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MITIGATING CATASTROPHIC FAILURES IN STRUCTURES USED IN OFFSHORE OIL AND GAS PRODUCTION

MEAN YIELD STRENGTH DESIGN AND EVALUATION ISSUE
ASSURING THE STRUCTURAL INTEGRITY OF EXISTING STRUCTURES
ASSURING THE STRUCTURAL INTEGRITY OF NEW STRUCTURES

BOEMRE CONTRACT NO. M10PC00061

January 7, 2011

For:

THE UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF OCEAN ENERGY MANAGEMENT
REGULATION AND ENFORCEMENT

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With input from numerous technical specialists

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1.0 BACKGROUND AND CURRENT SIGNIFICANCE OF THIS STUDY

This project was launched in early 2010 by the Bureau of Ocean Energy Management Regulation and Enforcement (BOEMRE) of the United States Department of the Interior, formerly the Minerals Management Service. The initial intent of this work was to evaluate the acceptability of the industry's use of the mean yield strength of steel instead of the minimum specified yield strength in the structural evaluation of offshore platforms. This practice was evaluated herein and was found to reduce the safety margins against plastic collapse during overload by about 25 percent. Such safety margin reduction is unacceptable. Further work herein focused on efforts to assure the structural integrity of offshore structures using recent developments in materials, design and inspection technologies.

1.1 Importance of Yield Strength in Structural Design and Analysis

Yield strength is the practical elastic limit of steel (taken from tensile tests at 0.2 percent plastic strain.) When nominal stresses are greater than the steel's yield strength, permanent plastic deformation occurs. Steel manufacturer's designate the minimum yield strength of steel (Fy) in accordance with the American Society for testing and Materials' (ASTM) material testing requirements. In conventional structural design and strength analyses the allowable loads and stresses in a structure are specified fractions of the yield strength.

Structures, including oil and gas offshore structures, are designed to resist loads with a safety factor against the plastic limit load. Codes and Standards safety margins are based on the assumption that the yield strength of the steel is the manufacture's specified minimum yield strength. Studies of mean properties vs. minimum specified properties show that the mean properties are about 25 percent higher. In fact the ASME Code uses minimum specified yield strength values equal to 80 percent of the

mean values. Accordingly, use of the mean yield strengths in lieu of the minimum specified values would reduce the safety margins for overloads by 25 percent.

1.2 History of Yield Strength in API Standards

The American Petroleum Institute (API) in its API RP 2A 20th edition introduced the suggestion of using "mean" yield strength in the assessment of existing offshore structures. Along with this mean yield strength suggestion, they also introduced the concepts of exposure categories, ultimate strength analysis, and plastic analyses for the structural evaluation of offshore structures. The ultimate strength or limit load is directly proportional to the yield strength so the use of higher yield strengths reduces the safety margins proportionately.

1.3 Recent Operating Experience

Between 2005 and 2010, approximately 300 out of 3,000 oil and gas related structures in the Gulf of Mexico failed. Some of these failures disrupted energy production, impacted the environment, and resulted in costly clean up and removal efforts. BOEMRE has undertaken several studies to identify and evaluate methods to help prevent future offshore structure failures.

1.4 Organization of this Report

Our evaluation showed that the use of the mean yield strength in lieu of the minimum yield strength would compromise the required minimum safety margins for overloads of offshore oil and gas structures by about 25 percent which is unacceptable. Accordingly, this research went on to develop: (1) the best means to assure the structural integrity of existing offshore structures, and (2) the best means to assure the structural integrity of new offshore structures, and (3) the benefits of using new underwater corrosion and crack inspection technologies.

Procedures listed in the API Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms, API RP 2A, 20th edition, issued by the American Petroleum Institute use mean yield strength in their evaluations of the structural integrity of offshore facilities. BOEMRE has concerns that the use of mean yield strength provides an overly optimistic structural assessment of platforms. In fact, we found that it would reduce the safety margins against overloads by about 25 percent.

As this project evolved, the tasks were adjusted to include studies on available new technology that can improve structural reliability. Bridges and offshore platforms share many common features in terms of design issues, materials of construction, fabrication, and inspection. Moreover, both bridges and platforms must have a high degree of reliability to prevent both the loss of life and serious failure consequences. The reliability of bridges has been greatly improved by the introduction of Fracture Control Plans that integrate modern design, materials, fabrication, and inspection technologies

Tasks were also added to urgently determine the need for adding structural redundancy to existing platforms and to improve the reliability of structures using inspection practices based on new underwater inspection technology and by identifying where cracks are most likely to take place.

2.0 PROJECT SCOPE - TASKS

This report addresses the issue of using the mean yield strength in the design and structural evaluations of offshore structures. The effect of this practice of using the mean yield strength of steel in the evaluation of offshore platforms significantly reduces the resulting safety margins. This work includes the three tasks directly related to yield strength, tasks 1, 2, and 3. The report then addresses other opportunities and considerations for improving the structural integrity of offshore platforms in tasks 4, 5, and 6. Several referenced documents have been abstracted in Attachments for readers interested in a more in depth exploration of technical matters.

Tasks performed to evaluate offshore structure's design standards include the following:

1. Review purchase specifications for steels used in both non-critical and critical components of offshore structures. As the project progressed, the scope and details of the tasks have been adjusted. It became apparent that BOEMRE did not have access to purchase specifications necessary to carry out the tasks originally planned. This task was revised to include a commentary and overview of the A709 bridge specifications.

2. Review existing studies and their relevance to issues concerning the differences between specified (minimum) and mean yield strength. Provide an independent assessment of the acceptability of using mean yield strength values instead of minimum specified yield strength values in the assessment of offshore structures.

3. Review steel production practices that impact the difference between specified and mean yield strength.

4. Provide load capacity calculations showing the effect of using different levels of mean yield strength. This task was used to quantify the effect on the resulting structural safety margins against overloads.

5. Review selected reports to identify fabrication issues that may have contributed to failures of existing platforms. This task was revised to provide a summary of fabrication issues observed in bridge construction and failures involving materials and welding technology similar to that used offshore, and to provide an overview of Fracture and Fatigue Failure Control Plans.

6. Provide a protocol for assessing fabrication and workmanship issues on fatigue and fractures in offshore structures. This includes specifying ratings based on the category of selected fabrication details as outlined in construction codes. It would be very beneficial to incorporate this system into inspections carried out on offshore structures

3.0 SIGNIFICANCE OF YIELD STRENGTH IN STRUCTURAL INTEGRITY

The strength of structures is proportional to the static yield strength when the material is ductile and exhibits little strain hardening. Under overload conditions failure occurs at the limit load or plastic collapse load in offshore structures. Offshore structures can also fail due to dynamic loads where fatigue, fracture and toughness properties control the failure conditions. Such cyclic loading changes the static stress-strain response of the material by cyclic hardening and softening mechanisms into what is termed "cyclic stress-strain properties." Fatigue design curves and criteria used in Codes and Standards and the local strain concentrations at notches are controlled by the cyclic stress-strain properties. Cyclic stress-strain properties in Handbooks and Standards are typically correlated against the minimum specified yield strength of the material.

3.1 Issue of the use of Mean vs. Specified Minimum Yield Strengths

Yield strength is an essential part of the evaluation of plastic collapse of a platform. Plastic collapse is caused by nominal stresses exceeding the yield strength of the material at the limit load. Such overloads occur when the applied loads exceed the allowable loads by more than the safety factors. The Safety Factor is defined as the ratio of the failure load to the allowable design load. Accordingly, the use of yield strength values higher than the specified minimum values reduces the Safety Factor directly. This is because the allowable design load is proportional to the yield strength which is used. Of course there are other failure modes which can occur at lower loads are also important in offshore structures. These include fatigue, fracture and corrosion failures. Offshore structures are welded structures where:

- The Federal Emergency Management Agency (FEMA) founded a joint venture of the Structural Engineers Association of California, the applied Technology Council, and the California Universities for Research in Earthquake Engineers (SAC) to solve the problem of brittle fracture of welded steel frame structures. Their Interim Guidelines and Advisory Number 2 (FEMA 267/267B) Part 8 Commentary on Metallurgy and Welding states that recent studies conducted by the Structural Shape Producers Council (SSPC), indicate that material produced to the A36 specification (minimum yield strength = 36 ksi) has wide variation in strength properties with actual yield strengths that often exceed 50 ksi.[11]

- Division 1 - Subsection NH of Section III of the ASME Boiler and Pressure Vessel Code, " Rules for Construction of Nuclear Facility Components" contains <u>average</u> isochronous stress strain curves which were developed using values 25 percent higher than the

minimum specified yield and ultimate strength values of the structural materials. However, the designer is required to use the minimum specified yield and ultimate strength for all of the allowable stress limits in order to maintain the required minimum safety margins.

- Fatigue failures in welded structures are essentially independent of strength properties[6]. The resistance to fatigue failure for A36 is identical to a 100 ksi yield strength steel. Fatigue strength depends on the number of cycles needed to grow a fatigue crack to the critical crack size for fracture. Crack growth rates are essentially independent of the steel strength level.

- As the yield strength increases, the notch toughness generally decreases[7], thereby reducing the tolerance to imperfections associated with fabrication by welding. Notch toughness, because of its importance with respect to tolerance of imperfections, is described in detail in the next section of this Report.

- Structural quality steels, which are produced to ASTM A6[8] requirements, are often <u>not</u> tested in a comprehensive fashion. Per A6: “For plate in the thickness range 3/8" to 2," the minimum number of tensile tests per Table B (A6) are two tests per heat, one taken from the minimum thickness in the thickness range, and one taken from the maximum thickness in the thickness range.” Product acceptance for a large number of plates from a single heat can be based on only two tension tests.

- API RP 2A Section 17.3.3 suggests that "the actual (coupon test) or expected mean yield stresses may be used instead of nominal yield

stresses" in performing a structural assessment of an offshore platform. This suggestion would reduce the safety margins against both the limit load and plastic collapse loads proportionately. A statistical analysis of yield strength data for the relevant materials shows that the mean values are about 25 percent higher than the specified minimum values. Even the use of actual certified properties in lieu of minimum specified properties, proposed to the ASME Boiler and Pressure Vessel Code, was rejected by their technical committees as not meeting the safety margins of the Code.

- Codes and Standards including the ASME Boiler and Pressure Vessel Code Section II Ferrous Material Specifications use mean property trend curves vs. temperature, and take the minimum specified properties to be 80 percent of the mean values. Accordingly, the mean values are 25 percent higher than the minimum specified values, and their use would reduce the safety margins against plastic collapse overloads by 25 percent.

Because notch toughness is of paramount importance in terms of resistance to fracture, any API practice used for the evaluation of offshore platforms should include notch toughness.

Because fatigue and fracture are major failure mechanisms for aggressive loading such as a hurricane; it is important to recognize that the structural integrity of welded structures cannot be evaluated based entirely on yield strength. However, the use of the mean yield strength instead of the specified minimum yield strength would reduce the resulting overload safety margins about 25 percent below the minimum values established by operating experience, consensus Codes and Standards, and Public Policy.

3.2 Steel Fabrication Effects on Yield Strength

Many fabrication practices impact the yield strength in a manner which is not consistent or stable under cyclic long term loading:

1. Hot rolling practice affects the yield strength and applies to steels sold as hot rolled steel without heat treatment.

2. Steel chemical composition affects the yield strength. The influence of chemical composition is summarized in the Barsom[1] review on properties for structural steels. Carbon content has the greatest effect and increases strength while decreasing notch toughness and weldability.

3. Straightening operations used to make plate flat or structural shapes without camber tends to increase yield strength. Plate can also be supplied in coil form in gages up to about 5/8-inch thick. Plate supplied in coil form typically has some camber from the deformation associated with the coiling operation. Such strain hardening tends to increase the yield strength but also reduces its remaining ductility and fatigue strength when it is excessive.

4. Steels ordered to both strength properties and notch toughness requirements per Fracture Control Plans exhibit less difference between the mean and the specified values.

5. Heat treatment as part of the production practice effects the yield strength but such effects may be altered by the welding process.

There are comprehensive studies addressing how production practices affect the properties of steels used for offshore platforms. These include the Welding Research Council Bulletin on Mechanical Property Characteristics (Ref. 9), and the Metallurgical Societies Publication on the "Welding Metallurgy of Structural Steel" (Ref. 10). The Welding Research Council is a research arm of the ASME Code.

4.0 DESIGN, FABRICATION AND FAILURE PREVENTION

Offshore structures such as those used in the Gulf of Mexico have important similarities to bridges in terms of gravity loading and cyclic variable loading where the environment (salt water for platforms and road salt for bridges) can have a major impact on the service performance of these structures. Corrosion is especially important in cyclic loading because it accelerates damage.

The loss of life associated with the collapse of bridges in the 1970s resulted in a major effort to improve the structural integrity of bridges. The root cause of many of these bridge failures was fatigue cracking of non-redundant structural members (Refs 2 and 14). "Non-redundant" means that a local failure can cause the bridge to collapse or require it being taken out of service. A structural member of this type is now known as a “fracture critical” member; its failure results in the collapse of a major portion of the structure. As a result of bridge failures, collapse of modern bridges is now mitigated by “redundant” design that transfers the loading to other members when a local failure occurs.

In many ways, the extensive damage and destruction of offshore structures from major hurricanes parallels the bridge failure experience that resulted in the improvements realized in bridge design and construction. Collapse[14] of the I-35 Mississippi River Bridge on August 1, 2007 is a reminder that large structures can fail due to overload with the attendant lost of life. The safety margins for such overloads are proportionately reduced if a higher yield strength is used in their design and structural evaluation.

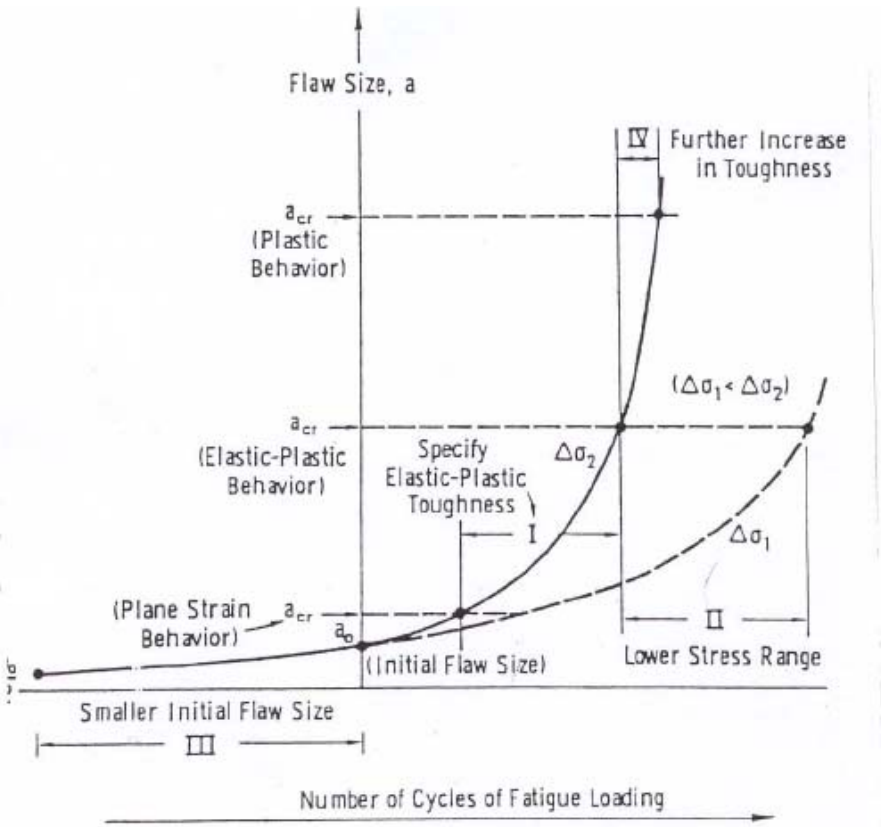
Important considerations in the prevention of catastrophic failures include the design, construction, in-service inspection, and Quality Assurance (such as Independent Fitness for Service Evaluations). Fracture Control and Fatigue Control Plans are key

elements of design and fabrication. Task 3 describes the materials used in bridges built to a Fracture Control Plan and Task 4 considers other important elements of the Fracture and Fatigue Control Plans.

These Plans contain the concept of redundancy, minimizing design details with reduce fatigue resistance because of stress concentration effects, and identifying key components where local failure causes major damage. It follows that inspection following exposure to unusual loading is important. Task 5 deals with the types and locations of cracking in welded structures and Task 6 deals with the assessment of existing platforms.

4.1 Notch Toughness

The following graph is presented on the cover of the Barsom Rolfe textbook (Ref. 12):



IG. 15.11 Schematic showing flaw size–fatigue life relations for various critical crack izes.

Inspection of this schematic graph shows the following:

- The number of cycles of fatigue loading (horizontal axis) that can be sustained is dependent on the critical flaw size (vertical axis) and the stress levels; two stresses ranges are shown, sigma 1 and sigma 2. The critical flaw size, a, is in turn controlled by the level of toughness and stress level. For a given stress the critical flaw size increases with toughness level. Toughness is strongly dependent on strain rate and temperature, especially for the type of steels used in structures. Strain rate effects are much higher for low strength steels than for high strength steels; above 140 ksi the effect is not significant.

Special Note: The development of high performance (low carbon martensitic microstructure) steels makes available steels that exhibit both high strength, superior weldability and excellent notch toughness; see A709[16]. These steels exhibit a high tolerance for imperfections that can enhance the local stresses (stress concentration) and therefore are excellent candidates for critical service.

Conclusions pertaining to offshore structures include:

A. A reduction in the initial flaw sizes increases the number of fatigue cycles substantially. See zone III on graph. Producing materials with small imperfections is more costly but is generally cost effective in minimizing failures. Fabrication is also a common source of imperfections especially for welded construction.
B. A reduction in the stress range level greatly increases the number of fatigue cycles that can be sustained. Because fatigue crack growth rate is roughly proportional to the stress raised to the power of 3, a small reduction in stress range has a marked effect on fatigue life. Under estimating the level of cyclic stress ranges results in a substantial over prediction of the life of the component.
C. When the design details are highly constrained against lateral contraction, the conditions approach “plane strain.” With low toughness, the critical flaw size can be very small. This is a condition promoting brittle fracture and a catastrophic event. When the toughness is moderate and stress concentrations are low, a relatively large number of fatigue cycles are required for failure. These are the conditions required by most bridge Codes.
D. Increasing the toughness allows for conditions where “crack arrest” is a possibility. Crack arrest occurs when a crack is growing into lower stressed material away from a stress raiser, and the crack stops growing. This behavior

occurs when the stress intensity at the top of the crack decreases in spite of the increase in stress intensity associated with the increased crack length.

4.2 Relevance of ASTM 709, Standard Specification for Structural Steel for Bridges

A709 was written specifically to be used with a Fracture Control Plan in conjunction with The American Association of State Highway and Transportation Officials and The American Welding Society (AASTO/AWS D1.5M/1.5). A709 provides useful back ground information on the Fracture Control Plan.

As detailed in Attachment 1, the document, “Properties of Bridge Steels” is a primary background document in that it contains a basic treatment of the metallurgical topics discussed herein. Attachment 2 shows the fatigue design curves for bridges using the “category” concept. As presented in the properties document (Attachment 1), letters A through E are used to identify various categories; A corresponds to un-welded plain plate, B corresponds to stiffeners welded to a plate, C through E are more complex geometries. Knowledge of the fatigue category of weldments provides a basis for focusing on the most likely location of a crack, and it is an opportunity for “intelligent inspection." Attachment 3 provides general information on A709 specification.

Attachment 3 (page 1 of A709) covers steels produced to yield strengths of 36, 50, 70, and 100 ksi, respectively. The four yield strengths cover the range of minimum strength levels to which structural grades of steel are produced. Structural grades are considered “generic” grades in contrast to “top-of-the-line” pressure vessel quality steels. The intent of A709 is to take the generic grades and incorporate them into a specification that provides pressure vessel steel qualities in requiring more testing, tighter ranges of chemical composition and tensile properties, and often stringent notch toughness

requirements. Of course, Pressure Vessel Quality steels are more costly than the generic structural grades but are well worth the extra cost in many offshore structures. (The term A36 for common structural steels comes from its parent specification and the fact that it is produced to a minimum yield strength of 36 ksi).

Attachment 4 contains two tables from A709; Table 1 lists the specified tensile and hardness properties for the nine steels listed in the Scope. Table 2 of Attachment 4 lists the chemical composition limits for A36; this table is identical to that shown in the parent specification. Attachment 5 provides more information on the nine steels listed in A709. Attachment 5 details the chemical composition limits for Grade 50 and Grade 50W of A709. The suffix W indicates the steel is a "weathering" grade; under alternating wet and dry conditions, the steel exhibits enhanced corrosion resistance.

Attachment 6 relates carbon content and carbon equivalent to weldability. Zone 1 refers to the most weldable steels and includes simple carbon steels; zone 2 refers to less weldable steels because of certain alloy additions, and zone 3 refers to least weldable steels. Basically all are weldable but the more difficult steels require greater control of preheat and welding parameters, such as interpass temperature and heat input. Controlling the carbon content increases weldability and toughness, both needed in offshore structures. By keeping the carbon to 0.08% maximum, the 100 ksi high performance steel (HPS) becomes a zone 1 type of steel with excellent weldability.

The A709 specification also includes separate notch toughness requirements for redundant and non-redundant bridge components. The toughness requirements are generally higher for a non-redundant component, providing more consistent safety margins.

4.3 Task 4 Fracture and Fatigue Failure Control Plans

Fracture Control and Fatigue Failure Control Plans are detailed procedures which:

1. Identify the factors that contribute to failure.
2. Assess the contribution of each factor including synergistic effects.
3. Quantify how these factors affect the margin to failure.
4. Assign responsibility for each task that affects the reliability of the structure through a Quality Control Program.

These Plans integrate the four key elements--design, materials, fabrication, and inspection that provide a high degree of structural reliability and maximize resistance to failure in a cost effective manner. While they do not provide 100% structural reliability, they balance good engineering, risk, and cost, so that there is a very high probability that the structure will survive even in unusually severe service.

Well engineered Fracture and Fatigue Control Plans integrated with a meaningful Quality Control Plan can reduce fabrication costs by “doing the job right the first time,” as well as the extreme costs of structural failures. It is also important to employ skilled welders in order to avoid poor workmanship and costly problems.

These plans require designs that recognize the severity of the service and reasonably anticipated loads which might compromise structural integrity. In the case of offshore structures, severe service involves the simultaneous loads imposed by currents, waves, and winds during a hurricane[21], and the related fatigue loading. Recognizing these loading conditions, it is necessary to make the design consistent with quality engineering avoiding fabrication details that enhance fabrication and inspection problems.

Local stresses are enhanced by stress concentration factors at geometrical discontinuities which result in non uniform stress distributions where local stresses are higher than the average stress. For example, the toe of a fillet weld exhibits a stress concentration factor of about three[22] and the ASME Code mandates the use of a fatigue strength reduction factor of four, which includes metallurgical notch effects. The fatigue and fracture of weldments is most prevalent at the weld toes. It follows that minimizing stress concentrations is an important design consideration. A large number of welded joints are fillet welds. Details of fillet weld design are available from the Welding Institute web site in the Job Knowledge for Welder series[23] (There are over 200 documents in the TWI series that offer brief discussions of topics discussed in the present Report.)

The designer has the opportunity to select materials for “fracture critical” components that lend themselves to quality welding. Selecting steels for welded construction should be based on minimizing the potential for fabrication induced imperfections. For example, selecting steels that are resistant to fabrication cracking without excessive preheating is an option with high performance steels such as those included in The American Society for Testing Material, ASTM A709, The Standard Specification for Structural Steel for Bridges. High preheats (up to 400 F) required by some ordinary steels makes welding uncomfortable for a workman and thereby contributes to poor workmanship especially under conditions of confined space. Fabricators of offshore platforms can benefit from ordering steel produced to the A709 specification which has been used in platforms operating in the North Sea[24].

The need of Fracture and Fatigue Failure Control Plans is illustrated by poorly designed double plates used to reinforce a ship mask, top figure of Attachment 8. The fillet weld near the deck has poor access for both the welding process and follow up inspection. The bottom table, Attachment 7 outlines the design consideration for platforms operating in the Gulf of Mexico. The highlighted item reflects the importance of

minimizing loss of life and prevention of an environmental damage event; key missions of the BOEMRE.

Attachment 8 shows tables listing the loading from a hurricane and the design consideration; bottom table. Key elements of the Fracture and Fatigue Control Plans include minimization of design details with high stress concentration factors, and the use of redundancy and High Performance Steels for fracture critical members of platforms. A further benefit of High Performance Steels is their low carbon content making them less prone to fabrication induced defects of the type causing cracking. The top picture, Attachment 9, shows a crack emanating from an attachment of a cover plate. The lower picture is of the addition of bolted plate to provide redundancy in a bridge structure. In Attachment 10, the top photograph shows a bridge where redundancy kept it from collapsing. The lower photograph shows the collapse of the Point Pleasant Bridge.

4.4 Task 5 Weld of Cracking in Structures

As already indicated, the FEMA studies that followed the Northridge Earthquake identified key items that contributed to the poor performance of weldments. Because of the importance of the studies on earthquakes, the Journal Of Materials In Civil Engineering, January/February 2002 devoted an entire issue to the lessons learned in this earthquake.

Welded connections performed poorly in the Northridge earthquake. The reasons for the poor performance were: 1. Many of the welds were made using low skilled workers, 2. Weld joints used “backup” bars allowing which interfere with good inspection, 3. Cracking often originated at cope holes that were “oxygen cut” for welding access, and 4. Welds used electrodes that did not have adequate notch toughness. These four

conditions made the poor performance an expected event during the dynamic loading conditions from the earthquake.

Attachment 11 shows figures illustrating the types of cracking observed in the Northridge earthquake. Cracks are associated with poor workmanship from gas cut cope holes which used for welder access or to relieve corner welding stresses. The numbered (1through 5) locations shown in the bottom of Attachment 11 are regions of high stress concentration and the location of cracking.

The type of information makes for effective failure prevention inspections. The final Attachment 12 illustrates some of the common types of imperfections that need to be addressed during inspections. Practices[20] that minimize these types of imperfections are presented in a Lincoln Electric brochure that can be accessed on Lincoln Electric Foundation web site.

4.5 Task 6 Evaluating Platforms Already In Service

"Fitness for Service" evaluations per API 579-1 / ASME FFS-1 provide the best means of quickly assessing the structural integrity of existing structures and identifying the need for adding additional structural redundancy. These evaluations should be made by independent Professional Engineers using Quality Assurance practices used in the nuclear industry.

For routine inspections, the AWS D1.1 Structural Welding Code is a reasonable standard for assessing structures. The selection of D1.1 has the advantage of AWS Standards for Visual Examination[26] and a Guide for Nondestructive[27] examination of welds. The visual examination should be supplemented by dye penetrate examination

to identify surface cracks. Penetrate examination uses capillary action to draw a liquid into a crack; this is followed by a "developer" that leaves dye mark outlining any crack. Penetrate testing is a relatively easy practice to learn and apply.

The value of an examination depends on the education and capabilities/training of the inspectors, their inspection technology, and accessibility. Education includes the identification of fracture critical members, the category of the weldment being examined, previous inspection results, and construction drawings. Information on the category of critical welded joints allows the inspector to focus on the most likely crack location(s). Such education and training is not typically provided to inspectors, and needs to be provided by high level professionals with extensive practical experience.

Limits on imperfections are detailed in AWS D1.1. The inspection should be based on conformance to this Code. Codes provide limits on overlap and undercutting because these fabrication details act as stress concentration factors. Specific documents that can be used by inspection are available through the AWS[26,27,28].

5.0 SUMMARY

The research conducted in this study showed that the API proposed use of mean yield strength in lieu of the minimum specified yield strength in the structural evaluation of offshore structures is not acceptable because it would reduce the minimum safety margins against overloads by up to 25 percent.

The structural integrity and reliability of existing structures and the need to add redundant supports can best be evaluated using API 579-1 / ASME FFS-1 Fitness for Service evaluations by Independent Professional Engineers.

The structural integrity and reliability of new offshore structures can best be assured by implementing Fracture Control and Fatigue Failure Control Plans in their design and construction.

The development of high performance (low carbon martensitic microstructure) steels has made available steels that exhibit high strength, superior weldability and excellent notch toughness; see ASTM A709. These steels exhibit a high tolerance for imperfections and therefore are excellent candidates for critical elements of offshore structures.

Recent developments in underwater inspection technology enable corrosion and cracking to be found. Moreover, welded joints can be classified in categories according to the fracture fragility in order to focus inspections on locations most likely to crack. Education, training and visual aids are needed for implementation by the inspectors.

6.0 RECOMMENDATIONS

We recommend that BOEMRE:

1. Research and provide specifications requiring owners of existing offshore structures to have independent Fitness-for-Service Evaluations performed by Professional Engineers per API 579-1/ASME FFS-1, including fatigue and fracture evaluations. The purpose of these evaluations is to determine what additional structural redundancy, if any, needs to be added to these structures to meet acceptable safety margins. The cost for this Independent Fitness for Service evaluations would be borne by the owners, and the results would be provided directly to BOEMRE. This would provide the quickest and most reliable evaluation of existing offshore structures. The model for this effort would follow the very successful Quality Assurance Structural Audits required by the Nuclear Regulatory Commission.

2. Research and provide the technical tools for BOEMRE management and professional personnel to enable them to effectively: (1) implement inspector/technician training to identify potential corrosion/fatigue damage on offshore structures, (2) coordinate new industry Fracture Control Plans, and (3) coordinate new Industry Fatigue Failure Control Plans.

3. Research and provide the technical elements for an industry supported Fracture Control Plan for the design, fabrication, inspection and repair of offshore structures. The successful Control Plan for Bridge Structures in the AAST O/AWS D1.5M/D1.5 Bridge Welding Code, an American National Standard, would be the model for this initiative.

4. Research and provide the technical elements for an industry supported Fatigue Failure Control Plan for the design, fabrication, inspection and repair of offshore structures. The model for this effort would be the British Department of Energy: "UK Offshore Installations: Guidance on Design and Construction – Fatigue of Welded Structures," and the American Society of Mechanical Engineers Section VIII Division 2 Code on Fatigue Design Criteria, which is an industry supported consensus standard.

5. Research new underwater inspection technology and provide BOEMRE inspectors with the specialized training and tools needed to locate potential corrosion and cracking in offshore structures and to obtain photos and data needed for evaluation by engineers. This would include the use of

inspection technology at and below the waterline. Individual Inspectors would have Classifications and be required to sign Inspection Reports for accountability.

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8.0 ATTACHMENTS

PROPERTIES OF BRIDGE STEELS

by Dr. JOHN M. BARSOM of USS Division/USX

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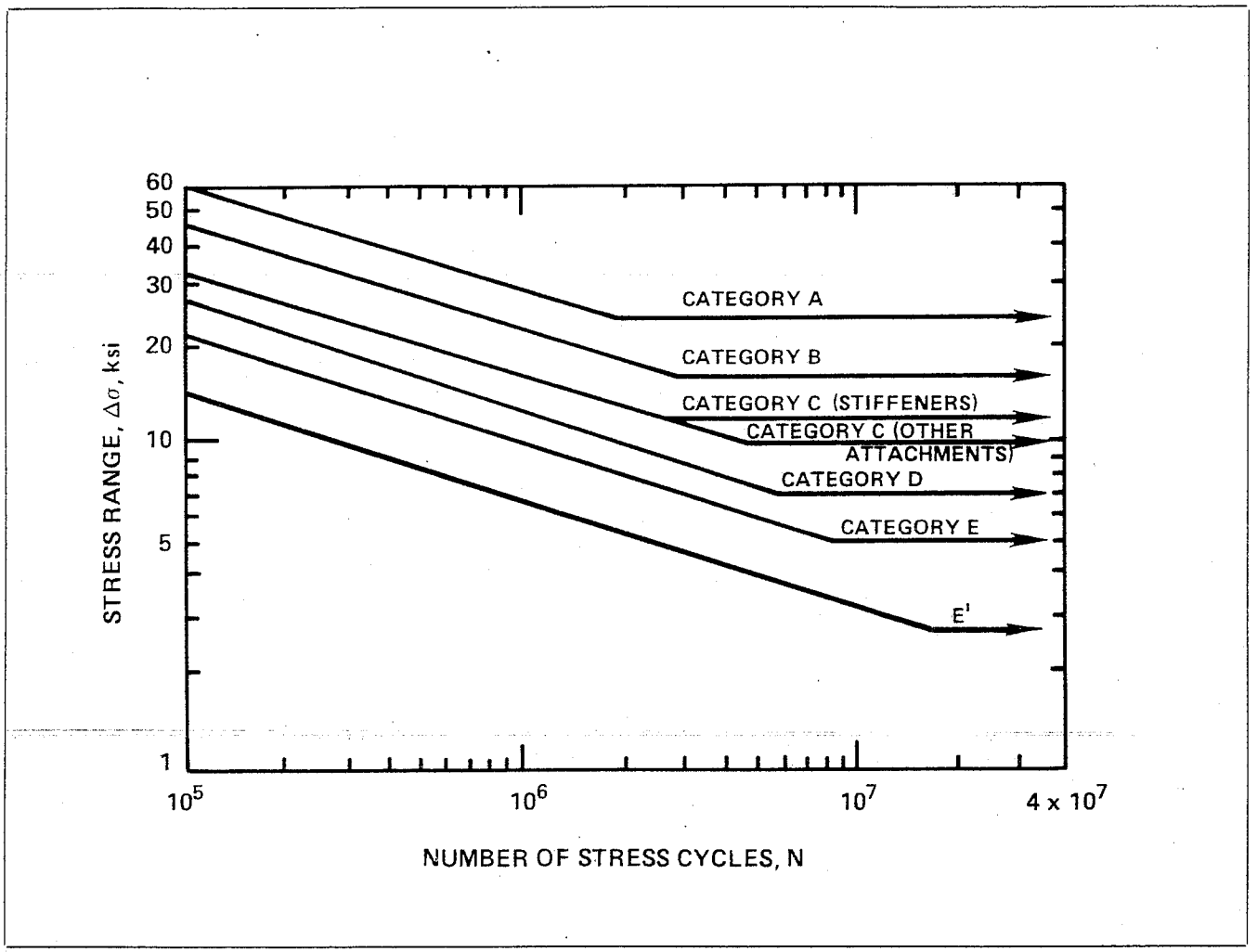

Figure 44.
Design stress range curves for categories A to E′.

Designation: A 709/A 709M – 06

Standard Specification for Structural Steel for Bridges[1]

This standard is issued under the fixed designation A 709/A 709M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This specification covers carbon and high-strength low-alloy steel structural shapes, plates, and bars and quenched and tempered alloy steel for structural plates intended for use in bridges. Nine grades are available in four yield strength levels as follows:

Grade U.S. [SI]	Yield Strength, ksi [MPa]
36 [250]	36 [250]
50 [345]	50 [345]
50S [345S]	50 [345]
50W [345W]	50 [345]
HPS 50W [HPS 345W]	50 [345]
HPS 70W [HPS 485W]	70 [485]
100 [690]	100 [690]
100W [690W]	100 [690]
HPS 100W [HPS 690W]	100 [690]

1.1.1 Grades 36 [250], 50 [345], 50S [345S], 50W [345W], 100 [690], and 100W [690W] are also included in Specifications A 36/A 36M, A 572/A 572M, A 992/A 992M, A 588/A 588M, and A 514/A 514M, respectively. When the supplementary requirements of this specification are specified, they exceed the requirements of Specifications A 36/A 36M, A 572/A 572M, A 992/A 992M, A 588/A 588M, and A 514/A 514M.

1.1.2 Grades 50W [345W], HPS 50W [HPS 345W], HPS 70W [HPS 485W], 100W [690W], and HPS 100W [HPS 690W] have enhanced atmospheric corrosion resistance (see 14.1.2). Product availability is shown in Table 1.

1.2 Grade HPS 70W [HPS 485W], 100 [690], 100W [690W], or HPS 100W [HPS 690W] shall not be substituted for Grades 36 [250], 50 [345], 50S [345S], 50W [345W], or HPS 50W [HPS 345W]. Grade 50W [345W], or HPS 50W [HPS 345W] shall not be substituted for Grades 36 [250], 50 [345] or 50S [345S] without agreement between the purchaser and the supplier.

1.3 When the steel is to be welded, it is presupposed that a welding procedure suitable for the grade of steel and intended use or service will be utilized. See Appendix X3 of Specification A 6/A 6M for information on weldability.

1.4 For structural products to be used as tension components requiring notch toughness testing, standardized requirements are provided in this standard, and they are based upon American Association of State Highway and Transportation Officials (AASHTO) requirements for both fracture critical and non-fracture critical members.

1.5 Supplementary requirements are available but shall apply only if specified in the purchase order.

1.6 The values stated in either inch-pound units or SI units are to be regarded separately as standard. Within the text, the SI units are shown in brackets. The values stated in each system are not exact equivalents; therefore, each system is to be used independently of the other, without combining values in any way.

1.7 For structural products produced from coil and furnished without heat treatment or with stress relieving only, the additional requirements, including additional testing requirements and the reporting of additional test results, of Specification A 6/A 6M apply.

2. Referenced Documents

2.1 *ASTM Standards:* [2]

A 6/A 6M Specification for General Requirements for Rolled Structural Steel Bars, Plates, Shapes, and Sheet Piling

A 36/A 36M Specification for Carbon Structural Steel

A 370 Test Methods and Definitions for Mechanical Testing of Steel Products

A 514/A 514M Specification for High-Yield-Strength, Quenched and Tempered Alloy Steel Plate, Suitable for Welding

A 572/A 572M Specification for High-Strength Low-Alloy Columbium-Vanadium Structural Steel

A 588/A 588M Specification for High-Strength Low-Alloy Structural Steel with 50 ksi [345 MPa] Minimum Yield Point to 4 in. [100 mm] Thick

A 673/A 673M Specification for Sampling Procedure for Impact Testing of Structural Steel

[1] This specification is under the jurisdiction of ASTM Committee A01 on Steel, Stainless Steel, and Related Alloys and is the direct responsibility of Subcommittee A01.02 on Structural Steel for Bridges, Buildings, Rolling Stock, and Ships.

Current edition approved March 15, 2006. Published March 2006. Originally approved in 1974. Last previous edition approved in 2005 as A 709/A 709M– 05.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

***A Summary of Changes section appears at the end of this standard.**

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TABLE 1 Tensile and Hardness Requirements[A]

NOTE 1— Where "..." appears in this table, there is no requirement.

Grade	Plate Thickness, in. [mm]	Structural Shape Flange or Leg Thickness, in. [mm]	Yield Point or Yield Strength,[B] ksi [MPa]	Tensile Strength, ksi [MPa]	Minimum Elongation, %				Reduction of Area[C,D] min, %	Brinell Hardness Number
					Plates and Bars[C,E]		Shapes[E]			
					8 in. or 200 mm	2 in. or 50 mm	8 in. or 200 mm	2 in. or 50 mm		
36 [250]	to 4 [100], incl	to 3 in. [75 mm], incl	36 [250] min	58–80 [400–550]	20	23	20	21	...	...
		over 3 in. [75 mm]	36 [250] min	58 [400] min	...	...	20	19	...	...
50 [345]	to 4 [100], incl	all	50 [345] min	65 [450] min	18	21	18	21[F]	...	...
50S [345S]	[G]	all	50–65 [345–450][H]	65 [450][H] min	...	...	18	21	...	...
50W [345W] and HPS 50W [HPS 345W]	to 4 [100], incl	all	50 [345] min	70 [485] min	18	21	18	21[I]	...	...
HPS 70W [HPS 485 W]	to 4 [100], incl	[G]	70 [485] min[B]	85–110 [585–760]	...	19[J]	...	...	...	...
100 [690], 100W [690W], and HPS 100W [HPS 690W]	to 2½ [65], incl	[G]	100 [690] min[B]	110–130 [760–895]	...	18[J]	...	...	[K]	235–293[L]
100 [690] and 100W [690 W]	over 2½ to 4 [65 to 100]	[G]	90 [620] min[B]	100–130 [690–895]	...	16[J]	...	...	[K]	...

[A] See specimen orientation and preparation subsection in the Tension Tests section of Specification A 6/A 6 M.
[B] Measured at 0.2 % offset or 0.5 % extension under load as described in Section 13 of Test Methods A 370.
[C] Elongation and reduction of area not required to be determined for floor plates.
[D] For plates wider than 24 in. [600 mm], the reduction of area requirement, where applicable, is reduced by five percentage points.
[E] For plates wider than 24 in. [600 mm], the elongation requirement is reduced by two percentage points. See elongation requirement adjustments in the Tension Tests section of Specification A 6/A 6M.
[F] Elongation in 2 in. or 50 mm: 19 % for shapes with flange thickness over 3 in. [75 mm].
[G] Not applicable.
[H] The yield to tensile ratio shall be 0.87 or less for shapes that are tested from the web location; for all other shapes, the requirement is 0.85.
[I] For wide flange shapes with flange thickness over 3 in. [75 mm], elongation in 2 in. or 50 mm. of 18 % minimum applies.
[J] If measured on the Fig. 3 (Test Methods A 370) 1½ –in. [40–mm] wide specimen, the elongation is determined in a 2-in. or 50-mm. gage length that includes the fracture and shows the greatest elongation.
[K] 40 % minimum applies if measured on the Fig 3 (Test Methods A 370) 1 ½ –in. [40-mm] wide specimen; 50 % minimum applies if measured on the Fig. 4 (Test Methods A 370) ½ –in. [12.5-mm] round specimen.
[L] Applies only to Grades 100 [690] and 100W [690W] plates that are ⅜ in. [10 mm] or less in thickness and are not tension tested (See 8.1).

TABLE 2 Grade 36 [250] Chemical Requirements (Heat Analysis)

NOTE 1— Where "..." appears in this table there is no requirement. The heat analysis for manganese shall be determined and reported as described in the Heat Analysis section of Specification A 6/A 6M.

Product Thickness, in. (mm)	Shapes[A] All	Plates[B]				Bars[B]		
		To ¾ [20], incl	Over ¾ to 1½ [20 to 40], incl	Over 1½ to 2½ [40 to 65], incl	Over 2½ to 4 [65 to 100], incl	To ¾ [20], incl	Over ¾ to 1½ [20 to 40], incl	Over 1½ to 4 [100], incl
Carbon, max, %	0.26	0.25	0.25	0.26	0.27	0.26	0.27	0.28
Manganese, %	...	...	0.80–1.20	0.80–1.20	0.85–1.20	...	0.60–0.90	0.60–0.90
Phosphorus, max, %	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Sulfur, max, %	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Silicon, %	0.40 max	0.40 max	0.40 max	0.15–0.40	0.15–0.40	0.40 max	0.40 max	0.40 max
Copper, min, % when copper steel is specified	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20

[A] Manganese content of 0.85 to 1.35 % and silicon content of 0.15 to 0.40 % is required for shapes with flange thickness over 3 in. [75 mm].
[B] For each reduction of 0.01 % below the specified carbon maximum, an increase of 0.06 % manganese above the specified maximum will be permitted up to a maximum of 1.35 %.

A 992/A 992M Specification for Structural Steel Shapes
G 101 Guide for Estimating the Atmospheric Corrosion Resistance of Low-Alloy Steels

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

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TABLE 3 Grade 50 [345] Chemical Requirements[A] (Heat Analysis)

Maximum Diameter, Thickness, or Distance Between Parallel Faces, in. [mm]	Carbon, max, %	Manganese,[B] max, %	Phosphorus, max, %	Sulfur, max, %	Silicon[C]		Columbium, Vanadium and Nitrogen
					Plates to 1½-in. [40–mm] Thick, Shapes with flange or leg thickness to 3 in. [75 mm] inclusive, Sheet Piling, Bars, Zees, and Rolled Tees, max, %[D]	Plates Over 1½ –in. [40-mm] Thick and Shapes with flange thickness over 3 in. [75 mm], %	
4 [100]	0.23	1.35	0.04	0.05	0.40	0.15–0.40	[E]

[A]Copper when specified shall have a minimum content of 0.20 % by heat analysis (0.18 % by product analysis).
[B]Manganese, minimum by heat analysis of 0.80 % (0.75 % by product analysis) shall be required for all plates over ⅜ in. [10 mm] in thickness; a minimum of 0.50 % (0.45 % by product analysis) shall be required for plates ⅜ in. [10 mm] and less in thickness, and for all other products. The manganese to carbon ratio shall not be less than 2 to 1. For each reduction of 0.01 percentage point below the specified carbon maximum, an increase of 0.06 percentage point manganese above the specified maximum is permitted, up to a maximum of 1.50 %.
[C]Silicon content in excess of 0.40 % by heat analysis must be negotiated.
[D]Bars over 1 ½ in. [40 mm] in diameter, thickness, or distance between parallel faces, shall be made by a killed steel practice.
[E]Alloy content shall be in accordance with Type 1, 2, 3, or 5 and the contents of the applicable elements shall be reported on the test report.

Type	Elements	Heat Analysis, %
1	Columbium[A]	0.005–0.05[B]
2	Vanadium	0.01–0.15
3	Columbium[A]	0.005–0.05[B]
	Vanadium	0.01–0.15
	Columbium plus vanadium	0.02–0.15[C]
5	Titanium	0.006–0.04
	Nitrogen	0.003–0.015
	Vanadium	0.06 max

[A] Columbium shall be restricted to Grade 50 [345] plate, bar, zee, and rolled tee thickness of ¾ in. [20 mm] max, and to shapes with flange or leg thickness to 1½ in. [40 mm] inclusive unless killed steel if furnished. Killed steel shall be confirmed by a statement of killed steel on the test report, or by a report of the presence of a sufficient quantity of a strong deoxidizing element, such as silicon at 0.10 % or higher, or aluminum at 0.015 % or higher.
[B] Product analysis limits = 0.004 to 0.06 %.
[C] Product analysis limits = 0.01 to 0.16 %

TABLE 4 Grade 50W [345 W] Chemical Requirements (Heat Analysis)

NOTE 1—Types A, B, and C are equivalent to Specification A 588/A 588M Grades A, B, and C, respectively.

Element	Composition, %[A]		
	Type A	Type B	Type C
Carbon[B]	0.19 max	0.20 max	0.15 max
Manganese[B]	0.80–1.25	0.75–1.35	0.80–1.35
Phosphorus	0.04 max	0.04 max	0.04 max
Sulfur	0.05 max	0.05 max	0.05 max
Silicon	0.30–0.65	0.15–0.50	0.15–0.40
Nickel	0.40 max	0.50 max	0.25–0.50
Chromium	0.40–0.65	0.40–0.70	0.30–0.50
Copper	0.25–0.40	0.20–0.40	0.20–0.50
Vanadium	0.02–0.10	0.01–0.10	0.01–0.10

[A] Weldability data for these types have been qualified by FHWA for use in bridge construction.
[B] For each reduction of 0.01 percentage point below the specified maximum for carbon, an increase of 0.06 percentage point above the specified maximum for manganese is permitted, up to a maximum of 1.50 %.

3.1.1 *fracture critical member*—a main load-carrying tension member or tension component of a bending member whose failure would be expected to cause collapse of a structure or bridge without multiple, redundant load paths.

3.1.2 *main load-carrying member*—a steel member designed to carry primary design loads, including dead, live, impact, and other loads.

3.1.3 *non-fracture critical member*—a main load-carrying member whose failure would not be expected to cause collapse of a structure or bridge with multiple, redundant load paths.

3.1.4 *secondary member*—a steel member used for aligning and bracing of main load-carrying members, or for attaching utilities, signs, or other items to them, but not to directly support primary design loads

3.1.5 *tension component*—a part or element of a fracture critical or non-fracture critical member that is in tension under various design loadings.

4. Ordering Requirements

4.1 In addition to the items listed in the ordering information section of Specification A 6/A 6M, the following items should be considered if applicable:

4.1.1 Type of tension component, non-fracture critical or fracture critical (see Section 10).

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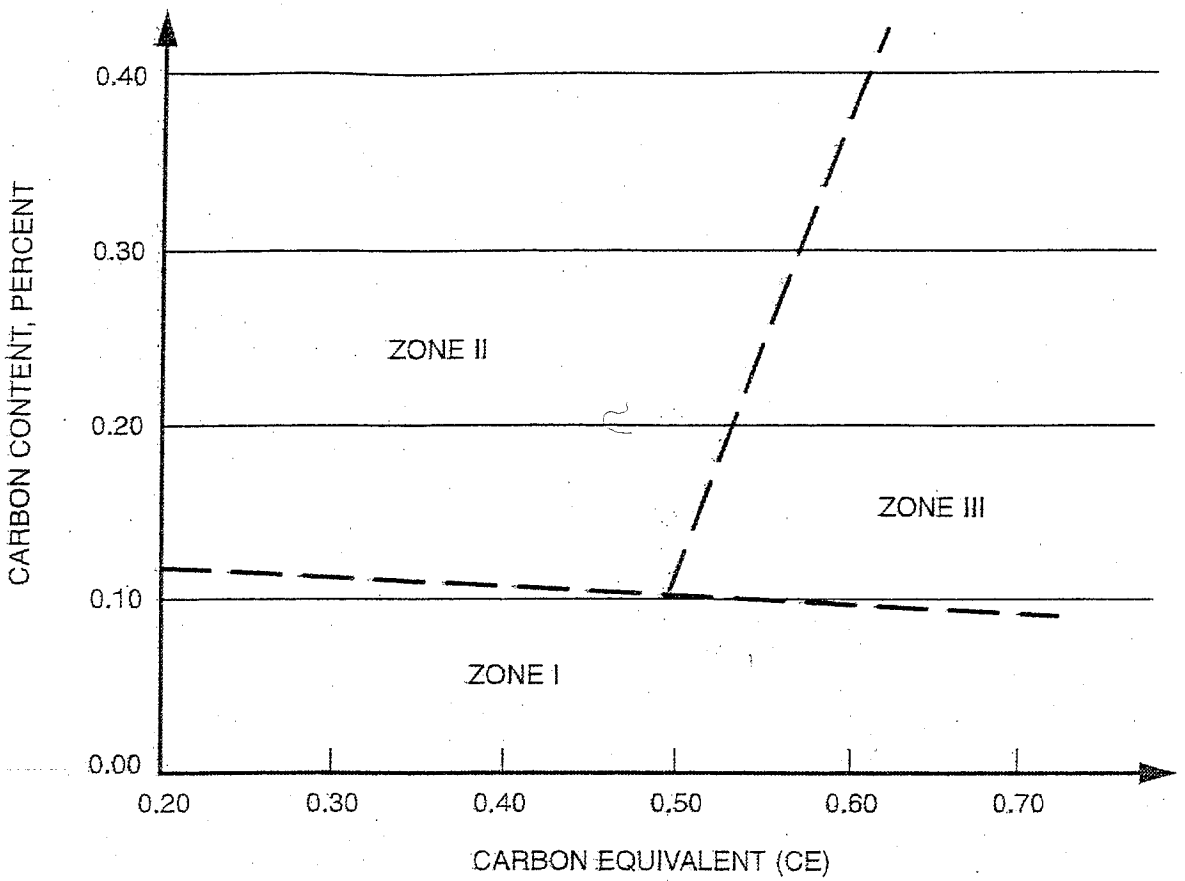

General Notes:

- CE = C + (Mn + Si)/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15.
- See VIII5.2.1, VIII5.2.2, or VIII5.2.3 for applicable zone characteristics.

Figure VIII-1—Zone Classification of Steels (see VIII5.1)

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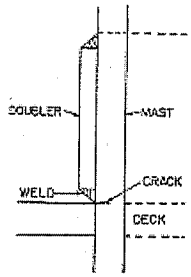
Example of Need for FCP "Doubler" Plate on Ship Mask

Fabrication

Inspection



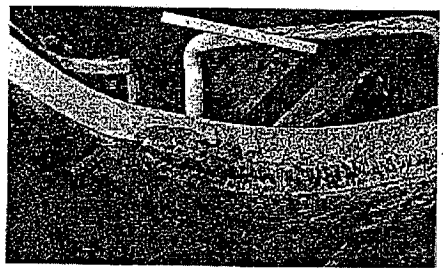


Fig. 1—Ship mast failure by brittle fracture.

7

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Design Considerations for Platforms

- Resist Destruction from Hurricanes by Cyclic Loading.
- Partial Submersion in Ocean Waters.
- Limited Access to Repairs and/or Retrofits.
- **Protection of Life and Prevention of Environmental Damage are Major Considerations for BOEMRE.**
- Structures May Undergo Severe Loading During Transportation and Installation; Limited Damage Tolerance.

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Loading from Hurricane

- Dead weight from the structure itself.
- Wave Action cyclic loading
- Strong winds cyclic loading
- Strong Currents cyclic loading

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Design Considerations (Fatigue Loading)

- Avoid Stress Concentration Details in Design
- Locate Welds in Low Stress Regions
- Avoid Potential for Corrosion Issues
- **Provide Redundancy for Fracture Critical Elements (Can be added to existing structures.**
- Enhance Fatigue Strength – AWS D1.5 Bridges Welding Code
- **Minimize crack like imperfections during fabrication.**

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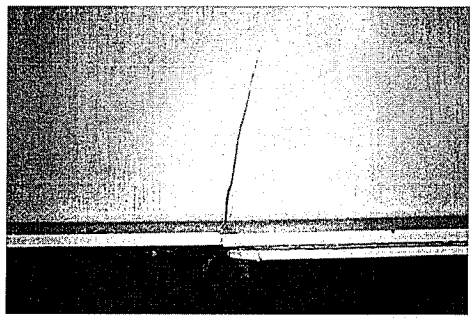

FIGURE 2 Development of fatigue crack at cover plate ends on the multibeam Yellow Mill Pond Bridge in Connecticut in 1976. (*Courtesy:* John W. Fisher.)

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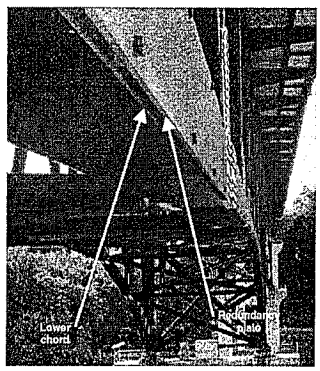

FIGURE 13 Redundancy plate bolted to lower chord of SR-33 bridge near Easton, Pennsylvania. (*Courtesy:* HNTB.)

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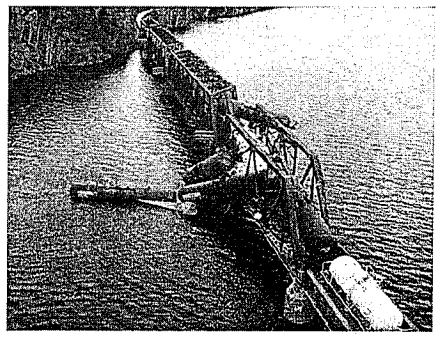

FIGURE 18 Example of train derailment on a fracture-critical truss bridge that severed several members but did not collapse. (*Courtesy*: Robert Sweeney.)

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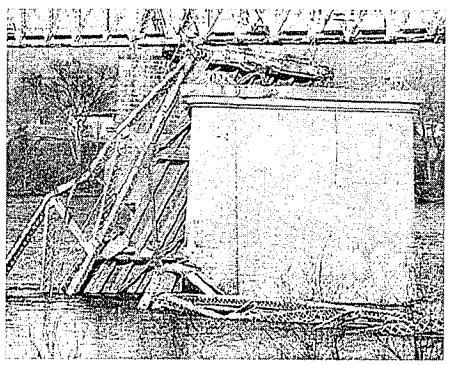

FIGURE 1 Collapse of Point Pleasant Bridge.

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Northridge Earthquake

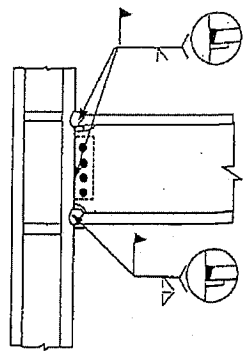

Fig. 1. Schematic of pre-Northridge connection

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Northridge Earthquake

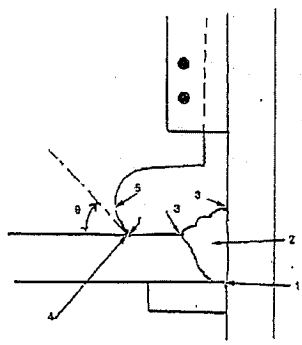

Fig. 3. Locations of stress concentration in pre-Northridge connection

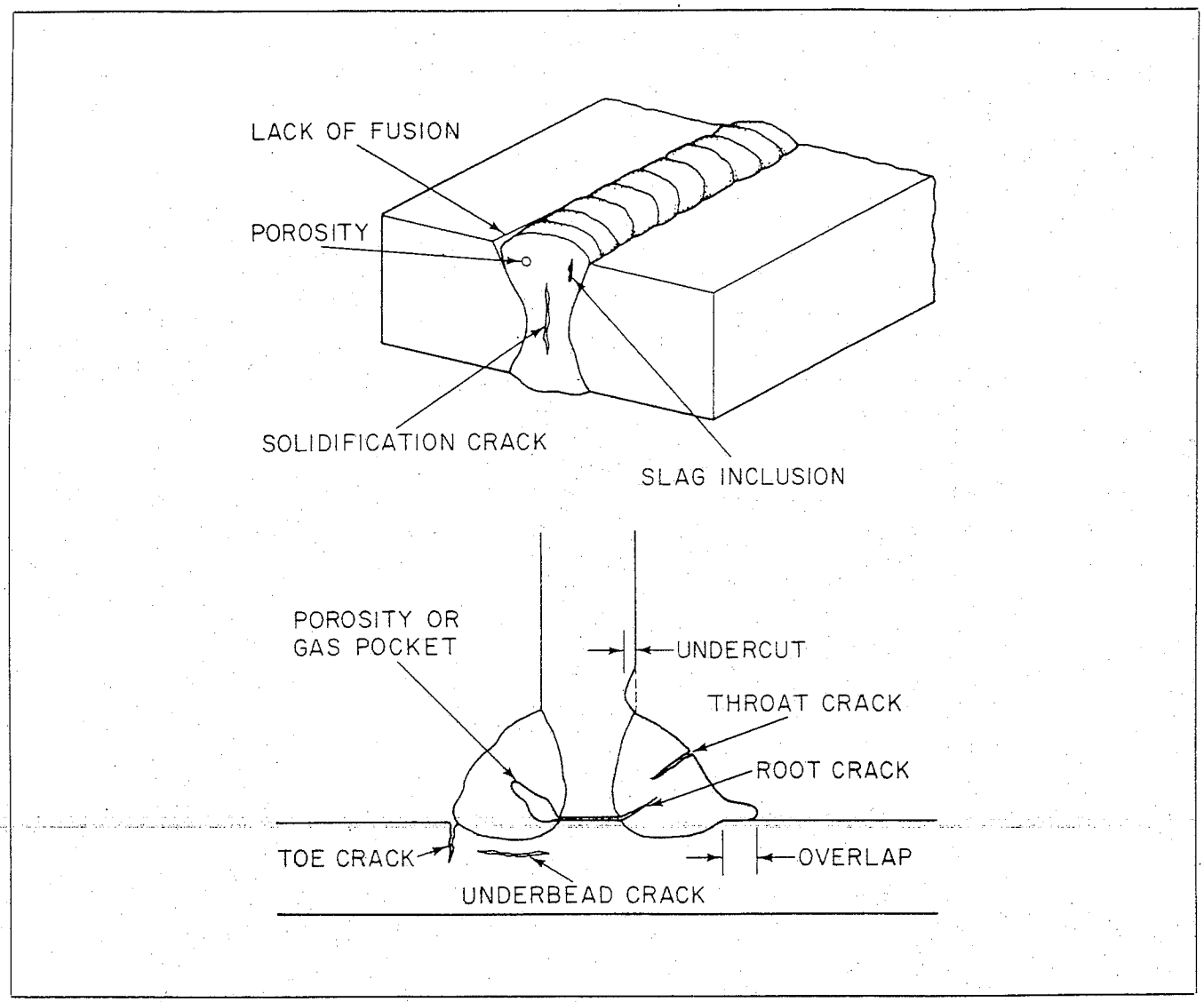

Figure 42.
Imperfections and cracks in welded joints.