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Metallic Bellows and Expansion Joints

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FOREWORD

The purpose of this volume is to bring together some of the recently reported work on metallic bellows and expansion joints. This information should be of interest to those involved in the design and manufacture of bellows expansion joints and in the design and operation of systems or components containing these joints. Several papers will be of particular interest to those concerned with the design and construction of bellows for ASME Boiler & Pressure Vessel Code Section III, Class 1 applications.

The first paper, by Jetter and Jaquay, provides some background and guidelines for using the new ASME Code Case on bellows expansion joints for Class 1 liquid-metal piping systems. In addition to identifying key features and their rationale, the paper also highlights additions and improvements that could be incorporated as more experience is gained with the application of the Code Case rules.

Becht and Skopp compare the results of elastic-plastic finite-element analysis with strain gage data from a bellows test. They conclude in their paper that the stresses in bellows can be predicted with reasonable accuracy if the predictions are based on the actual geometry and resultant strain concentrations.

Campbell, Cloud, and Bushnell address the problem of designing a bellows that will pass the stability tests required by the new bellows Code Case. They recommend using simplified isochronous methods for conservative design predictions and modifying existing shell computer codes to provide cost-effective bellows design methods.

Harris describes the selection and development of an expansion joint used in the shell of a steam generator. The paper describes some of the concepts, manufacturing approaches, and materials considered prior to deciding on a 3-D machined convolution fabricated from a seamless 2-1/4 Cr – 1 Mo ring forging.

Merrick, O'Toole, and Malkmus consider the very practical problem of repairing bellows expansion joints. The problem was addressed by intentionally damaging and repairing a bellows assembly and then subjecting it to a fatigue test. They conclude that there are three methods of repair that may be justifiable under closely controlled circumstances.

In their paper, Campbell and Kipp find that the most practical method of accelerated testing to meet the ASME Code Case requirement is to increase the test temperature without significantly changing other parameters such as pressure, motion, and number of cycles.

Kobatake, Takahashi, Osaki, and Shimakawa investigated the behavior of a bellows at 750°C and 900°C representative of gas-cooled reactor applications. They performed tests and analyses of the bellows and conclude that inelastic analysis considering damage only from tensile hold time predicts bellows life more accurately than does the Code Case N-47 methodology (although the latter does provide a conservative estimate.)

McCoy reports on elevated testing at Oak Ridge National Laboratory. He finds that the test results can be correlated with cyclic fatigue data and that the failure was the normal intergranular cracking observed in specimen testing.

Becht and Skopp experimentally and analytically investigated the phenomena of root bulge of bellows and drew comparisons with EJMA and Section III, Class 1 design criteria. They found that both experimental results and analysis supported the classification of pressure-induced bending stresses as primary bending similar to the stress classifications in Section III, Class 1 design of vessels.

The final paper, by Becht, Horton, and Skopp reports on experiments conducted to verify theoretical plastic ratchet predictions for bellows. They conclude that the theoretical plastic ratchet boundary as used in the Code Case for Class 1 bellows is close to the actual boundary as observed in their experiments. As the strain approaches the Code Case strain limits, the bellows begins to accumulate large deformations; however, they feel that this does not invalidate the theory as a methodology for a bounding evaluation.

In summary, the above papers are a valuable overview of currently developing bellows expansion joint technology. In several instances, particularly the papers by Becht and by Campbell et al., the work has directly influenced the recently approved ASME Code Case for bellows expansion joints in liquid metal piping systems.

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BACKGROUND ON THE DEVELOPMENT OF RULES FOR CONSTRUCTION OF BELLOWS EXPANSION JOINTS FOR ASME CODE SECTION III CLASS 1 PIPING

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Code Case N-290, "Expansion Joints in Class 1, Liquid Metal Piping, Section III, Division 1,"(1) has recently been approved by the ASME Boiler and Pressure Vessel Code. The purpose of this document is to provide background into the development of those rules. The intent of each section of the rules is described to aid the user of the Code Case in understanding its application. Further areas for development are also identified. This is not an official ASME document and represents the opinions of the authors solely. Official responses to inquiries can be obtained through the Secretary of the ASME Boiler and Pressure Vessel Committee.

INTRODUCTION

The desirability of implementing ASME Code rules for Class 1 bellows was given impetus in the mid-1970s by Liquid Metal Fast Breeder Reactor (LMFBR) design studies which showed that a considerably smaller containment building and consequent cost savings were possible if bellows were used in the layout of the piping systems for loop-type plants. Accordingly, DOE initiated a development program with the object of qualifying bellows for use in LMFBRs. An integral part of that program was the development of a Code Case that would permit construction of bellows expansion joints in accordance with the rules of the ASME Boiler and Pressure Vessel Code.

The ASME Code already contained rules for construction of bellows expansion joints in Subsection NC. However, the greatest economic gains for LMFBRs were believed to lie in the application of bellows in Class 1 systems. Thus, the initial objective of the DOE-sponsored program was to obtain construction rules for bellows expansion joints in Class 1 systems. Since one of the anticipated applications was the reactor outlet line, it was necessary to consider elevated temperature environments where creep was significant.

As an initial step in the program, an informal survey was conducted by interviewing individuals with a background in bellows applications representing engineers and constructors, manufacturers, consultants, and regulatory agencies. The interviews sought their opinions concerning the major problems associated with using bellows in Class 1 piping systems at both elevated temperatures and at temperatures where creep is not significant. Those problems can be broadly categorized as follows.

Elevated Temperature Design and Analysis Procedures

The concern here is with the difficulty of (1) accurately predicting the stress/strain behavior of a bellows convolution, particularly when consideration is given to variability in thickness, convolution configuration, and other geometric parameters and (2)determining how long-term creep will affect bellows behavior, particularly when one considers the possibilities of heat-to-heat variations in creep behavior and nonuniform distortion of the relatively thin convolution wall.

Bellows Fabrication

The concern is the degree to which the particular bellows analyzed or tested is representative of the bellows installed.

Bellows Expansion Joint Care and Installation After Delivery at the Site

This is perhaps the greatest area of concern. Those interviewed felt that many of the problems attributed to bellows expansion joints were really the result of damage due to mishandling at the site and improper installation that subjected the bellows to loads and deflections exceeding its design capacity.

Other Concerns

In addition to the above inputs, data were also obtained from the aerospace industry. In particular, a designer and builder of large rocket engines was consulted because of the successful use of bellows in engine systems used on all major space programs. Initially, the aerospace industry experienced erratic bellows performance, but through rigorous fabrication control, testing, and careful installation, they achieved highly reliable and predictable bellows performance.

Armed with the above considerations, two task forces with broad representation were set up under Section III, Nuclear Components, of the ASME B&PV Code to develop rules for design and construction of bellows in Class 1 systems. The following discussion centers around the background and objectives of Code Case N-290.

CODE CASE N-290

Code Case N-290 is organized in standard Code format with paragraphs as noted below:

- -1000 Introduction
- -2000 Materials
- -3000 Design
- -4000 Fabrication
- -5000 Examination
- -6000 Testing
- -7000 Protection Against Over Pressure
- -8000 Nameplates, Stamping, and Reports

Each of these areas is addressed below.

-1000 Introduction

As identified in the Code Case title, the case applies to expansion joints in liquid-metal systems. This is primarily due to pressure considerations. Liquid-metal piping systems operate at low pressures compared with steam piping systems because of the low vapor pressure of liquid metal. Rather than place an arbitrary pressure limitation, it was decided that the same objective could be achieved while still meeting the primary use if the Code Case were restricted to liquid-metal systems.

Three additional main points are covered in the Introduction. First, for Class 1 systems, it is noted by reference to a following paragraph that an expansion joint consists of a primary pressure retaining bellows, the expansion joint hardware, and a redundant secondary pressure boundary that is to be constructed to the rules for Class 2 bellows expansion joints. Thus, any Class 1 expansion joint is to consist of a primary pressure boundary constructed to the rules of the Code Case and a redundant secondary boundary constructed to the rules of Class 2. It was deemed appropriate to require redundant bellows because this is a new application of bellows components to Class 1 piping.

Second, this Code Case covers a complete temperature range from "low temperatures" covered by the allowable stresses in Appendix I of the B&PV Code to elevated temperatures covered by Code Case N-47.

Third, the Introduction defines responsibilities. The responsibility for the design and fabrication of the expansion joint rests with the certificate holder accepting overall responsibility for the piping system containing the expansion joint. This recognizes the close tie between the design of the piping system, the design of the expansion joint, and the necessity for considering them as an integrated system in all phases of design through installation and testing.

-2000 Material

Acceptable materials for bellows convolutions are identified in this section. The selected materials are those that have not only been approved for Section III construction but have also been demonstrated through use as satisfactory bellows materials. For elevated-temperature applications, the bellows must also meet requirements of Code Case N-47, "Class 1 Components in Elevated Temperature Service, Section III, Division 1."(2) This means that, for elevated-temperature applications, the bellows must be annealed to assure that the long-term creep properties are maintained. This is indeed required in Code Case N-290 for elevated-temperature bellows; however, a final sizing operation is permitted provided that the convolutions are formed to the proper tolerances and annealed prior to final sizing.

This section qualifies either seamless round product or flat product rolled and welded as the starting stock ("bellows tube") for forming the bellows convolutions. Since it is not practical to perform volumetric examination of the bellows convolution after forming, extra precautions are taken with the bellows tube.

Surface finish is controlled to minimize subsequent fatigue damage. Grain size is controlled to ensure that the bellows can be formed without "orange peeling" or cracking around extra-large grains. A further step to ensure a defect-free condition after forming is achieved by the forming qualification in which sample convolution is formed, liquid penetrant examined, sectioned lengthwise including the logitudinal weld, if applicable, and then is polished and examined for surface or internal cracks.

Bellows tubes obtained by rolling and welding sheet stock are subject to additional qualifications. The unfinished weld geometry is closely controlled, although grinding is permitted for thicknesses greater than 1/8 in. Welds less than 1/8 in. thick must be planished. After welding, but before forming, the longitudinal weld is examined to the criteria in -5000. The completed bellows tube can either be liquid penetrant examined after welding or the starting sheet can be liquid penetrant examined followed by a visual examination after welding and a liquid penetrant examination of the weld before weld finishing. Defects can be removed and repaired, with some restrictions, prior to forming the convolutions. Defect removal by grinding is permitted after the convolutions are formed, provided the resultant thickness is not less than the minimum permitted by the fabrication tolerances.

-3000 Design

It was recognized that, for any given design application, a large variety of expansion joint configurations could be employed, each with inherent advantages and disadvantages with respect to response predictability and reliability. Due to the criticality of Class 1 service and the lack of expansion joint service experience in LMFBR applications, it was decided to restrict configurations to those judged most likely to exhibit a satisfactory service life. Thus, favorable design features such as flow sleeves, bellows protection covers, position-indicating devices, flow direction markings, and handling devices were required. Design features that reduced response predictability, such as nonintegral convolution reinforcement or multiple construction, were prohibited.

Due to the relatively low mass and natural frequencies of bellows, special requirements were drafted to reduce the potential for damaging resonant conditions under normally benign oscillatory loadings. The requirement for pressure boundary redundancy was also quantified by requiring that pressure integrity be maintained at maximum service pressure under a postulated leak of either pressure boundary.

Separate analysis and testing requirements were formulated for each of the three major subcomponents in order to better address their differences in structural behavior, response predictability, and criticality. The key design requirements for these three subcomponents — the primary pressure retaining bellows, the load-carrying hardware, and the redundant (secondary) pressure boundary — are discussed separately below.

The primary pressure retaining bellows is not only the key functioning element of the expansion joint, it is also the most difficult of the subcomponents to evaluate analytically. This is principally due to the difficulties encountered in fabricating an exact geometry coupled with both a technology limitation on complete dimensional measurement and an economic limitation on the analytical modeling of all geometric deviations, even if they could be determined. Therefore, those failure modes that are sensitive to local geometric deviations were judged to be better controlled by requiring test, rather than analytical, demonstration of design adequacy. Accordingly, the Code design methodology for the primary pressure retaining bellows evolved into a combination of analytical and testing requirements.

The analytical requirements provide protection against primary and primary-plus-secondary stress intensity governed failure modes in a manner essentially identical to those for Section III Class 1 pressure vessels. Detailed stress intensity classifications were included based on analytically and experimentally observed behavior of U-shaped bellows. Since this is a signficiant feature of the Code Case, their determination is presented in more depth below.

The classifications are fairly routine except for the convolutions. Recent testing and analysis of a single-ply bellows reported in Ref. 3 found that the results could be correlated best by considering the pressure-induced bending stress as primary bending, P_B. The specific objective of the testing and analysis was to investigate root bulge of bellows. It was found experimentally that root bulge correlated with the formation of plastic hinges, as would be predicted by the classification of pressure-induced bending as primary stress. It was further found by analysis that the plastic zones did not redistribute, as it would be expected to if the stresses were secondary. A review of the limits in EJMA(4) showed that the criterion for pressure-induced bending stress is about twice the yield strength, which corresponds to the secondary stress limit from Section III Class 1. The acceptability of the EJMA approach is attributed to the fact that it is based on test data from cold-worked bellows, whereas, at least for elevated temperature applications, the bellows for Class 1 applications must be annealed. The testing and analyses reported in Ref. 3 were based on annealed bellows. Note that the classification of pressure-induced bending stress as primary is consistent with Section III philosophy. Also consistent with Section III is the classification of displacement-induced membrane and bending stresses as secondary.

Another significant feature of the analytical requirements for the primary pressure-retaining bellows was development of an upper bound elastic analysis for bellows strain limits. The strain limit criteria can be satisfied by the equivalent limits from Section III, Subsection NB, if the service life of the bellows is not at elevated temperatures; by a modified Subsection NB approach if appropriate time at temperature limitations are satisfied; by inelastic analysis; or by an upper bound elastic analysis, which is an extension of the elastic analysis rules in Appendix T of Code Case N-47. The elastic analysis criteria contained in Code Case N-47 were obtained, at least conceptually, by considering the ratchetting of pressurized cylinders subjected to radial through-the-wall thermal gradients. The equivalent ratchetting rules in Code Case N-290 were developed specifically for bellows-type configurations considering internal pressure and displacement induced loads as described in Ref. 5. This approach was tested, and reasonable correlation between the analysis and test data was obtained as reported in Ref. 6.

As an alternative to using analysis to satisfy strain limits, the Code Case permits using testing to demonstrate that the limits are satisfied. The testing must account for the distortion producing environments of the complete lifetime histogram including creep effects. The creep effects may be accelerated, as discussed further below.

With respect to testing requirements for the primary pressure-retaining bellows, these serve primarily to provide protection against the local-geometry-sensitive failure modes of (creep) fatigue and (creep) squirm (instability) and excessive distortion due to pressure. The life tests are required to bound the effects of creep-fatigue damage. The squirm tests were adopted from the Class 2 bellows design rules with modifications to address elevated temperature behavior. An additional series of tests of the primary pressure-retaining bellows is required to demonstrate design adequacy against time-independent pressure distortion that is equivalent to that required for Class 2 bellows. This requirement resulted from a desire to reinforce confidence in the Code Case's pressure design requirements utilizing the successful service experience of Class 2 bellows (analogous to the Code Case N-47 adoption of S_0 design condition limits from Section VIII vessel rules).

To maximize replication between the test bellows and the bellows put into service, special similitude requirements were imposed. These included nondestructive motion tests to create a data base against which the response of the bellows put into service can be measured as part of its acceptance testing. Also, because of concern over heat-to-heat variations and the potentially exaggerated effect this might have on thin-walled convolutions, the testing is to be carried out using bellows from the same lot or heat as the bellows to be put into service.

Since the object of the tests, particularly for the life tests, is to bound deleterious creep effects and provide a proven design margin, overtesting is required. To provide the required design margin demonstration in a reasonable time, the testing must be accelerated. The Code Case does not restrict the methodology chosen to achieve the accelerated life testing provided that it "... includes as a minimum consideration of the damaging and interacting effects of creep, fatigue, thermal shock, and plasticity." It does, however, provide an acceptable nonmandatory methodology to accelerate the tests. Ref. 7 also provides some additional background on the methodology for establishing an accelerated life test histogram.

The structural behavior of the load-carrying hardware was considered adequately predictable by analytical methods, and design-by-analysis rules from Section III for similar subcomponents were adopted. An alternate load-rating approach was permitted for thrust restraints and motion limiters in low-temperature service. Due to concerns about internally developed loadings and to provide additional design confidence, it was decided to further require that the hardware be subjected to the life tests discussed above.

Special hardware design requirements for instability and nonductile fracture were imposed since situations could be postulated where these failure modes were relevant. Additionally, the possibility of prevalent hardware problems identified by expansion joint manufacturers was minimized by introducing special design feature requirements.

Recognizing that the secondary pressure boundary is not an active pressure component and that a leak monitoring system is required to detect leaks in this pressure boundary during service, it was decided that rigorous demonstration of Class 1 design adequacy was not warranted for this subcomponent. The less stringent Class 2 bellows design rules were judged adequate, provided that a single series of time-independent pressure distortion and squirm tests were satisfactorily passed and that the secondary pressure boundary could pass a leak test after being cycled the equivalent of five service lifetimes of fatigue damage.

-4000 Fabrication and Installation Requirements

This is one of the more significant sections of the Class 1 rules for bellows. As noted above, a major concern in the performance of bellows is the reliability and consistency of bellows performance in response to piping motions. In addition, it has been demonstrated in the space program that reliable and repeatable performance can be obtained through rigorous fabrication control.

There are three sets of fabrication tolerances: a basic tolerance, a convolution repeatability tolerance, and a bellows repeatability tolerance. The basic tolerance is the loosest of the three and is designed to ensure that high-quality manufacturing processes are being used and that the basic bellows configuration is consistent with the assumptions underlying the design rules. The second set of tolerances is referenced to mean or average values and is designed to ensure that the individual convolutions are consistent and repeatable. The third set of tolerances assures that each bellows within a lot is consistent and repeatable. The reason for this three-tiered approach was to avoid restricting the fabrication processes used to manufacture the bellows (hence, the basic tolerances are relatively wider) and yet to achieve the consistency and repeatability necessary to ensure the validity of the bellows analysis and testing (this was achieved by the last two sets of repeatability tolerances). Note that fabrication tolerances are referenced to the design drawings. This was done to enable deviations from these requirements to be reconciled through the Design Report rather than tieing tolerances down as a direct Code requirement, which would have required rejection for deviations.

Rules for installation are the other main body of requirements under this section. These rules were developed to address concerns over the sensitivity of bellows expansion joints to mishandling and improper installation. Rather than provide detailed, explicit requirements in which it would probably be impossible to cover all possible situations, it was decided to base the requirements on procedures prepared by the installer and then provided to the N Certificate holder responsible for the piping. As stated in the Design section, the N Certificate holder is also responsible for providing fit-up requirements and other necessary instructions to the installer to ensure a proper procedure. The certificate holder then has the responsibility for verifying that the installation is carried out in accordance with the procedures. This includes verifying that the installation tolerances are not exceeded and that the connecting piping, which is supposed to be essentially stress free, is not cold sprung into position, which would subject the expansion joint to unaccounted-for loads.

Although, as noted, the installation requirements are contained in procedures prepared by the installer, minimum requirements are also noted in the Code Case. For example, a visual inspection is required prior to installation, and the expansion joint should not be removed from its container except for this inspection. Requirements for correctly positioning the expansion joint and connecting piping are identified, and, to ensure a stress-free installation, closure spools or the equivalent are required. During installation, the installed configuration cannot be modified unless approved by the N Certificate holder responsible for the piping and then only when the modification has been reconciled in a certified revision to the design report.

-5000 Examination

Radiographic acceptance standards and liquid penetrant standards are the same as Subsection NB except for radiography of the longitudinal bellows seam weld and liquid penetrant inspection at the bellows seam weld, attachment welds, and parent material. In these cases, the standards have been tightened to provide meaningful criteria for the bellows convolutions since they are much thinner than normal pressure boundary components. For both radiographic and liquid penetrant examinations, no cracks or crack-like defects are permitted within the sensitivity of the examination technique. The radiographic sensitivity is implied by the requirement that the threshold for rejection of indications is 0.005 in. measured to the nearest 0.001 in. In the case of liquid penetrant examination, the required sensitivity is the ability to detect calibrated cracks at least 0.001 in. deep and 0.00005 in. wide. This is well within the sensitivity of current practice without resorting to "black light" techniques. Another aspect of specifying the liquid penetrant sensitivity was to avoid the use of ultrasensitive penetrants capable of detecting intergranular microcracks on a metallurgical scale not associated with inspections for normal structural integrity.

-7000 Protection Against Overpressure

These requirements are the same as for other Class 1 components.

-8000 Nameplates, Stamping, and Reports

The NPT symbol is used for bellows expansion joints, which is consistent with assigning the responsibility for the expansion joint to the N Certificate holder with overall responsibility for the piping.

COMMENTS

In the preceeding discussion, the principal provisions of the Code Case were reviewed. There are several areas of the Case in which additions and improvements would seem warranted if there were sufficient backup. Some of the areas that could be considered are discussed below.

Relaxation of Life-Testing Requirements

It would be desirable to relax the requirement that five bellows from the same lot of tubes as the to-be-stamped bellows complete the life test. The rationale for the requirement that the tested bellows be from the same lot of tubes is based on minimizing the effect of heat-to-heat variations, particularly in the elevated-temperature regime. Since this Code Case also covers materials at "low temperature," it would seem that, when creep effects are negligible, it would be appropriate to modify the requirement that the tested bellows must be from the same lot of tubes. However, even at noncreep temperatures, bellows performance can be strongly influenced by tensile properties. Thus, some form of control would probably still be required to ensure an adequate correlation between tested bellows and installed bellows.

A similar issue relates to the use of bellows where creep effects are not significant for strain limits and creep-fatigue damage. For example, N-47, the Code Case for elevated temperature Class 1 components, has provisions for simplified creep-fatigue and ratchetting analyses when certain time-temperature criteria are satisfied. Similar provisions could be incorporated into the Code Case for bellows expansion joints to simplify testing requirements.

Use of Multiply and Externally Reinforced Bellows

Multiply and externally reinforced bellows were not considered for the current Code Case because of the anticipated difficulties in accurately analyzing and predicting their performance. However, it is clear that there are significant advantages to these bellows types. Additional work is required to develop analysis techniques for those bellows to establish where analysis in combination with testing can lead to accurate performance predictions. Testing will be required to identify the effects of such manufacturing variables as interply contact loads and their impact on fatigue life.

In the case of multiple bellows, there is an additional potential advantage in using the additional plies to meet the redundancy requirement. Work clearly needs to be done in this area, but, perhaps with interply leak detection, such a system could be justified.

Additional Materials

Particularly at elevated temperatures, the current list of materials is limited to those approved for use in Class 1 elevated temperature by Code Case N-47. It would be desirable to add materials such as Inconel 718. This material has been used successfully in bellows, primarily in the aerospace industry, but is not currently approved for welded construction. The difficulty is with the properties of welds in thick sections, a concern that would not be directly applicable to thin-section bellows.

Rules for Class 2 and 3 Bellows Expansion Joints

The introduction to N-290 states that the redundant outer bellows should be constructed to the applicable rules for Class 2 bellows. This guidance is amplified in the design section of the Code Case, which identifies additional testing requirements. Further, in the case where the outer bellows is at elevated temperature, the N Certificate holder is assigned the responsibility for evaluating the "...materials time-dependent behavior...using data obtained from the rules for design of Class 2 and 3 components at elevated temperature." The reason for this awkward approach is that the rules for Class 2 and 3 components of elevated temperature state that proof tests and short-time experiments contained in Section III, Subsections NC and ND, are not adequate proof of acceptable design. Thus, one is left without specific guidance for Class 2 or 3 bellows with sustained operation at elevated temperature, a situation that should be addressed. Clearly, some form of elevated temperature testing is required with hold times of sufficient duration to identify creep effects if present; as yet, that testing has not been defined for Classes 2 and 3.

SUMMARY

In the preceeding discussion, some of the background and rationale for the rules for bellows expansion joint construction for Class 1 piping were presented. This discussion could not, nor was it intended to, completely describe all facets of those rules. It was intended as a guide to assist in understanding the rules and their interpretation. Some specific areas for further investigation were also identified. In that regard, it should be noted that the overall approach taken in developing the Code Case was to require redundancy, thorough analysis, testing, and rigorous control of fabrication and installation. Further experience with the application of these rules may provide a basis for relaxing some of these stringent requirements.

REFERENCES

1. Code Case N-290, "Expansion Joints in Class 1, Liquid Metal Piping," Section III, Division 1

2. Code Case N-47-18, "Class 1 Components in Elevated Temperature Service," Section III, Division 1

3. Becht, C., and Skopp, G., "Root Bulge of Bellows," ASME Special Publication, "Metallic Bellows and Expansion Joints," June 1981

4. "Standards of the Expansion Joint Manufacturers Association, Inc.," 5th Edition, EJMA, Inc., White Plains, New York, 1980

5. O'Donnell, W. J., and Porowski, J. S., "Upper Bounds for Creep Ratcheting in Convoluted Bellows," O'Donnell & Associates, Inc., Pittsburgh, Pennsylvania, March 1977

6. Becht, C., Horton, P., and Skopp, G., "Verification of Theoretical Plastic Ratchet for Bellows," ASME Special Publication, "Metallic Bellows and Expansion Joints," June 1981

7. Campbell, R., and Kipp, T., "Accelerated Testing of Flexible Piping Joints Operating at Creep Temperature," ASME Special Publication, "Metallic Bellows and Expansion Joints," June 1981

STRESS ANALYSIS OF BELLOWS

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If bellows are to be used in critical components for long-life application in severe environments, accurate analytical prediction of their performance is necessary. An elastic-plastic test was run with an 18-in. diameter bellows to develop data to verify state-of-the-art analytical techniques.

An elastic-plastic finite element model was developed to represent the as-built geometry of the bellows. The strain predictions derived from finite element analyses are compared to detailed strain gage measurements of the test bellows. In addition, actual bellows performance is compared to various predictions based on empirical equations. Parameters such as strain concentration in weak convolutes are explicitly addressed.

INTRODUCTION

Bellows analysis and design have commonly been performed by using equations which are derived from a combination of testing and theory. Stresses are calculated with various equations and compared to allowables. These allowables are based on correlations of bellows failure data with stresses calculated with the equations. The true stress-strain conditions are not calculated.

Although this may be satisfactory for many applications, it is not satisfactory for long-life applications in elevated temperature service. As long-term test data are not available on bellows, the design must be based on current theory for elevated temperature structures. As part of the development of bellows for Class 1, liquid-metal piping, a code prototypic, subscale bellows was tested. Current, state-of-the-art analysis techniques were used to attempt an exact prediction of bellows response. Some of the currently available equations that predict bellows performance were compared to test data to determine their accuracy. The bellows response was characterized, and an evaluation of the potential for strain concentration was performed.

Finally, detailed finite element analyses were performed and compared to surface strain data. Elastic pressure and deflection cases were run, as well as the inelastic analysis of part of a deflection cycle.

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