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Validation of the Nonlinear Superposition Method (NSM) for elastic shakedown limit pressures via comparison with experimental test results of spherical vessels with radial and oblique nozzles

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ABSTRACT

The present research revisits rare experiments which determined elastic shakedown (SD) limit pressures of full scale radial and oblique nozzles partially penetrating spherical vessels. The experiments were conducted at Berkeley Nuclear Laboratories in England [1]. The SD limit pressures were determined via conducting consecutive series of internal pressure cycles and observing cyclic strain variation recorded by strain gauges cemented at predetermined various critical locations within the junctions' vicinities. The Nonlinear Superposition Method (NSM), formulated for computing elastic SD limit loads based on Melan's lower bound SD theorem, is successfully validated against recorded experimental outcomes for both nozzle configurations. Furthermore, full elastic-plastic cyclic loading finite element simulations were executed and illustrated very good correlation to the NSM results.

1. Introduction

Pressure vessels with welded nozzles are integral parts of nuclear, conventional power generation plants, petrochemical, pharmaceutical industries … etc. Due to the cyclic loading nature of such critical components, failures generally occur within the vicinities of the vessel/nozzle junctions. Operation beyond the shakedown (SD) limit load leads to catastrophic failures due to low cycle fatigue (reversed plasticity response, also termed: alternating plasticity) and/or cyclic accumulation of plastic strain (ratcheting response) eventually leading to failure due to exhaustion of material ductility. Procter and Flinders [1] performed cyclic pressurization and depressurization on full sized spherical vessels to inspect the SD behavior of several vessel/nozzle junctions at Berkeley Nuclear Laboratories in England. The spherical vessels possessed the same sizes while the radial and oblique welded nozzles possessed different wall thicknesses and cross sectional geometries. Generally, SD loads are deduced from sets of ratcheting tests in which the cyclic load amplitudes are sequentially reduced until reversed plasticity and/or ratcheting responses vanish indicating prevailing SD conditions. Hence, in terms of the level of cyclic load, the SD state was approached from above [2–8]. However, the approach of Procter and Flinders [1] was different since the limit SD pressures were obtained through increasing the levels of cyclic internal pressures until indication of reversed plasticity response was observed thereby approaching the SD limit from below. Ure et al. [9] successfully predicted the experimental SD pressures reported in Ref. [1] for the medium and thin oblique nozzles utilizing the Linear Matching Method (LMM). The scope of the present research focuses on validating the NSM accuracy to determine SD limit pressures via comparison to corresponding experimentally recorded lower bound SD limit pressures of both radial and oblique nozzles reported in Ref. [1]. As mentioned earlier within the abstract section, full elastic-plastic (ELPL) cyclic loading finite element simulations were executed to validate NSM results. Comparisons between NSM and LMM [9] results are also presented and briefly discussed.

2. Literature review

The Shakedown term initially appeared within the realm of structural and solid mechanics by Grüning in 1926 in analysis of beams with ideal I-cross sections [10]. Bleich then expanded the work of Grüning via diversifying analyses of more I-cross section beams in 1932 [11]. However, Ernst Melan [12] gained most of the credit for initially formulating a comprehensive mathematical lower bound SD theorem in 1936 expressed as follows: "*An elastic-perfectly-plastic structure shall shakedown given a load set if and only if there exists a residual stress field*

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Nomenclature

D	Outer diameter of a straight pipe
E	Modulus of elasticity (Young's modulus)
P	Internal pressure
P_{SD}	Elastic shakedown limit pressure
P_i	Internal pressure increment within an elastic-plastic solution
P_{ref}	Reference cyclic internal pressure
P_y	Initial yield pressure
R_{in}	Spherical vessel inner radius
R_{out}	Spherical vessel outer radius
S_{mn}	Stress deviator tensor
S_u	Ultimate tensile strength
S_y	Yield strength
i	Solution increment within a finite element analysis
k, m, n	Positive integers ranging from 1 to 3
t	Wall thickness of a straight pipe
δ	Kronecker delta
ν	Poisson's ratio
$\sigma_{mn}^{EL,i}$	Elastic normal stress tensor
$\sigma_{mn}^{ELPL,i}$	Elastic-plastic normal stress tensor at every pressure load solution increment
$\sigma_{eq}^{r,i}$	Residual stress tensor
$\sigma_{mn}^{ul,i}$	Normal stress tensor at every pressure unload solution increment
$\sigma_{eq}^{ul,i}$	Equivalent unload normal stress tensor at every pressure unload solution increment
ε_o	Initial yield strain

Abbreviations

EL	Elastic
ELPL	Elastic-Plastic
EPP	Elastic-Perfectly-Plastic
FE	Finite Elements
NSM	Nonlinear Superposition Method
PEEQ	Equivalent plastic strain
SD	Shakedown
eq	Equivalent
ul	Unloading

that nowhere within the structure violates the applied yield criterion when superimposed on the elastic stress field resulting from the applied load set". The American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code for Nuclear Power Plant Components [13] defines SD as: "*the absence of significant progressive cyclic inelastic deformation*". Generally, the ASME definition of SD focuses majorly on avoiding structural ratcheting responses. The methodology behind the NSM was implicitly initiated via Preiss [14]; however, he did not explicitly specify the NSM terminology. More specifically, Preiss [14] applied Melan's SD theorem and calculated SD limit loads for pressurized vessels utilizing deviatoric maps of states of stress in order to attain self-equilibrating fields of stress which was somehow tedious process. Muscat and Hamilton [15] and Muscat and Mackenzie [16] were the first to introduce the NSM terminology. Almost very close to the time domain when Muscat and Hamilton [15] and Muscat and Mackenzie [16] introduced the NSM, Abdalla et al. [17–28] performed extensive investigation of Melan's lower bound SD theorem and devised a method termed the "Simplified Technique" in their early publications and recently termed the "Direct Non-Cyclic Technique" [29], embracing almost similar merit as compared to the NSM approach. The "Simplified Technique" has been rigorously verified against analytical solutions of classical SD benchmark problems [17,18] and validated against experimental test outcomes [2] and has also been validated against full elastic-plastic (ELPL) cyclic loading FE analyses of diverse pressure vessels and piping components [17–29]. In order to avoid existence of various technique terminologies contributing to a common target of estimating lower bound elastic SD limit loads, it is deemed appropriate to embrace both the terms "Simplified Technique" and "Direct Non-Cyclic Technique" under the term "NSM" for future research endeavours.

Iterative elastic methods were proposed to determine approximate magnitudes of structural limit and SD limit loads [30]. Iterative elastic methods perform series of iterative elastic FE solutions during which the elastic moduli of various elements are altered with every iteration. The elastic FE iterations progress till a stress field is achieved satisfying equilibrium with the external applied load(s). Several iterative elastic methods are available within literature including the Elastic Compensation Method (ECM) proposed by Mackenzie and Boyle [30] which is established upon a numerical algorithm initiated by Marriott [31], the Linear Matching Method (LMM) pioneered by Chen, H. and Ponter A. [32], the GLOSS R-Node method introduced by Seshadri [33], and the Dhalla Reduction Procedure presented by Dhalla [34]. Nadarajah et al. [35] employed the ECM and determined limit and SD moments of cylindrical vessel/nozzle junctions subjected to steady internal pressures and cyclic in-plane bending moments on the nozzles. Mackenzie and Boyle [30] calculated SD limit pressures for thick-walled and thin-walled cylindrical vessels with flush nozzles utilizing the ECM and the outcomes were in good agreement with the closed form solutions presented earlier by Leckie and Penny [36]. Oh, C.S. et al. [37] employed the NSM and generated SD boundaries for 90°degree pipe bends subjected to a spectrum of steady internal pressures and cyclic in-plane bending moments. Oh, C.S. et al. [37] highlighted scarcity of published works on limit loads and SD limit loads of geometrically complex structures such as pipe bends and nozzles similar to those reported by Abdalla et al. [17] and Carter [38]. Further, Abdalla et al. [25] modified the NSM via adopting Ziegler's kinematic hardening material model and constructed SD boundaries for 90° pressurized scheduled pipe bends subjected to steady internal pressures and cyclic in-plane and out-of-plane bending moments. Very recently, Cho, N.-K. and Chen, H [39]. published notable geometric and loading parametric study on SD and ratchet analyses of 90° back-to-back pipe bends under steady internal pressures and cyclic in-plane opening bending moments. The same component was previously analysed by Abdalla [24], but for two 90°pipe bends set back-to-back having nominal pipe size of 10 in. Schedule 40 Standard under the same loading conditions. Cho, N.-K. and Chen, H [39]. reported that the NSM yields conservative SD boundaries as compared to the LMM.

Abdalla et al. [22] generated SD boundaries and limit loads of a cylindrical vessel/radial nozzle junction subjected to steady internal pressures and cyclic in-plane bending moments applied on the nozzle end utilizing the NSM. Later, Abdalla et al. [23] analysed the same pressurized vessel/nozzle structure, but subjected to cyclic out-of-plane bending moments and illustrated that cyclic in-plane bending possessed remarkably higher elastic SD boundary. Vlaicu [40], Korba et al. [26], Hafiz et al. [27], El-Saadany et al. [28], Oda et al. [29], Oh C.S. et al. [37], and Vermaak et al. [41] adopted the NSM, under the name "Simplified Technique", and determined SD boundaries for components with complex geometries utilized within pressure vessel and aerospace applications. Authentic SD research efforts have been conducted on vessel/nozzle junctions by several researchers including, for instance, Procter and Flinders [1], Leckie and Penny [36], Muscat and Mackenzie [16], Nadarajah et al. [35], Vlaicu [40], Staat and Heitzer [42], Staat [43], and Vu et al. [44]. Nevertheless, SD and post-SD responses of vessel/nozzle junctions demand extensive research investigation as