

# Estudos em Ciências Exatas e da Terra

Desafios, Avanços e Possibilidades

Alireza Mohebi Ashtiani  
(organizador)

 EDITORA  
ARTEMIS  
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<b>Bibliotecário</b>	Maurício Amormino Júnior – CRB6/2422

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**Dados Internacionais de Catalogação na Publicação (CIP)**  
**(eDOC BRASIL, Belo Horizonte/MG)**

E82 Estudos em Ciências Exatas e da Terra: Desafios, Avanços e Possibilidades / Organizador Alireza Mohebi Ashtiani. – Curitiba, PR: Artemis, 2023.

Formato: PDF

Requisitos de sistema: Adobe Digital Editions

Modo de acesso: World Wide Web

Inclui bibliografia

Edição bilíngue

ISBN 978-65-87396-74-3

DOI 10.37572/EdArt\_240223743

1. Ciências exatas e da terra – Pesquisa – Brasil. I. Ashtiani, Alireza Mohebi.

CDD 509

**Elaborado por Maurício Amormino Júnior – CRB6/2422**



## APRESENTAÇÃO

As ciências exatas e da terra têm uma importância muito especial e são consideradas a origem e a base principal do progresso de outras áreas de conhecimento, que ganharam destaque com a evolução tecnológica e a complexidade dos desafios humanos.

De modo geral, pode-se dizer que as importantes conquistas dos séculos passados e atuais se devem à atuação e ao avanço do campo das ciências exatas e da terra, que, através de desafios, situações e aplicações, avançaram e cruzaram as fronteiras tradicionais de outras áreas de conhecimento, resolvendo problemas complexos que abrangem diversas áreas: a isto chamamos “interdisciplinaridade”.

Diante dessa realidade, o primeiro volume de **“Estudos em Ciências Exatas e da Terra: Desafios, Avanços e Possibilidades”** publicado pela Editora Artemis e apresentado em 10 capítulos, tem por objetivo dar um panorama geral dos desafios, avanços e possibilidades que envolvem essa área de conhecimento, tanto na teoria quanto na prática.

Os trabalhos aqui apresentados, de pesquisadores de diversos países, entre eles Argentina, Brasil, México, Paraguai, Portugal e Rússia, oferecem aos leitores e interessados a oportunidade de ampliar seus conhecimentos e adquirir uma visão mais profunda da área.

Alireza Mohebi Ashtiani

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## COMPARISON OF ANALYTICAL AND NUMERICAL SOLUTIONS TO THE STRESSES PROBLEM IN A CYLINDRICAL SHELL WITH A CIRCULAR HOLE<sup>1</sup>

Data de submissão: 23/12/2022

Data de aceite: 10/01/2023

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**ABSTRACT:** The cylindrical shell with a circular hole under three types of boundary conditions is considered: axial tension, internal pressure and torsion. A new mathematical approach that allows reducing an infinite system and finding unknown coefficients for the deriving stress is offered. This approach lifts classical mathematical restrictions for

curvature parameter. The comparison of analytical and numerical results by collocation method is described.

**KEYWORDS:** Shell Theory. Cylindrical Shell. Circular Cutout.

### 1 INTRODUCTION

In recent works, Kashtanova and Rzhonsnitskiy [1,2] reconsidered the classical approach to the solution of the problem of cylindrical shell a circular cutout under an axial tension. The protagonist of this problem is a certain geometric parameter  $\beta$ , that contains the ration between the radius of the hole, the radius of the cylindrical shell and the shell thickness. When this parameter is equal to zero, we have a plane problem (the Kirsch problem in case when the boundary condition is an axial tension). There were several reasons that forced us to look for a different approach: a very small range of applicability of the solution (close to Kirsch problem), a linear dependency in the system for finding coefficients for basis function, different results in the literature, a failure of the limit transition, no explicit formulas for the field of stresses and no opportunity to make an analytical

<sup>1</sup> CILAMCE-PANACM-2021. Proceedings of the joint XLII Ibero-Latin-American Congress on Computational Methods in Engineering and III Pan-American Congress on Computational Mechanics, ABMEC-IACM, Rio de Janeiro, Brazil, November 9-12, 2021.

analysis. The classical way was to decompose the solution and the coefficients into small parameter  $\beta$ , which immediately put restrictions on the range of applicability. The authors of the present paper offered to decompose the solution into Fourier series and to divide variables [1], then they found and exclude a linear-dependent equation and after some substitution of variables proofed the reducibility of the infinite system [2]. This method allows getting a model in range of  $\beta$  up to 4. In this paper this idea, in addition to axial tension, is applied to other boundary conditions: internal pressure and torsion. The comparison of analytical and numerical results by collocation method that were received by Van Dyke [4] is described.

## 2 THE PROBLEM

We consider a cylindrical shell of radius  $R$  and thickness  $h$  with a circular hole  $r_0$  under various boundary conditions. The main parameter that is responsible for the ratio between geometric characteristics is

$$\beta^2 = r_0^2 \cdot \frac{\sqrt{3(1-\nu^2)}}{4Rh},$$

$\nu$  – Poisson's coefficient. Note that limit transition while  $\beta \rightarrow 0$  leads us to the plane problem.

The governing equation of the problem reduces by Lurie [3] to

$$\Delta\Delta\Phi + 8i\beta^2 \frac{\partial^2\Phi}{\partial x^2} = 0. \quad (1)$$

Here function  $\Phi = \frac{Eh}{8\beta^2 R} w - iU$  is used, which contains the deflection  $w$ , the stress function  $U$  and  $E$  – Young's modulus. The stress function  $U$  is connected with stress tensor  $T$  by next correlation

$$\begin{pmatrix} T_x & T_{xy} \\ T_{xy} & T_y \end{pmatrix} = \begin{pmatrix} \frac{\partial^2 U}{\partial y^2} & -\frac{\partial^2 U}{\partial y \partial x} \\ -\frac{\partial^2 U}{\partial y \partial x} & \frac{\partial^2 U}{\partial x^2} \end{pmatrix}, \quad (2)$$

median surface stress is  $\sigma = T/h$ .

We consider this problem with follow three types of boundary conditions:

I. axial tension  $p$  at infinity along  $x$ -coordinate

- at infinity  $T_x = p$ ,  $T_{xy} = 0$ ,  $T_y = 0$ ,  $w = 0$ ;
- at the boundary of the hole in polar coordinates  $(r, \vartheta)$  – free edge

$$T_{rr}\Big|_{r=r_0} = 0, T_{r\vartheta}\Big|_{r=r_0} = 0, M_r\Big|_{r=r_0} = 0, Q_r\Big|_{r=r_0} = 0; \quad (3)$$

II. uniform internal pressure  $q_0$  ( $q = \frac{q_0 r_0}{2}$ ):

$$- T_x = q; T_y = 2q; T_{xy} = 0;$$

$$\text{or (in polar coordinates)} \quad 2T_r = q(3 - \cos 2\vartheta); 2T_{r\vartheta} = q \sin 2\vartheta; 2T_\vartheta = q(3 + \cos 2\vartheta)$$

- at the boundary of the hole in polar coordinates  $(r, \vartheta)$

$$T_{rr}\Big|_{r=r_0} = 0, T_{r\vartheta}\Big|_{r=r_0} = 0, M_r\Big|_{r=r_0} = 0, Q_r\Big|_{r=r_0} = -\frac{q_0 r_0}{2}; \quad (4)$$

III. torsion

$$- \text{at infinity } T_x = 0, T_y = 0, T_{xy} = \tau, \tau = \frac{M}{2\pi R^2}$$

$$\text{or in polar coordinates } T_r = \tau \sin 2\vartheta, T_\vartheta = -\tau \sin 2\vartheta, T_{r\vartheta} = \tau \cos 2\vartheta$$

- at the boundary of the hole in polar coordinates  $(r, \vartheta)$

$$T_{rr}\Big|_{r=r_0} = 0, T_{r\vartheta}\Big|_{r=r_0} = 0, M_r\Big|_{r=r_0} = 0, Q_r\Big|_{r=r_0} = 0. \quad (5)$$

The solution offered by authors can be written in the next form (for case I, II and III respectively):

$$\Phi_I = -i \frac{py^2}{2} + \sum_{n=0}^{\infty} (a_n + ib_n) \cdot f_n, \quad (6)$$

$$\Phi_{II} = -i \frac{qy^2}{2} - i \frac{2qx^2}{2} + \sum_{n=0}^{\infty} (a_n + ib_n) \cdot f_n, \quad (7)$$

$$\Phi_{III} = i \tau x y + \sum_{n=0}^{\infty} (a_n + ib_n) \cdot f_n, \quad (8)$$

where for I and II types of boundary conditions we have

$$f_n(r, \vartheta) = \frac{g(r, n, 0)}{2} + \sum_{l=1}^{\infty} g(r, n, l) \cdot \cos 2l\vartheta \quad (9)$$

and for III type

$$f_n(r, \vartheta) = \sum_{l=1}^{\infty} \tilde{g}(r, n, l) \cdot \sin 2l\vartheta. \quad (10)$$

The third type has a slightly different structure due to the antisymmetry of the problem, because of this  $\sin 2l\vartheta$  appears, which is equal to zero for  $l=0$ .

In its turn

$$g(r, n, l) = (-1)^{\lfloor \frac{n}{2} \rfloor + l} \cdot \frac{H_n^{(1)}((1+i)\beta r)}{H_n^{(1)}((1+i)\beta)} \cdot (J_{n+2l}((1+i)\beta r) + J_{n-2l}((1+i)\beta r)), \quad \begin{matrix} n = 0, 1, \dots, \infty \\ l = 0, 1, \dots, \infty \end{matrix} \quad (11)$$

$$\tilde{g}(r, n, l) = (-1)^{l + \lfloor \frac{n}{2} \rfloor} \cdot \frac{H_n^{(1)}((1+i)\beta r)}{H_n^{(1)}((1+i)\beta)} (J_{n-2l}((1+i)\beta r) - J_{n+2l}((1+i)\beta r)), \quad \begin{matrix} n = 1, \dots, \infty \\ l = 1, \dots, \infty \end{matrix} \quad (12)$$

In formulas (6)-(8) we need to find unknown coefficients  $a_n$  and  $b_n$ . After getting the function  $\Phi$ , using the correlation (2), we will find stresses for our problem with various boundary conditions.

### 3 CREATING SYSTEMS

Finding unknown coefficients  $a_n$  and  $b_n$  from the system with an infinite number of equations that we get from boundary conditions of the stresses problem is the important part of the work. We proved that one equation is a linear combination of four others that helped us to solve the system [1]. In work [2] it was proved the reductibility of these infinite systems. For all types of boundary conditions, the matrixes of the system are received: by the substituting solution (6) into (3) for the first type, (7) into (4) for the second and, respectively, (8) into (5) for the third case.

As you can see below, all systems have the same structure.

System FOR TYPE I and II.

n \ l	0		1		2		3		unknown	Free Type I	Free Type II
	Im	Re	Im	Re	Im	Re	Im	Re			
0	$t_3(0,0)$	$t_3(0,0)$	$t_3(1,0)$	$t_3(1,0)$	$t_3(2,0)$	$t_3(2,0)$	$t_3(3,0)$	$t_3(3,0)$	$a_0$	0	0
0	$t_4(0,0)$	$t_4(0,0)$	$t_4(1,0)$	$t_4(1,0)$	$t_4(2,0)$	$t_4(2,0)$	$t_4(3,0)$	$t_4(3,0)$	$b_0$	0	$16\beta^2 q$
1	$g(0,1)$	$g(0,1)$	$g(1,1)$	$g(1,1)$	$g(2,1)$	$g(2,1)$	$g(3,1)$	$g(3,1)$	$a_1$	$-\frac{p}{4}$	$\frac{q}{4}$
1	$g'(0,1)$	$g'(0,1)$	$g'(1,1)$	$g'(1,1)$	$g'(2,1)$	$g'(2,1)$	$g'(3,1)$	$g'(3,1)$	$b_1$	$-\frac{p}{2}$	$\frac{q}{2}$
1	$t_3(0,1)$	$t_3(0,1)$	$t_3(1,1)$	$t_3(1,1)$	$t_3(2,1)$	$t_3(2,1)$	$t_3(3,1)$	$t_3(3,1)$	$a_2$	0	0
1	$t_4(0,1)$	$t_4(0,1)$	$t_4(1,1)$	$t_4(1,1)$	$t_4(2,1)$	$t_4(2,1)$	$t_4(3,1)$	$t_4(3,1)$	$b_2$	0	0
2	$g(0,2)$	$g(0,2)$	$g(1,2)$	$g(1,2)$	$g(2,2)$	$g(2,2)$	$g(3,2)$	$g(3,2)$	$a_3$	0	0
2	$g'(0,2)$	$g'(0,2)$	$g'(1,2)$	$g'(1,2)$	$g'(2,2)$	$g'(2,2)$	$g'(3,2)$	$g'(3,2)$	$b_3$	0	0
...											

$$t_3(n, l) = i(-4l^2 \nu g(n, l) + \nu g'(n, l) + g''(n, l))$$

$$t_4(n, l) = i(12l^2 \cdot g(n, l) - (1 + \nu + 4l^2(2 - \nu)) g'(n, l) + g'''(n, l))$$

System FOR TYPE III.

n	l	1		2		3		4		unknown	Free Type III	
		Im	Re	Im	Re	Im	Re	Im	Re			
1	1	$\tilde{t}_3(1,1)$	$\tilde{t}_3(1,1)$	$\tilde{t}_3(2,1)$	$\tilde{t}_3(2,1)$	$\tilde{t}_3(3,1)$	$\tilde{t}_3(3,1)$	$\tilde{t}_3(4,1)$	$\tilde{t}_3(4,1)$	:	$a_1$	0
1	1	$\tilde{t}_4(1,1)$	$\tilde{t}_4(1,1)$	$\tilde{t}_4(2,1)$	$\tilde{t}_4(2,1)$	$\tilde{t}_4(3,1)$	$\tilde{t}_4(3,1)$	$\tilde{t}_4(4,1)$	$\tilde{t}_4(4,1)$		$b_1$	0
1	1	$\tilde{g}(1,1)$	$\tilde{g}(1,1)$	$\tilde{g}(2,1)$	$\tilde{g}(2,1)$	$\tilde{g}(3,1)$	$\tilde{g}(3,1)$	$\tilde{g}(4,1)$	$\tilde{g}(4,1)$		$a_2$	$-\frac{\tau}{2}$
1	1	$\tilde{g}'(1,1)$	$\tilde{g}'(1,1)$	$\tilde{g}'(2,1)$	$\tilde{g}'(2,1)$	$\tilde{g}'(3,1)$	$\tilde{g}'(3,1)$	$\tilde{g}'(4,1)$	$\tilde{g}'(4,1)$		$b_2$	$-\tau$
2	2	$\tilde{t}_3(1,2)$	$\tilde{t}_3(1,2)$	$\tilde{t}_3(2,2)$	$\tilde{t}_3(2,2)$	$\tilde{t}_3(3,2)$	$\tilde{t}_3(3,2)$	$\tilde{t}_3(4,2)$	$\tilde{t}_3(4,2)$	$a_3$	0	
2	2	$\tilde{t}_4(1,2)$	$\tilde{t}_4(1,2)$	$\tilde{t}_4(2,2)$	$\tilde{t}_4(2,2)$	$\tilde{t}_4(3,2)$	$\tilde{t}_4(3,2)$	$\tilde{t}_4(4,2)$	$\tilde{t}_4(4,2)$	$b_3$	0	
2	2	$\tilde{g}(1,2)$	$\tilde{g}(1,2)$	$\tilde{g}(2,2)$	$\tilde{g}(2,2)$	$\tilde{g}(3,2)$	$\tilde{g}(3,2)$	$\tilde{g}(4,2)$	$\tilde{g}(4,2)$	$a_4$	0	
2	2	$\tilde{g}'(1,2)$	$\tilde{g}'(1,2)$	$\tilde{g}'(2,2)$	$\tilde{g}'(2,2)$	$\tilde{g}'(3,2)$	$\tilde{g}'(3,2)$	$\tilde{g}'(4,2)$	$\tilde{g}'(4,2)$	$b_4$	0	
...												

$$\tilde{t}_3(n, l) = i(-4l^2 \nu \tilde{g}(n, l) + \nu \tilde{g}'(n, l) + \tilde{g}''(n, l))$$

$$\tilde{t}_4(n, l) = i(12l^2 \cdot \tilde{g}(n, l) - (1 + \nu + 4l^2(2 - \nu)) \tilde{g}'(n, l) + \tilde{g}'''(n, l))$$

## 4 RESULTS

Figure 1. Stresses  $\sigma_{\theta\theta}/p$  for types I, II and III respectively received in the present paper.

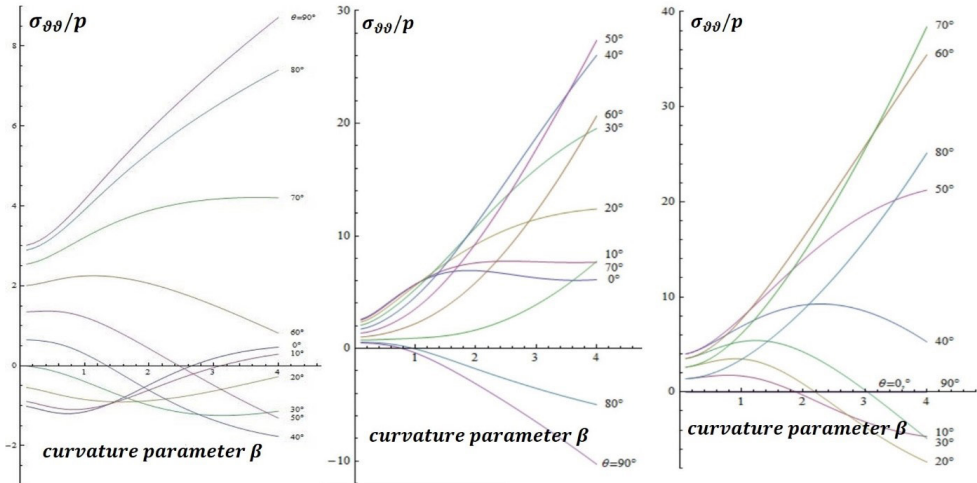


Figure 2. Stresses  $\sigma_{\vartheta\vartheta}/p$  for types I, II and III respectively received in the work of Van Dyke [4] in 1965 by collocation method.

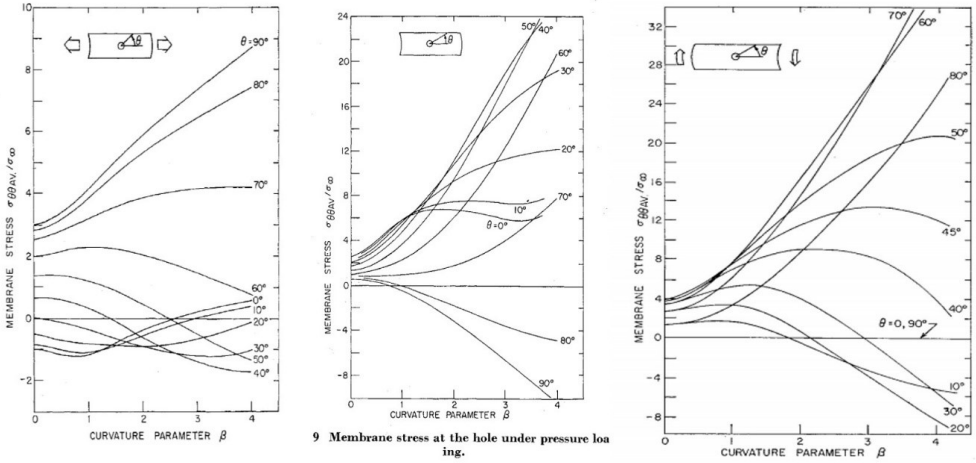


Figure 3a. Field of stresses  $\sigma_{\vartheta\vartheta}/p$  for type I (axial tension) for different  $\beta$ .

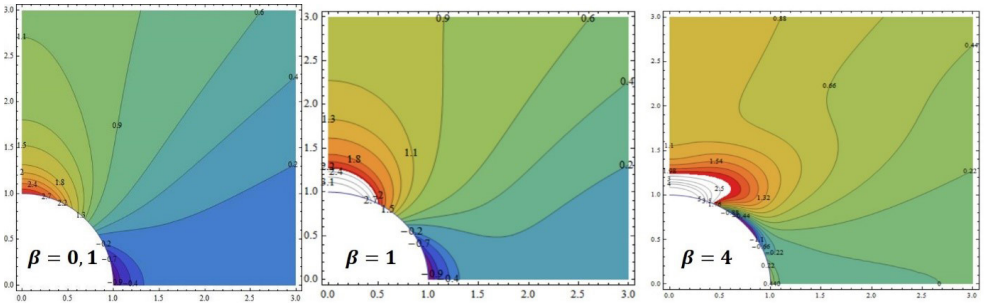


Figure 3b. Field of stresses  $\sigma_{\vartheta\vartheta}/p$  for type II (internal pressure) for different  $\beta$ .

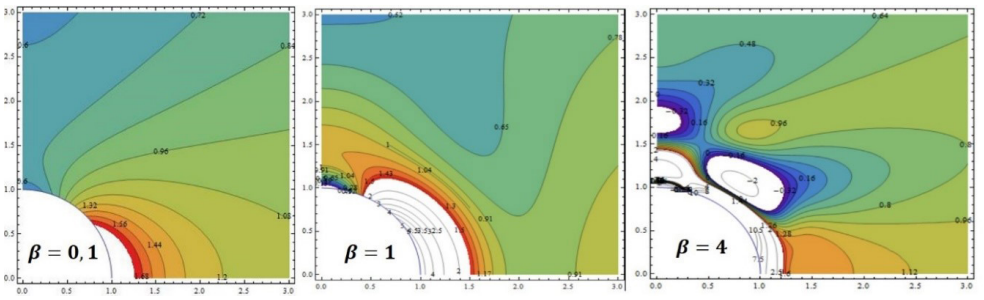
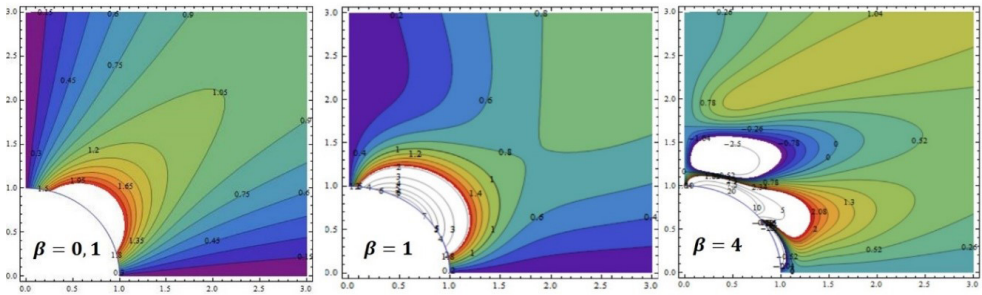


Figure 3c. Field of stresses  $\sigma_{\theta\theta}/p$  for type III (torsion) for different  $\beta$ .



## 5 CONCLUSIONS

The results that were received by new analytical approach are absolutely coincide with results that were obtained by collocation method by Van Dyke [4] in 1965 for all three cases of boundary conditions. Our model has no mathematical restrictions, as it was before, and from the point of view of mechanics it works up to 4.

## 6 ACKNOWLEDGEMENTS

The reported study was funded by RFBR, project number 19-31-60008.

## 7 AUTHORSHIP STATEMENT

The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

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<http://lattes.cnpq.br/5025709771742662>

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