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Shakedown boundary determination of a 90° back-to-back pipe bend subjected to steady internal pressures and cyclic in-plane bending moments

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ABSTRACT

No experimental data exist within open literature, to the best knowledge of the author, for determining shakedown boundaries of 90° back-to-back pipe bends. Ninety degree back-to-back pipe bends are extensively utilized within piping networks of nuclear submarines and modern turbofan aero-engines where space limitation is considered a paramount concern. In the current research, the 90° back-to-back pipe bend setup analyzed is subjected to a spectrum of steady internal pressures and cyclic in-plane bending moments. A previously developed direct non-cyclic simplified technique for determining elastic shakedown limit loads is utilized to generate the elastic shakedown boundary of the analyzed structure. The simplified technique outcomes showed excellent correlation with the results of full elastic–plastic cyclic loading finite element simulations.

1. Introduction

Pressure vessel components are often subjected to the combined effect of simultaneous steady and cyclic load types. The combination of both the steady and the cyclic loads often results in exceeding the material initial yield strain (ε_0) within several parts or regions of the pressure vessel structure. It is the objective of the designer to ensure that exceeding the initial yield strain (ε_0) would not lead to either development of progressive damage due to low cycle fatigue (reversed plasticity) and/or collapse due to incremental accumulation of plastic strain (ratchetting) associated with every load cycle. The upper ceiling of loads which does not cause either reversed plasticity and/or ratchetting responses is the elastic shakedown boundary. The utilized simplified technique was successfully verified and rigorously tested against both closed form solutions of classical shakedown benchmark problems [1–3] and ratchetting experimental outcomes of pressurized pipe bends subjected to reversed in–plane bending [4]. The structure presently analyzed is formed by bending a straight pipe to acquire the geometry of two 90° pipe bends set back-to-back each having a nominal pipe size (NPS) of 10 in. Schedule 40 Standard (STD). Besides being installed in modern nuclear submarines and turbofan aero-engines on smaller scales, 90° back-to-back pipe bend configurations are also found on larger scales, due to installation constraints, of piping networks of nuclear power plants, chemical and pharmaceutical industries, and huge liquefied natural gas tankers. In addition to determining the elastic shakedown boundary, both elastic and inadaptation [i.e. reversed plasticity (RP) and/or ratchetting (*R*)] domains are also determined to generate the structure's Bree diagram. Additionally, the maximum moment carrying capacities (limit moments) are also determined and imposed on the generated Bree diagram of the analyzed structure.

2. Literature review

Pipe bends are not only used to change direction of fluid flow, but to add necessary flexibility to the entire piping network. It was initially demonstrated by Bantlin [5] in 1910 through an experimental setup that a curved pipe behaves in a different manner than that predicted by simple beam theory. In 1911, von Kàrmàn [6] explained this discrepancy through theoretical stress analysis that pipe bends acquire smaller flexural rigidity compared to straight pipes of the same material and dimensions. This added flexibility is attributed to the tendency of pipe bends to embrace a shell-type behavior by virtue of their curved geometries unlike straight pipes which tend to behave like beams. Contrarily, such acquired flexibility is accompanied by stress and strain magnitudes that are much higher than those present in straight pipes. Consequently, pipe bends are considered amongst the critical components within a piping network.

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Nomenclature

D_i	pipe bend inner diameter
D_m	pipe bend mean diameter
D_o	pipe bend outer diameter
E	modulus of elasticity (Young's modulus)
L	length of straight pipes
P	internal pressure
P_Y	internal pressure to initiate yielding of a straight pipe
PEEQ	equivalent plastic strain
R	ratchetting
RP	reversed plasticity
SP	through thickness integration section point
S_y	material initial yield strength
M_P	straight pipe fully plastic moment
i	elastic–plastic solution increment
r	pipe bend radius
t	wall thickness
ε_0	material yield strain
ν	Poisson's ratio
σ_E	elastic stress components
σ_{ELPL}	elastic–plastic stress components
σ_{unload}	unload stress component
$\sigma_{unload_{eq}}$	unload equivalent stress

The initial lower bound shakedown theorem was formulated by Gruning [7] in 1929 for beams of ideal I-cross-sections. Further, Bleich [8] extended Gruning's work and presented solutions for more I-cross-section beams in 1932. In 1936, Melan [9] advanced the lower bound shakedown theorem to the more general case of a continuum stated as follows: "*For a given load set P, if any distribution of self-equilibrating residual stresses can be found (assuming perfect plasticity) which, when taken together with elastically calculated stresses, constitute a system of stresses within the yield limit, then P is a lower bound shakedown load set and the structure will shakedown*". The 2003 ASME Boiler and Pressure Vessel Code [10] defines shakedown as follows: "*the absence of significant progressive, cyclic, inelastic deformation*." Despite the establishment of the lower bound shakedown theorem within the mid-late thirties of the previous century [9,11,12], active research efforts started in the mid-sixties. Most of the work accomplished, in the mid-sixties, focused on determining shakedown domains for pressure vessels [13], nuclear reactor components [14], and aeronautical applications [15].

Iterative elastic techniques have been proposed to obtain rapid and approximate bounds for both limit loads and shakedown limit loads. The Iterative elastic techniques start with an initial elastic solution which is modified in an iterative manner, through a series of linear elastic finite element (FE) solutions, to redistribute stresses within the structure by changing the elastic moduli of the elements. The iterations proceed until a stress distribution in equilibrium with the externally applied load is reached. The iterative elastic techniques include the Elastic Compensation Method (ECM) introduced by Marriot [16] further modified and widely utilized by Mackenzie and Boyle [17], the Dhalla Reduction Procedure proposed by Dhalla [18], the GLOSS R-Node method proposed by Seshadri [19], and the Linear Matching Method (LMM) introduced by Chen and Ponter [20]. Yang et al. [21] modified the ECM through introducing additional parameters and renamed the ECM to be the Modified Elastic Compensation Method (MECM) and determined limit loads for nozzle to vessel junctions. Muscat and Mackenzie [22] utilized a superposition method based on Melan's shakedown theorem and investigated the shakedown response of axisymmetric nozzles under internal pressure. Muscat and Mackenzie [22] concluded that the 3 S_m method majorly ensures determination of plastic shakedown limit. Polizzotto [23] introduced a modification to Melan's theorem accounting for combined non proportional loading. Muscat et al. utilized Polizzotto's modification and investigated two benchmark shakedown problems namely: a plate with a central hole subjected to cyclic biaxial stresses [24,25] and a thick vessel-nozzle intersection subjected to steady in-plane moment and cyclic internal pressure [25]. The outcomes of the thick vessel-nozzle intersection agreed well with the results of Preiss [26] while the outcomes of the plate problem agreed well with the ECM solution of Hamilton et al. [27]. Moreover, the outcomes of both problems agreed well with the outcomes of full elastic plastic cyclic loading FE analyses.

Abdalla et al. [2] applied the simplified technique on two classical benchmark shakedown uni-axial stress problems namely; the 2-bar structure, analytically analyzed by Megahed [28], and the Bree thin-cylinder problem [14]. The outcomes of the simplified technique showed excellent correlation to the analytical results of both problems. Later Abdalla et al. [3] applied the simplified technique on another classical benchmark shakedown problem namely: the problem of a large square plate with a small central hole subjected to cyclic tensile stresses on the plate edges; thereby, extending the application of the simplified technique to multiaxial state of stress problems and also accounting for material kinematic hardening. Abdalla et al. also extended the application of the simplified technique to a long radius 90° pipe bend subjected to a spectrum of steady internal pressures and cyclic in-plane closing (IPC) [1], in-plane opening (IPO) and out-of-plane (OP) bending moment loadings [29] employing an elastic-perfectly-plastic (EPP) material model. Additionally, Abdalla et al. [30] performed a parametric study and generated Bree diagrams for 90° scheduled Nominal Pipe Size 10″ pipe bends namely: Schedule 20, Schedule 40 Standard (STD), and Schedule 80 subjected to a spectrum of steady internal pressures and cyclic IPC, IPO, and OP bending moment loadings. Comparison of the generated Bree diagrams of the scheduled pipe bends revealed that as the wall thickness increased, both the limit loads and the shakedown limit loads increased as well. Additionally, Abdalla et al. [30] analyzed the scheduled pipe bends employing a simple linear kinematic hardening material model. The generated shakedown boundaries accounting for material kinematic hardening were slightly higher than their corresponding shakedown boundaries employing EPP material model for the medium to high steady internal pressure spectrum. Abdalla et al. [31] developed another technique for elastic shakedown limit load determination named the "Iterative Large Displacement Technique," which accounts for geometric nonlinearity owing to the considerable ovalization experienced by pipe bends within the plastic domain. The iterative large displacement technique employs an EPP material model and performs a successive series of full ELPL cyclic loading FE simulations with varying peak loads until the maximum unload equivalent stress ($\sigma_{unload_{eq}}$) achieved, at cyclic load removal, is slightly less than the material yield strength. A comparison between the shakedown diagrams generated from both the simplified technique and the iterative large displacement technique was presented for the 90° pipe bend under IPC, IPO, and OP bending moment loadings. Recently, Abdalla et at [32]. generated the shakedown boundaries, limit loads, and elastic domains of a vessel-nozzle intersection subjected to a spectrum of steady internal pressures