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Metallic Bellows and Expansion Joints: Part II

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FOREWORD

This volume is the second part in a series of special publications on metallic bellows and expansion joints. The first volume PVP-51 was published in 1981 by the pressure vessel and piping division of the ASME, and sponsored by the Operations, Applications, and Components Committee. The first volume dealt principally with the analysis and testing of bellows expansion joints with respect to elevated temperature applications (with the exception of one paper that discussed the development of a thick shell expansion joint used in a steam generator). A considerable amount of outstanding experimental data is found in the first volume.

This second complimentary volume is principally devoted to design philosophy of expansion joints. Four papers address the design, analysis, and manufacture of expansion joints for heat exchanger applications. Three papers address the philosophy behind expansion joint application, specification, installation, and EJMA standards. The results of two separate test programs provide further data on which the designer may benchmark his analyses.

Stastny reviews the purpose of metal bellows expansion joints. Basic definitions of expansion joints that are available and their application in piping systems is explained. The requirement for anchors and guides in piping systems is presented as well as the data necessary to specify an expansion joint. Installation and inservice inspection recommendations are also included.

Reimus describes the contents and history of the Expansion Joint Manufacturers Association (EJMA) Standards. A complete summary of each section of the Standards is explained. An engineer involved in piping system and vessel design can easily determine whether the design and application of metal bellows expansion joints will aid him in his job performance.

Becht provides a history of the development of bellows analysis methods from early work in the 1940's to the present in his paper on Predicting Bellows Response by Numerical and Theoretical Methods. The state of the art is assessed and directions requiring further development are discussed such as nonlinear interaction effects for multi-ply and ring reinforced bellows and numerical methods to predict bellows squirm, particularly at elevated temperatures.

Becht describes the design and analysis of a high pressure, high temperature bellows expansion joint design. Severe service requirements for a heat exchanger floating head expansion joint that exceeds the limits of standard expansion joints led to the study of a fabricated omega bellows. Criteria for elevated temperature effects are discussed and stress and buckling analyses are performed with shell analysis programs. In this instance, the author finds that ASME code case N-290 and EJMA standards contain some guidance, however N-290 is applicable to nuclear reactors and EJMA do not address phenomena such as creep fatigue.

Thomas summarizes a test program which was conducted by the Expansion Joint Manufacturers Association (EJMA) to verify the design equations for circular metal bellows expansion joints. This paper describes the test program, compares the test results to those results obtained by the use of the design formulas, and summarizes the validity of the design procedure presented in the EJMA Standards.

Misvel and Chakrabarti provide a description of the design and a summary of the analysis for a convoluted shell expansion joint (CSEJ) that is used to reduced the thermal breeder reactor heat exchanger. Since the CSEJ is a thick wall shell, the performance criteria that apply to the expansion joint are for pressure vessels rather than for bellows criteria. The CSEJ is formed by machining from an electro slag remelt (ESR) 2 1/4 Cr-1 Mo Steel ring forging.

Habbar describes the application of a three dimensional machining technique to a metallurgically homogenous and clean steel forging as a first time usage for an expansion joint in a pressure vessel. This manufacturing and metallurgical solution to a large diameter thick wall expansion joint is applied to the Westinghouse liquid metal breeder reactor steam generator expansion joint (CSEJ). The advantages cited are: reliability, advantages of a straight tube concept, and ease in in-service inspection.

Merrick, O'Toole, Reimus and Bressler present results from a series of tests which demonstrate the feasibility of repairing bellows by welded patches, base metal repair, and contour grinding. Also included are the results of a test which demonstrates the capability of a bellows to withstand mechanical damage. Guidelines are presented which assist in the evaluation of a damaged bellows and its possible repair without replacement.

Brown reviews expansion joint concept considerations with respect to heat exchanger and other thermal expansion component applications. A discussion of the design parameter categories that an engineer might consider in the process of development from concepts to production for expansion devices to reduce the thermal interactive stresses in a heat exchanger. A number of active and passive expansion device types are discussed and a product evaluation criteria for selecting concepts with a higher probability of success for further evaluation is outlined.

The editors believe that the papers provide a valuable overview of currently developing bellows expansion technology and a complimentary addition to Metallic Bellows and Expansion Joints — PVP-51 edited by R. I. Jetter, S. J. Brown, and M. R. Pamidi.

S. J. Brown

W. S. Reimus

CONTENTS

METALLIC CONVOLUTED EXPANSION JOINTS: APPLICATION, SPECIFICATION, AND INSTALLATION

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ABSTRACT

Bellows-type expansion joints, although having been utilized in complex piping systems for nearly 50 years, are usually specified very late in the design cycle, and unfortunately, many times as an afterthought. Despite piping analysis computer programs which have reduced the time needed to evaluate a proposed piping system, reluctance upon the individual design engineer in using expansion joints persists owing mostly to his misunderstanding of an expansion joint's capabilities and design advantages over other methods of accommodating thermal and equipment induced pipe movements.

A basic explanation of the general industry accepted criteria under which expansion joints are applied, specified, and installed is provided along with recommendations for system design so that "built-in" problems are not created during the initial stages of design analysis. This is done to better acquaint the piping design engineer with the background of the design and manufacturing processes used by expansion joint manufacturers.

INTRODUCTION

Thermal expansion is probably the most common and persistant problem encountered by piping design engineers. Any piping system subject to appreciable variations in the temperature of the pipe material or by significant changes in the outside environment will experience a dimensional change.[1] Such uncontrolled movement can create high stresses which may result in failure of the piping system or connected equipment unless adequate means are provided for controlling and accommodating these movements. Piping movements may be absorbed by pipe expansion loops or by expansion joints.[2]

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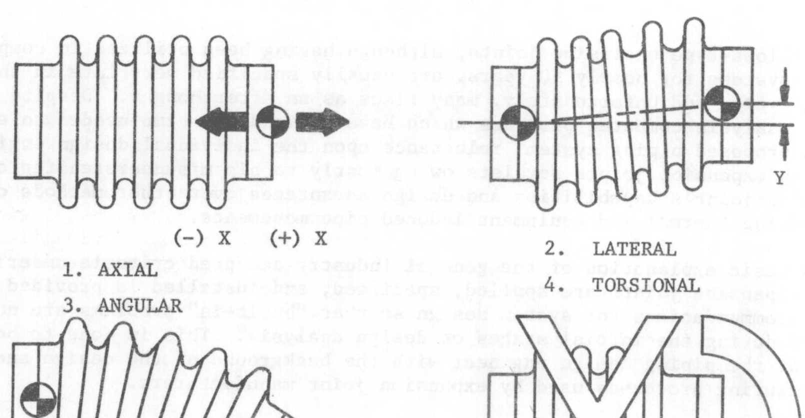
[1] Footnote numbers denote References at end of paper.

Pipe loops, the principle solution to thermal pipe growth many years ago, are now not in great demand since increased construction costs, higher land values, and the necessity for more compact plant design has led to the increased specification of expansion joints.[3] This increased usage unfortunately, has not been paralleled by the education of specifying engineers in the application of this product. The subject of this paper shall be limited to a discussion of metallic convoluted bellows expansion joints, their application, specification, and installation along with other pertinent information deemed helpful to the piping design engineer.

EXPANSION JOINT DEFINITION

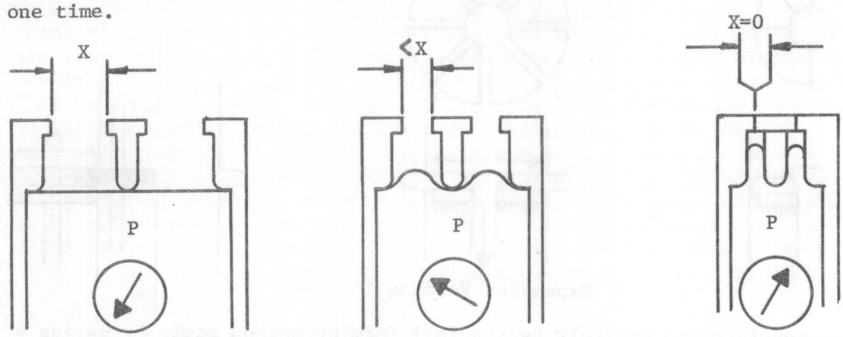
An expansion joint is a device containing one or more bellows designed to absorb dimensional changes, such as those caused by thermal expansion or contraction of a pipeline, duct or vessel. The bellows within an expansion joint is the flexible element consisting of one or more convolutions and the end tangents. A convolution is the smallest flexible unit of a bellows and is manufactured from a thin metallic longitudinally welded cylinder.[4] The movement and pressure capacity of the expansion joint assembly is related to the thickness and quantity of individual convolutions. An expansion joint is designed to contain the flowing media and internal or external pressure while reducing resulting forces and moments on the piping system or attached equipment. This assembly is also subjected to the cyclic movements caused by thermal gradients experienced by the operation of the system or vessel. Designed to accommodate mechanically, or thermally induced movements, in any one or combination of three basic motions, expansion joints should not be subjected to torsional rotation about the pipe centerline as rapid failure may occur.



1.) Axial motion is displacement which either compresses (-) or extends (+) the bellows along its longitudinal axis from its neutral position.
2.) Lateral motion is displacement of the bellows perpendicular to its longitudinal axis.
3.) Angular rotation is displacement of the longitudinal axis of the bellows from its neutral straight line position into a circular arc.
4.) Torsional rotation is the rotation of one end of the expansion joint with respect to the other about its longitudinal axis. It produces extremely high shear stresses in the bellows and for this reason should be avoided.[4]

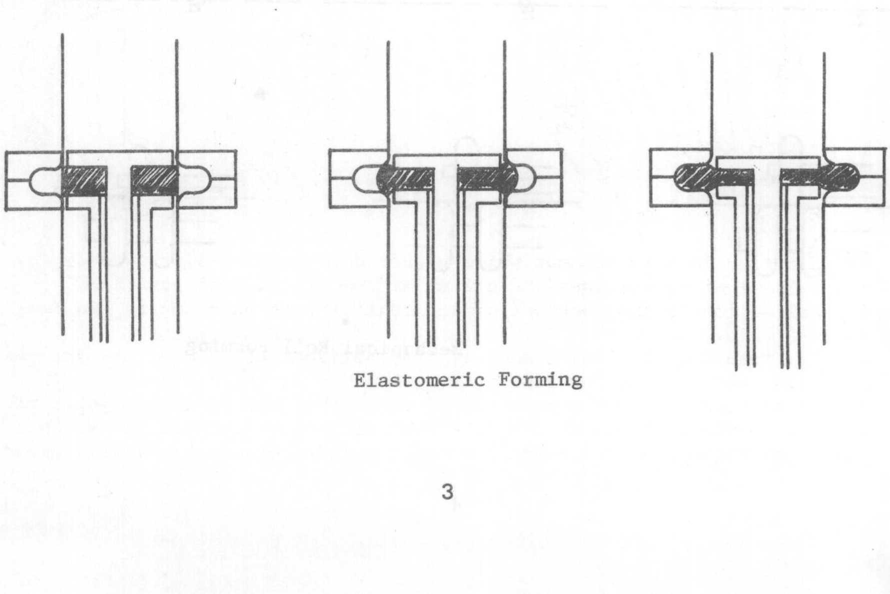
EXPANSION JOINT MANUFACTURE

Metallic convoluted expansion joints have their primary component, a bellows, formed from a thin, longitudinally welded cylinder. The material used in the manufacture of the bellows is predominantly stainless steel of various grades, but can be made from any weldable, sufficiently ductile material, that is compatible with the flowing media.[5] This cylinder can be formed into a convoluted bellows by a number of manufacturing methods, one of which is by subjecting it to internal hydrostatic pressure while externally restrained at prescribed intervals along the length of the cylinder by precisely contoured dies.[4] By a careful relationship of simultaneously increasing the hydrostatic pressure and longitudinally reducing the die spacing, the bellows cylinder is circumferentially expanded into the die cavity. This forming procedure, for moderate diameter bellows yields the optimum convolution design. Compared to other procedures, hydrostatic forming produces the minimum localized thinning along the developed length of each convolution, especially at the bellows crest.[5] The hydraulic forming process allows convolutions to be formed individually or all at one time.



Hydrostatic Forming

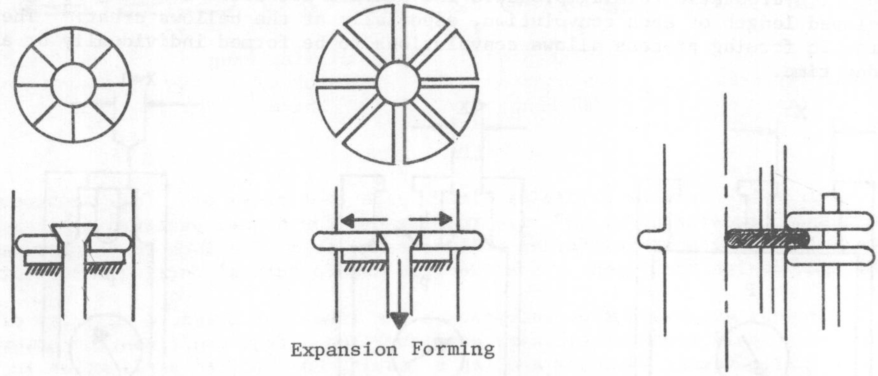
Elastomeric forming utilizes a mandrel containing a rubber or equivalent elastomeric torus. The metallic bellows cylinder is positioned over the mandrel and, while the torus is subjected to an axial force, is displaced outward along with a portion of the cylinder. Upon relaxation of the axial force, the expanded cylinder is longitudinally compressed into the final convolution shape by external contoured dies. Convolutions are formed individually and the cylinder is allowed to draw towards the convolution during manufacture thereby minimizing material thinning in the bellows root and crest.[4]



Elastomeric Forming

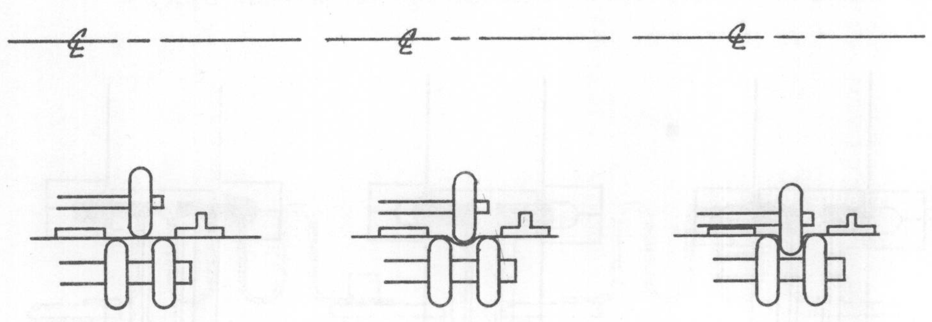
Convoluted expansion joints are available in standard nominal pipe sizes from 3/4 inch to 72 inch diameters. When a specific piping system is of a diameter larger or other than these nominal diameters, hydraulic or elastomeric forming may be precluded from use since the external circumferential contoured dies are machined for unique individual diameters and cannot be economically modified, therefore various other manufacturing methods must be employed.[6]

Expansion forming of individual convolutions is performed by a segmented metal expanding punch located inside the bellows cylinder. The punch is operated outward thereby expanding the bellows cylinder. This process is usually accomplished without the aid of external forming dies. The final convolution shape is subsequently produced by mechanically roll forming the bellows in a similar manner to the one described below.



Expansion Forming

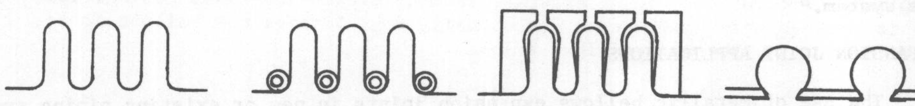
Bellows manufactured entirely by the roll forming method begin by having a cylinder placed over a cylindrical support roll in a forming machine whose forming wheels mechanically exert pressure simultaneously to the inside and outside surfaces of the bellows tube. This occurs while either the tube rotates about fixed shaft forming wheels, or the forming wheels rotate about the fixed cylinder's circumference. Controlled longitudinal shortening of the bellows cylinder occurs during the forming operation to minimize the material thinning of the convolution root and crest.[4]



Mechanical Roll Forming

BELLOWS TYPES

The three basic circular bellows design configurations are the unreinforced "U" shape, reinforced "U" shape, and the toroidal. The unreinforced bellows, having a meterial thickness from .010 inch to .062 inch is normally used for low pressure applications from full vacuum to 50 psig. Special design considerations and bellows configurations can allow an unreinforced bellows to be used at much higher pressure applications.



Unreinforced "U" Shape

Root Ring Reinforced "U" Shape

Equalizing Ring Reinforced "U" Shape

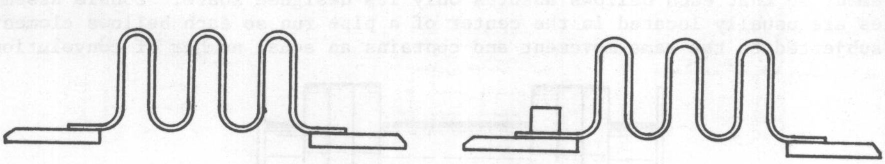
Toroidal Shape

Bellows Types

Reinforced bellows utilizing either pipe root rings or fully contoured tee shaped "equalizing rings", are recommended for higher pressure applications. Material thickness of reinforced bellows range from .050 inch to thicker depending upon design conditions and a specific manufacturers' forming capability.[7]

Toroidal bellows design encompasses the excellent pressure capacity of a relatively small diameter circular configuration. This configuration however has minimal movement capacity and, as a result, has limited application in complex piping systems. Toroidal bellows can only be manufactured by the hydraulic forming process.

The bellows configurations described above can be furnished in multiple ply design, consisting of two or more cylinders telescoped together and formed simultaneously. This multi-ply construction results in such features as inter-ply pressure sensing and multiple material usage. The pressure sensing capability is accomplished by attaching a pressure tap coupling to the tangent of the outer bellows ply which then allows monitoring of the anulus between the plies. Multi-ply bellows may also use different materials for their respective inner and outer ply construction. The inner ply, being in contact with the flowing media, may be of a highly corrosive resistant material, whereas the outer ply could be of a less costly high strength material for pressure capacity.



Standard Multi-Ply Bellows

Multi-Ply Bellows with Inter-Ply Sensing Connection

Expansion joints are predominantly manufactured from 300 series stainless steels, but can be made from any weldable sheet material of sufficient ductility to permit forming.[5] Materials in this category are some 400 series stainless steels, the Monel, Inconel, Incoloy series of Nickel alloys, Aluminum, Hastelloy, Carpenter 20, and Titanium. Bellows material should be specified by the piping design engineer based on the system operation and flow media characteristics. The type of material specified would depend upon the corrosive or erosive nature of the media, design pressure and temperature, movements and fatigue life requirements. The 300 series stainless steels are prone to pitting and corrosion cracking at elevated temperatures when used in chloride or sulfur laden atmospheres. It is absolutely essential to consider not only the media which flows through the expansion joint, but also the atmosphere which surrounds the system.[8]

EXPANSION JOINT APPLICATIONS

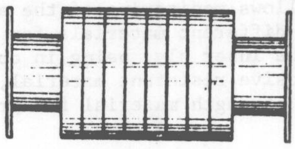
The use of metallic bellows expansion joints in new or existing piping systems can be advantageous under the following conditions:

1.) Where restrictive space makes it uneconomical or impossible to utilize the natural flexibility of the system, or to install expansion loops to absorb pipe expansion or contraction.[9]
2.) Where short piping runs connect process equipment.
3.) Where pressure drop limitations preclude the use of extensive expansion loops.[10]
4.) When the allowable force and moment limitations on sensitive equipment are small and they cannot be isolated from the equipment by use of restraints such as guides or directional anchors.[4]
5.) Where piping materials are so costly that loops become uneconomical.
6.) Where radiant heat losses would be excessive if large expansion loops were to be used.[2]

EXPANSION JOINT TYPES

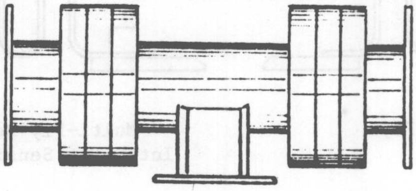
Single Expansion Joint

A single Expansion joint is the least complex and most economical type of assembly. It contains only one bellows element and is capable of absorbing all three basic forms of motion, although the use of a single expansion joint for lateral motion greatly reduces its ability to absorb axial motion.



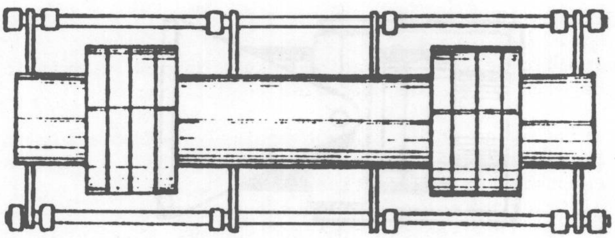
Double Expansion Joint

A double expansion joint consists of two bellows elements joined by a common pipe segment which must be anchored to an external structure. It is normally used for axial movement that is too great to be absorbed by a single assembly. The intermediate anchor attached to the common pipe divides this movement so that each bellows absorbs only its designed share. Double assemblies are usually located in the center of a pipe run so each bellows element is subjected to the same movement and contains an equal number of convolutions.



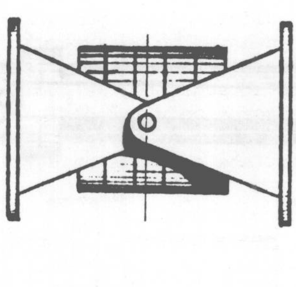
Universal Expansion Joint

A universal expansion joint consists of two bellows elements joined by a common pipe segment, but unlike the double joint, this pipe is not anchored to a structure. This allows the universal expansion joint to absorb any combination of the three basic forms of motion where they exceed the capacity of a single bellows assembly. Universal assemblies usually have tie or limit rods with stops that distribute the motion between the bellows and also stabilize the common pipe segment.



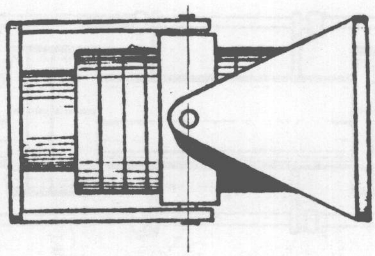
Hinged Expansion Joint

A hinged expansion joint contains one bellows and is designed to permit angular rotation in one plane only by the use of a pair of hinge pins and plates attached to the assembly ends. The hinge hardware must be designed to restrain the pressure thrust of the assembly and, in addition, may be required to support the weight of piping and equipment, absorb thermal loads, wind loads and other external forces. Hinged joints are usually used in sets of two or three, to absorb pipe movement in one or more directions in a single plane piping system. Each individual assembly in the system is restricted to pure angular rotation by its hinge hardware. However, each pair of hinged assemblies, separated by a section of piping, will act together to absorb lateral deflection in a similar manner as a universal expansion joint in a single plane application.



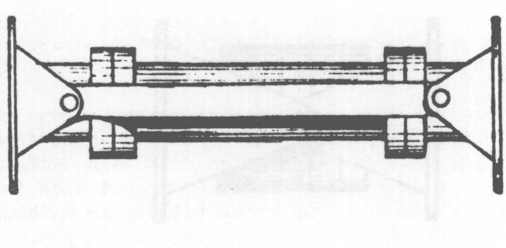
Gimbal Expansion Joint

A gimbal expansion joint contains one bellows and is designed to permit angular rotation in any plane by the use of two pairs of hinge pins and plates attached to a common floating gimbal ring. Like a hinge assembly, the gimbal hardware must be designed to restrain the pressure thrust of the bellows and any imposed external forces. Unlike the hinge assembly, the gimbal joint can absorb angular rotation in any plane, which allows it to be used in multi-plane piping systems. Gimbal assemblies may be used together or in conjunction with hinge assemblies.



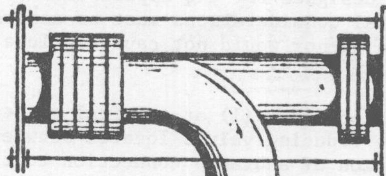
Swing Expansion Joint

A swing expansion joint consists of two bellows elements joined by a common pipe segment and designed to absorb lateral deflection and/or angular rotation in one plane only. It employs a pair of swing bars pinned to the assembly ends through appropriately designed hardware. The swing bars and hardware must be designed to restrain the pressure thrust of the bellows and any imposed external forces.



Pressure Balanced Expansion Joint

A pressure balanced expansion joint is a combination of bellows elements interconnected to oppose each other so that the internal pressure thrust of one balances the interanl pressure thrust of the other. The balanced pressure loading condition prevents this normally applied load from being transmitted to pipe anchors or attached equipment. The compressive spring forces of the two sets of bellows are additive but are usually negligible in relation to the pressure thrust forces which are eliminated through the "balance" design. This type of expansion joint is used where a pipeline changes direction, and can be designed for any combination of movements. [11]



EXPANSION JOINT ACCESSORIES

The expansion joint's ability to accommodate the previously described applied movements may, in fact, be limited by the design of such external hardware items as tie rods, hinges, limit rods, or gimbal rings. These limitations may be a design requirement of the piping system (tie rods to contain pressure thrust) or for protection of the expansion joint bellows itself (hinge hardware to prevent transmission of torsional rotation into the bellows, limit rods to protect the bellows from excessive movement). Whatever the requirement, hardware analysis and design is best approached by the expansion joint manufacturer and will be based on a combination of field experience and recognized design rules.

Other forms of accessories available for inclusion on expansion joint assemblies are:

1.) External cover (shroud): A circumferential member around the exterior of the bellows convolutions to protect the expansion joint from mechanical damage and to serve as a base for insulation. It is a useful and economical method of extending the operational life of an expansion joint, since one of the greatest causes of expansion joint failure is mechanical damage to the exterior of the bellows.

2.) Internal sleeve (liner): A cylindrical sub-assembly located within the expansion joint designed to minimize the contact between flowing media and the inner surface of the bellows, reducing friction losses and turbulence. It also prevents erosion of the bellows caused by foreign matter entrained in high velocity flow and protects against high velocity-incuded vibration. Sleeves are recommended for all applications except for high viscosity fluids such as tar which may "cake-up" between the bellows and sleeve.

ANCHORS

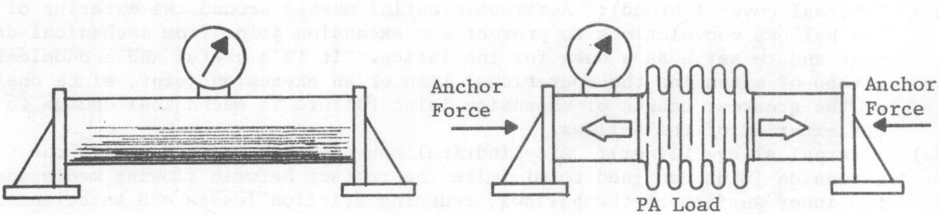
The specification of metallic expansion joints for a pipe system is only a small portion of the overall responsibility of the design engineer. Improper application of pipe restraints and alignment guides can defeat the purpose of an expansion joint, and ultimately result in its failure. The restraints serve to limit the movement absorbed by the expansion joint only in directions intended by the design engineer.

Piping system anchors are necessary to secure the system at certain vital points and stabilize the pipe between terminal connections. Where expansion joints are installed, anchors segregate the system into individual sections so that each expansion joint absorbs only that growth related to its section. An anchor must resist all imposed forces and not allow movement of the pipe system at the point of attachment. Anchors can assume a variety of physical appearances; major pieces of equipment (turbines, pumps, compressors, heat exchangers or other vessels), because of their size, often act as anchors. Other anchor styles must be specifically designed for the application and location within the piping system. Structural considerations must be assessed so that the severe loading imposed upon an anchor would not cause failure or unacceptable deflection of the attached members.[1, 4]

Main anchors are to be located: (1) at terminal points of the pipe system, (2) at shut off and pressure reducing valves located between two expansion joints, (3) at the intersection of a branch connection to the main pipeline, (4) between two expansion joints of different diameters which have been installed in the same straight run, and (5) at a directional change of the pipe system.[4, 5]

A main anchor must be designed to withstand the forces and moments imposed upon it by all of the attached pipe sections. If a pipe section contains an expansion joint, these forces and moments will consist of the full line pressure thrust (consideration must be made of hydrostatic testing loads, and surge pressures created by quick closing valves), flow induced dynamic effects, the forces/moments required to deflect the expansion joints, and frictional forces created by pipe alignment guides, directional anchors and pipe supports.[4]

One of the most misunderstood elements in the application of expansion joints is the pressure thrust resulting from their use as applied to the main anchors. When a straight length of pipe is located between two anchors (thermal growth discounted), the pressure load is contained in tension in the pipe wall. When an expansion joint is introduced into the system, the pipe is no longer able to contain this tensile load and the two ends would be "blown apart" thereby over-extending the bellows unless resisted by an external force usually provided by the main anchor. The force (pressure thrust) created by the expansion joint is equal to the internal pressure (P) times the calculated effective area of the bellows (Ae).[12]



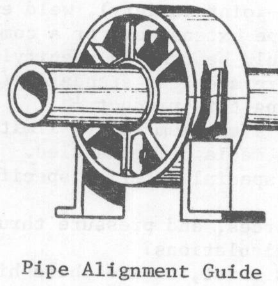
Anchor Loading

Intermediate anchors serve to divide long pipe runs into individual sections, each of which must contain an expansion joint designed to absorb the related thermal movement of that section. An intermediate anchor must be designed to withstand the same forces and moments a main anchor is designed for, except it is not intended to withstand the pressure thrust. This force is absorbed by the main anchors, or transmitted by structural members on the expansion joints such as tie rods, swing bars, and hinge or gimbal hardware. The importance of analyzing and properly determining anchor loads cannot be overemphasized.

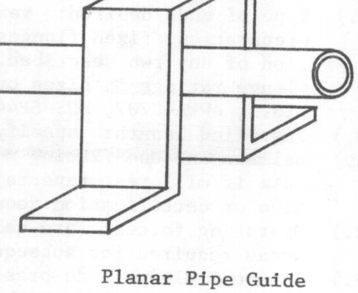
PIPE GUIDES

It is imperative that the piping adjacent to the installed expansion joint be adequately guided so that the movement is applied to the expansion joint the way it was designed, to prevent bellows distortion due to imposed lateral or angular misalignment of the pipeline and prevent buckling of long pipelines when subjected to compressive loads as they expand. Pipe spans are similar to structural columns with both exhibiting a tendency to buckle under compressive end loads. This tendency is directly proportional to the pipe's slenderness ratio which is greatly reduced by the proper application of pipe alignment guides. As a general rule expansion joints are designed to accommodate movement in a single plane, and are subject to damage, or compromised operating life when unanticipated motion is imposed upon the assembly. This direction of motion is accomplished through the use of pipe alignment guides either of the full guide or planar guide variety. Rigorous analysis of the thermal effects in a piping system is of limited value unless it is paralleled by judicious guide design and usage. Proper guiding must be provided for from the inception of design, with actual guide locations considered in early layout plans, and followed through with installation during construction of the final piping system. Should this not be the case, an improperly guided line will behave like an end-loaded column; the bellows will deform and fail.

A typical pipe alignment guide consists of a steel spider which is circumferentially clamped over the outside of the pipe. This spider is located inside a cylindrical casing which in turn is bolted or welded to a suitable support structure. Pipe movement resulting from thermal gradients, cause the pipe to expand or contract and the spider to slide within the casing, which permits longitudinal movement while restricting all lateral movement because of the close radial fit between the spider and casing. This action therefore insures proper direction of the pipe growth into the bellows expansion joint. A planar pipe guide is similar to a pipe alignment guide, except that it allows not only longitudinal movement but also lateral movement in one plane. Planar guides are only used in applications involving movements resulting from L-shaped pipe configurations.[4]



Pipe Alignment Guide



Planar Pipe Guide