UNITED STATES
NUCLEAR REGULATORY COMMISSION
OFFICE OF NUCLEAR REACTOR REGULATION
WASHINGTON, D.C. 20555

April 25, 1997

NRC INFORMATION NOTICE NO. 97-22: FAILURE OF WELDED-STEEL MOMENT-RESISTING FRAMES DURING THE NORTHRIDGE EARTHQUAKE

Addressees

All holders of operating licenses or construction permits for nuclear power reactors.

Purpose

The U.S. Nuclear Regulatory Commission (NRC) is issuing this information notice to alert addressees to the factors contributing to the failure of welded-steel moment-resisting frames (WSMFs) during the Northridge earthquake. It is expected that recipients will review the information for applicability to their facilities and consider actions, as appropriate, to avoid similar problems. However, suggestions contained in this information notice are not NRC requirements; therefore, no specific action or written response is required.

Description of Circumstances

On January 17, 1994, at 4:31 a.m. Pacific Standard Time, a magnitude 6.7 earthquake occurred in the Northridge area of metropolitan Los Angeles, California. This earthquake caused considerable damage to industrial facilities, lifelines, commercial centers, and industrial buildings located within 40 km [25 miles] of the epicenter. San Onofre Nuclear Generating Station, located about 130 km [80.8 miles] from the epicenter, is estimated to have experienced a peak horizontal ground acceleration (PHGA) of less than 0.02g, and Diablo Canyon Nuclear Power Plant, located about 239 km [149 miles] from the epicenter, is estimated to have experienced a PHGA of less than 0.01g. The earthquake caused no damage to these plants. Reference 1 is a comprehensive assessment of the effects of the Northridge earthquake on various facilities.

The post-earthquake investigations of many (more than 100), otherwise intact buildings indicated considerable structural damage to WSMFs. The frames were designed to withstand large seismic forces on the basis of the assumption that they are capable of extensive yielding and plastic deformation. The intended plastic deformation consisted of plastic hinges forming in the beams, at their connections to columns. Damage was expected to consist of moderate yielding at the connections and localized buckling of the steel elements. Instead, the WSMF failures were brittle fractures with unanticipated deformations in girders, cracking in column panel zones, and fractures in beam-to-column weld connections. Federal Emergency Management Agency (FEMA) Publication 267 (Reference 2) provides a detailed discussion of the WSFM damage and provides interim guidelines for the evaluation, repair, and modification of WSMFs.

Discussion

A number of factors related to seismic analysis and design, materials, fabrication and construction are identified as contributing to the failure of WSMFs and are the focus of FEMA-sponsored research projects. Although the steel structures in nuclear power plants are fabricated and constructed using the same national standards [e.g., the American Institute of Steel Construction (AISC) specifications and the American Welding Society (AWS) welding code] as were used in the construction of WSMF structures, the method of computing seismic loads, combination with other loads, acceptance criteria, and quality assurance requirements are significantly different from those for non-nuclear buildings designed using national building codes, such as the Uniform Building Code and the Building Officials and Code Administrators International Code. The following paragraphs discuss the extent of applicability of the factors contributing to the failure of WSMF, as they relate to steel structures in nuclear power plants.

1. Seismic Analysis and Design: Two levels of ground motion have been defined for designing the safety-related structures, systems, and components in the operating nuclear power plants. For the first-level earthquake, the Operating-Basis Earthquake (OBE), the load factors and acceptable allowable stresses ensure that the stresses in plant structures remain at least 40 percent below the yield stress of the material. For the second-level earthquake, the Safe-Shutdown Earthquake (SSE—whose vibratory motion is usually twice that of the OBE), the associated load factors and allowable stresses ensure that the stresses in steel structures remain close to the yield stress of the material; a small excursion in the inelastic range is allowed when the SSE load is combined with accident loads. The design requirements, promulgated by Standard Review Plan provisions, prohibit the use of significant inelastic deformation of any steel member or connection (that is allowed in the design of WSMFs) in nuclear power plants under design-basis seismic events. Also, the use of broadband response spectra, conservatively defined structural damping values, consideration of amplified forces at higher elevations in the plants, and consideration of all three components of the design-basis earthquakes ensure that the loads and load paths of the design-basis seismic events are properly considered in the design, as opposed to the use of static base shear forces in non-nuclear structures.

   Localized inelastic deformations of steel structures are allowed for impactive and impulsive forces associated with high-energy pipe ruptures, chemical explosions, and tornado- and turbine-generated missiles. However, even under the deformed conditions, designers are required to assess the overall stability of the structure.

2. Materials: Three distinct factors related to the steel material used in WSMFs were identified: (1) higher-than-specified yield strength of American Society of Testing and Materials (ASTM) A36 steel, (2) lack of adequate through-thickness strength of thick-column flanges, and (3) inadequate notch toughness of the base metal.

   The post-earthquake investigations (Ref. 2) indicated that consistently higher yield strength (25 to 35 percent higher than the minimum specified yield strength) restricted the girder rotation at the design moment. Thus, the restrained connections were required to dissipate the large amount of energy associated with the seismic event by fracturing. It was the inability of the girder to rotate that induced large unaccounted-for through-thickness forces in the thick-column flanges of the WSMFs. American National Standards Institute/AISC (ANSI/AISC) N690 (Ref. 3) requires through-thickness testing and ultrasonic examination when high-heat input welds and/or highly restrained conditions are encountered to alleviate the possibility of lamellar tearing. For Classes 1, 2, 3, and MC component supports, Subsection NF of Section III of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (the ASME code) (Ref. 4) requires through-thickness testing for plates (which could be part of a rolled shape) thicker than 2.5 cm (1 in), if they are subjected to through-thickness loading. However, for nuclear power plant steel structures, both these requirements are relatively recent (promulgated after 1984) and would not have been used in a majority of the operating nuclear power plants designed and built before 1984. Some architect-engineers and utility engineers may have utilized similar requirements in their project specifications.

To address factor (3), inadequate notch toughness of the base metal, AISC conducted a statistical survey of the toughness of material produced in structural shapes (wide flanges, tees, angles, etc.), based on data provided by six producers for a production period of approximately 1 year (Ref. 5). This survey showed a mean value of Charpy V-notch (CVN) toughness for all shape groups to be in excess of 27J (20 ft-lbf) at 21 °C (70 °F) and 20J (15 ft-lbf) at 4 °C (40 °F). For structures or structural components that are designed to withstand impactive and impulsive loadings, Reference 3 requires the average CVN values to vary between 20 and 40J (15 and 30 ft-lbf), at a temperature of 17 °C (30 °F) below the lowest service metal temperature of the structure. Reference 4 also has similar requirements for vital component supports in nuclear power plants. Considering the normal service metal temperatures of steel structures in nuclear power plants and the range of CVN values as experienced in the survey, factor (3) is probably not a concern for the steel structures in nuclear power plants. However, this factor may be applicable for safety-related steel structures (or non-safety steel structures that could affect the safety function of a safety-related structure, system, or component) designed to withstand impactive and impulsive loadings if the structures may experience low service metal temperatures, i.e., structures located outdoors.

3. Fabrication and Construction: For damaged WSMFs, a number of issues related to connection detailing and weld quality, such as fracture toughness, weld material, welding procedures, weld inspection, and welders' qualification, were addressed.

The research project carried out at the Center for Advanced Technology for Large Structural Systems (ATLSS) at Lehigh University examined the effects of weld metal toughness and fabrication defects on the seismic performance of WSMF connections. The examination and testing performed at ATLSS revealed that the weld fractures were initiated from porous weld roots adjacent to the back-up bar and that the fracture toughness of welds made with E70T-4 weld electrodes used in the connections was very low [< 14 J (10 ft-lbf) at 21 °C (70 °F)] (Ref. 6).

The arc welding process used in the steel structures could be (1) shielded metal arc welding (SMAW), (2) flux cored arc welding (FCAW), (3) submerged arc welding (SAW), or (4) gas metal arc welding (GMAW). The American Welding Society's "Structural Welding Code - D1.1," provides the requirements for weld design, welding techniques, standards for workmanship, procedure and personnel qualifications, and inspections. For safety-related steel structures in nuclear power plants, the quality assurance requirements of Appendix B to 10 CFR Part 50, as promulgated by ANSI N45 (now NQA) series standards, are also applicable. The use of the E70T-4 electrode is associated with the FCAW process. Its use is allowed by the AWS Code. The electrode must meet specific physical and chemical requirements. Its minimum mechanical properties requirements areas follows: a tensile strength of 72 ksi, a tensile yield strength of 60 ksi, and an elongation of 22 percent. However, the electrode need not be tested for notch toughness. It should be recognized that there are other AWS-permissible FCAW electrodes which are also not required to be tested for notch toughness unless specifically called for in the project specification. They are E60T-4, E60T-7, E60T-11, E70T-7, and E70T-11. For projects with notch toughness requirements, use of these electrodes would not be permitted unless a separate notch toughness qualification had been performed.

This information notice requires no specific action or written response. However, comments and input related to the technical issues discussed are encouraged. If you have any questions about the information in this notice or you wish to provide additional information related to the technical issues discussed, please contact the technical contact listed below or the appropriate Office of Nuclear Reactor Regulation (NRR) project manager.

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Thomas T. Martin, Director
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Attachments:
1. References
2. List of Recently Issued NRC Information Notices

Attachment Filed in Jacket

REFERENCES

1. "The January 17, 1994, Northridge Earthquake: Effects on Selected Industrial Facilities and Lifelines," prepared by Mark Eli, S. Sommer (LLNL), and T. Retch, K. Merz (EQE International), dated February 1995. Available from the National Technical Information Service, U. S. Department of Commerce, 5285 Fort Royal Road, Springfield, VA 22161.

2. FEMA 267: "Interim Guidelines: Evaluation, Repair, Modification and Design of Welded Steel Moment Frame Structures," prepared by a joint venture of (1) Structural Engineers Association of California, (2) Applied Technology Council, and (3) California Universities for Research in Earthquake Engineering. Available from: Federal Emergency Management Agency, P. O. Box 70274, Washington, DC 20024.

3. ANSI/AISC N690: "Nuclear Facilities—Steel Safety-Related Structures for Design, Fabrication and Erection," 1984, 1995. Available from the American Institute of Steel Construction, Inc., One East Wacker Drive, Suite 3100, Chicago, IL 60601.

4. Subsection NF of Section III of the ASME Code: "Supports," 1995 and earlier editions. Available from the American Society of Mechanical Engineers, United Engineering Center, 345 E. 47th Street, New York, NY 10017.

5. AISC Report, "Statistical Analysis of Charpy V-Notch Toughness for Steel Wide-Flange Structural Shapes," dated July 1995. Available from the address in listed Ref. 3.

6. Kaufman, E., Xue, M., Lu, L., Fisher, J.: "Achieving Ductile Behavior of Moment Connections," published in <u>Modern Steel Construction</u>, January 1996. Available from the address listed in Ref. 3.

LIST OF RECENTLY ISSUED NRC INFORMATION NOTICES

Information Notice No.	Subject	Date of Issuance	Issued to
97-21	Availability of Alternate AC Power Source Designed for Station Blackout Event	04/18/97	All holders of OLs for nuclear power reactors
97-20	Identification of Certain Uranium Hexafluoride Cylinders that do not comply with ANSI N14.1 Fabrication Standards	04/18/97	All holders of OLs for nuclear power
97-19	Safety Injection System Weld Flaw at Sequoyah Nuclear Power Plant, Unit 2	04/18/97	All holders of OLs or CPs for nuclear power reactors
94-14, Supp. 1	Failure to Implement Requirements for Biennial Medical Examinations and Notification to the NRC of Changes in Licensed Operator Medical Conditions	04/14/97	All holders of OLs or CPs for nuclear power and non-power reactors and all licensed reactor operators and senior reactor operators
97-18	Problems Identified During Maintenance Rule Baseline Inspections	04/14/97	All holders of OLs, CPs, and decommissioning-stage licenses for nuclear power reactors
97-17	Cracking of Vertical Welds in the Core Shroud and Degraded Repair	04/04/97	All holders of OLs or CPs for boiling-water reactors

OL = Operating License
CP = Construction Permit

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Tech Editor reviewed and concurred on March 11, 1997.
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