: Computer Program for Two-Dimensional Analysis of U-Frame or W-Frame Structures (CWFRAM)	Sep 1990
Instruction Report ITL-90-2	User's Guide: Pile Group–Concrete Pile Analysis Program (CPGC) Preprocessor to CPGA Program	Jun 1990
Technical Report ITL-91-3	Application of Finite Element, Grid Generation, and Scientific Visualization Techniques to 2-D and 3-D Seepage and Groundwater Modeling	Sep 1990
Instruction Report ITL-91-1	User's Guide: Computer Program for Design and Analysis of Sheet-Pile Walls by Classical Methods (CWALSHT) Including Rowe's Moment Reduction	Oct 1991
Instruction Report ITL-87-2 *(Revised)*	User's Guide for Concrete Strength Investigation and Design (CASTR) in Accordance with ACI 318-89	Mar 1992
Technical Report ITL-92-2	Fiinite Element Modeling of Welded Thick Plates for Bonneville Navigation Lock	May 1992
Technical Report ITL-92-4	Introduction to the Computation of Response Spectrum for Earthquake Loading	Jun 1992
Instruction Report ITL-92-3	Concept Design Example, Computer Aided Structural Modeling (CASM)	
	Report 1: Scheme A	Jun 1992
	Report 2: Scheme B	Jun 1992
	Report 3: Scheme C	Jun 1992
Instruction Report ITL-92-4	User's Guide: Computer-Aided Structural Modeling (CASM) - Version 3.00	Apr 1992
Instruction Report ITL-92-5	Tutorial Guide: Computer-Aided Structural Modeling (CASM) - Version 3.00	Apr 1992

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WATERWAYS EXPERIMENT STATION REPORTS PUBLISHED UNDER THE COMPUTER-AIDED STRUCTURAL ENGINEERING (CASE) PROJECT

(Concluded)

	Title	Date
Contract Report ITL-92-1	Optimization of Steel Pile Foundations Using Optimality Criteria	Jun 1992
Technical Report ITL-92-7	Refined Stress Analysis of Melvin Price Locks and Dam	Sep 1992
Contract Report ITL-92-2	Knowledge-Based Expert System for Selection and Design of Retaining Structures	Sep 1992
Contract Report ITL-92-3	Evaluation of Thermal and Incremental Construction Effects for Monoliths AL-3 and AL-5 of the Melvin Price Locks and Dam	Sep 1992
Instruction Report GL-87-1	User's Guide: UTEXAS3 Slope-Stability Package; Volume IV, User's Manual	Nov 1992
Technical Report ITL-92-11	The Seismic Design of Waterfront Retaining Structures	Nov 1992
Technical Report ITL-92-12	Computer-Aided, Field-Verified Structural Evaluation	
	Report 1: Development of Computer Modeling Techniques for Miter Lock Gates	Nov 1992
	Report 2: Field Test and Analysis Correlation at John Hollis Bankhead Lock and Dam	Dec 1992
Instruction Report GL-87-1	User's Guide: UTEXAS3 Slope-Stability Package; Volume III, Example Problems	Dec 1992
Technical Report ITL-93-1	Theoretical Manual for Analysis of Arch Dams	Jul 1993
Technical Report ITL-93-2	Steel Structures for Civil Works, General Considerations for Design and Rehabilitation	Aug 1993
Technical Report ITL-93-3	Soil-Structure Interaction Study of Red River Lock and Dam No. 1 Subjected to Sediment Loading	Sep 1993

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13. ABSTRACT *(Maximum 200 words)*

Design, repair, or rehabilitation of structural steel elements for civil works projects may require knowledge in a multitude of specialties such as allowable stresses, finite element analysis, material selection, buckling, welding, corrosion, and fatigue. This report provides additional background, guidance, and references in many of these specialty areas to enhance the capabilities of design engineers.

This report contains general considerations for structural design and repair of hydraulic steel structures on Corps of Engineers' civil works projects. The types of structures covered by this report include gates of all types, bulkheads, trash racks, and appurtenances for these structures, such as embedments and bearings.

The topics addressed in this report include material selection, minimum sizes, plate design requirements, connection design, welding, fabrication

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nondestructive testing methods, corrosion protection, and performance of hydraulic steel structures. Coverage of these topics is not comprehensive; it is more a collection of knowledge and experiences based on design and operation of Corps of Engineers projects.

14. (Concluded).

Allowable stress design	Fabrication	Material selection
Alloy elements	Fatigue	Nondestructive testing
Buckling	Fracture	Thickness
Connections	Galvanizing	Tolerance
Corrosion	Load and resistance factor design	Thickness
Detail		Welding
		Weldability