# Evaluation of Stress States in Areas with Geometric Structure Discontinuities in the Configuration of Pressure Equipment. I. Direct Discontinuity

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***Abstract:*** *The various geometric discontinuities in the structure of the pressure equipment components, existing from the initial phase or during their operation, lead to the appearance of stress states that must be evaluated with great precision. Their values can be compared with the load-bearing capacity of the structures or with that established at the time of evaluation. In this way, the future lifetime of the structure or its decommissioning can be determined.*
*This article considers a geometric discontinuity between three cylindrical elements, with different thicknesses, built from the same material, with a sudden transition between them. The intermediate element is considered a short cylinder. The analysis of the continuity of the radial and angular deformations, the deduction of the connection loads and the subsequent evaluation of the developed stresses under the action of the existing external loads are accepted.*

***Keywords:*** *Structural geometric discontinuities, deformation continuity, stress states*

## 1. Introduction

The human requirements for obtaining the most diversified products, using both metallic and non-metallic materials, imposed the design, manufacture and use of specialized equipment, with a well-justified life span. Chemically and/or mechanically aggressive substances can lead to component damage, which is an essential reason for which theoretical, analytical, and numerical, as well as experimental, methods must be developed to estimate the current stress states. Those stated refer to static equipment under pressure: pressure vessels with geometric discontinuities or structural imperfections [1 - 16], technological pipes [17, 18], assemblies with flanges [19], jackets for heating/cooling [20]; dynamic equipment: centrifuges [21, 22]; material breakage criteria [23], holes, notches, for example.

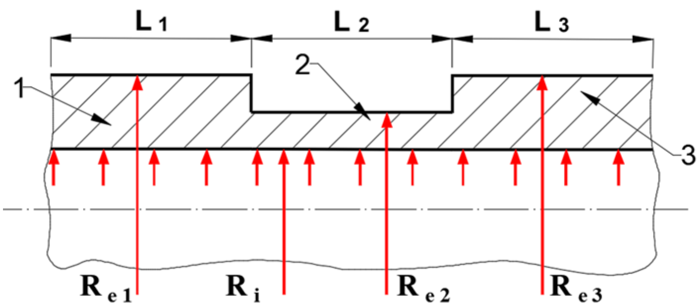
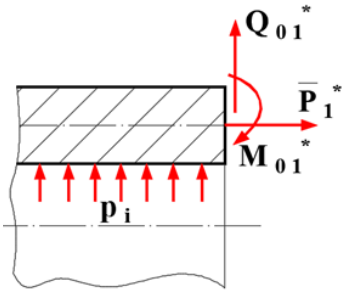


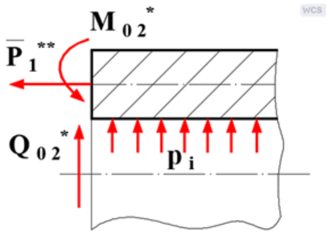

**Fig. 1.** The geometric structure subject to analysis

This article deals with the analytical evaluation of the stress states developed in a geometric structure composed of neighboring cylindrical areas, with different geometries, with a passage without connection between them - figure 1. As working parameters, the internal pressure and temperature are considered (the analysis of stress states is not excluded in the case of above-ground pipes, buried ones or structures required by dynamic loads).

To determine the connection loads (unitary shear forces $Q_{01}, Q_{02}$ $[N/m]$ and unitary bending moments $M_{01}, M_{02}\,[N \cdot m/m]$) – figure 2 - the compatibility of the continuity equations of radial displacements and rotations of neighboring elements is used.




a)

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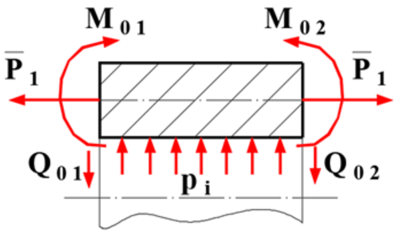


**c)**

**Fig. 2.** Discretization and loading of the analyzed geometric structure
a - structural element 1; b) – structural element 3; c) structural element 2 (short cylindrical element)

## 2. Working assumptions

1. The construction material of the cylindrical sections is considered homogeneous, isotropic and continuous. The load is considered to be in the elastic range. The transition between sections, with different thicknesses, is abrupt (no linear transition or curve).
2. The intermediate section has a constant thickness, less than that of the side sections. Its length falls into the category of short cylinders [24]: $L_2 < L_{sc} \approx 12.5 \cdot \sqrt{R_{m2} \cdot \delta_2}$ (length less than the characteristic half-wavelength [24])

## 3. Determination of connection loads

As previously mentioned, to determine the connection loads in the present case, the deformation continuity equations are written, resulting in the linear algebraic system:

$$[A] \cdot \{M_{01}, Q_{01}, M_{02}, Q_{02}\}^T = \{b_1, b_2, b_3, b_4\}^T, \tag{1}$$

where $[A]$ represents the non-zero matrix of the influence factors of the connection loads:

$$[A]=\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix}, \qquad (2)$$

where:

$$a_{11}=\frac{1}{2\cdot k_1^2\cdot\Re_1}\cdot\frac{R_{m2}}{R_{m1}}+\frac{1}{2\cdot k_2^2\cdot\Re_2}\cdot f_{1m};\; a_{12}=-\frac{1}{2\cdot k_1^3\cdot\Re_1}\cdot\frac{R_{m2}}{R_{m1}}+\frac{1}{2\cdot k_2^3\cdot\Re_2}\cdot f_{1q};$$

$$a_{13}=\frac{1}{2\cdot k_2^2\cdot\Re_2}\cdot f_{md}(L_2);\; a_{14}=\frac{1}{2\cdot k_2^3\cdot\Re_2}\cdot f_{qd}(L_2);$$

$$a_{21}=\frac{1}{k_1\cdot\Re_1}\cdot\frac{R_{m2}}{R_{m1}}+\frac{1}{k_2\cdot\Re_2}\cdot f_{2m};\; a_{22}=-\frac{1}{2\cdot k_1^2\cdot\Re_1}\cdot\frac{R_{m2}}{R_{m1}}+\frac{1}{2\cdot k_2^2\cdot\Re_2}\cdot f_{23q};$$

$$a_{23}=-\frac{1}{2\cdot k_2\cdot\Re_2}\cdot f_{mr}(L_2);\; a_{24}=-\frac{1}{2\cdot k_2^2\cdot\Re_2}\cdot f_{qr}(L_2);$$

$$a_{31}=\frac{1}{2\cdot k_2^2\cdot\Re_2}\cdot f_{md}(L_2);\quad a_{32}=\frac{1}{2\cdot k_2^3\cdot\Re_2}\cdot f_{qd}(L_2); \qquad (3)$$

$$a_{33}=\frac{1}{2\cdot k_3^2\cdot\Re_3}\cdot\frac{R_{m2}}{R_{m3}}+\frac{1}{2\cdot k_2^2\cdot\Re_2}\cdot f_{1m};\quad a_{34}=-\frac{1}{2\cdot k_3^3\cdot\Re_3}\cdot\frac{R_{m2}}{R_{m3}}+\frac{1}{2\cdot k_2^3\cdot\Re_2}\cdot f_{1q};$$

$$a_{41}=\frac{1}{2\cdot k_2\cdot\Re_2}\cdot f_{mr}(L_2);\; a_{42}=-\frac{1}{2\cdot k_2^2\cdot\Re_2}\cdot f_{qr}(L_2);$$

$$a_{43}=\frac{1}{k_3\cdot\Re_3}\cdot\frac{R_{m2}}{R_{m3}}+\frac{1}{k_2\cdot\Re_2}\cdot f_{2m};\; a_{44}=-\frac{1}{2\cdot k_3^2\cdot\Re_3}\cdot\frac{R_{m2}}{R_{m3}}+\frac{1}{2\cdot k_2^3\cdot\Re_2}\cdot f_{23q};$$

$\left\{M_{01},Q_{01},M_{02},Q_{02}\right\}^T$ - the transposed vector of the connection loads – figure 2;

$\left\{b_1,b_2,b_3,b_4\right\}^T$ - the transposed vector of the free terms:

$$b_1=\frac{p_i}{16}\cdot\left[\frac{R_{m2}}{k_1^4\cdot\Re_1\cdot R_{m1}}-\frac{1}{k_2^4\cdot\Re_2}-\nu\cdot R_i^2\cdot\left(\frac{1}{k_1^4\cdot\Re_1\cdot R_{m1}^2}-\frac{1}{k_2^4\cdot\Re_2\cdot R_{m2}^2}\right)\right]+$$
$$+E\cdot\alpha_T\cdot\left(\frac{\delta_1\cdot R_{m2}\cdot\Delta T_1}{k_1^4\cdot\Re_1\cdot R_{m1}^2}-\frac{\delta_2\cdot\Delta T_2}{k_2^4\cdot\Re_2\cdot R_{m2}}\right);\; b_2=0; \qquad (4)$$

$$b_3=\frac{p_i}{16}\cdot\left[\frac{R_{m2}}{k_3^4\cdot\Re_3\cdot R_{m3}}-\frac{1}{k_2^4\cdot\Re_2}-\nu\cdot R_i^2\cdot\left(\frac{1}{k_3^4\cdot\Re_3\cdot R_{m3}^2}-\frac{1}{k_2^4\cdot\Re_2\cdot R_{m2}^2}\right)\right]+$$
$$+E\cdot\alpha_T\cdot\left(\frac{\delta_3\cdot R_{m2}\cdot\Delta T_3}{k_3^4\cdot\Re_3\cdot R_{m3}^2}-\frac{\delta_2\cdot\Delta T_2}{k_2^4\cdot\Re_2\cdot R_{m2}}\right);\; b_4=0. \qquad (5)$$

**Note:**

1. The radial displacements of elements 1 and 3 have been corrected by bringing them to the values corresponding to the median surface of element 2 - figure 2.

2. In the previous analysis only the effect of an internal pressure was considered. In the situation where the structure is subjected not only to internal pressure but also to external pressure, $p_e$, as in the case of buried pipes, for example, the significance of $p_i$ will be reconsidered by means of the load $p_i^{\bullet} = p_i - p_e$.

The mentioned connection tasks are established using the equality:

$$\left\{ M_{01}, Q_{01}, M_{02}, Q_{02} \right\}^T = \left[ A \right]^{-1} \cdot \left\{ b_1, b_2, b_3, b_4 \right\}^T, \quad (6)$$

where $\left[ A \right]^{-1}$ represents the inverse of the nonzero matrix $\left[ A \right]$.

**Notations used above:**

- the influence factors, dimensionless, from the previous expressions, have the configuration:

$$s_h = sh\left( k_2 \cdot L_2 \right) = 0{,}5 \cdot \left[ exp\left( k_2 \cdot L_2 \right) - exp\left( -k_2 \cdot L_2 \right) \right];$$

$$c_h = ch\left( k_2 \cdot L_2 \right) = 0{,}5 \cdot \left[ exp\left( k_2 \cdot L_2 \right) + exp\left( -k_2 \cdot L_2 \right) \right];$$

$$N = N\left( k_2 \cdot L_2 \right) = sh^2\left( k_2 \cdot L_2 \right) - sin^2\left( k_2 \cdot L_2 \right);$$

$$s = sin\left( k_2 \cdot L_2 \right); \; c = cos\left( k_2 \cdot L_2 \right);$$

$$f_{1m} = f_{1m}\left( k_2 \cdot L_2 \right) = \left( s_h^2 + s^2 \right) / N; \; f_{2m} = f_{2m}\left( k_2 \cdot L_2 \right) = -\left( s \cdot c + s_h \cdot c_h \right) / N;$$

$$f_{1q} = f_{1q}\left( k_2 \cdot L_2 \right) = \left( s \cdot c - s_h \cdot c_h \right) / N; \; f_{2q} = f_{2q}\left( k_2 \cdot L_2 \right) = s_h^2 / N;$$

$$f_{3q} = f_{3q}\left( k_2 \cdot L_2 \right) = s^2 / N; \; f_{23q} = f_{23q}\left( k_2 \cdot L_2 \right) = f_{2q} + f_{3q};$$

$$f_{md} = f_{md}\left( k_2 \cdot L_2 \right) = f_{1m} \cdot c \cdot c_h + f_{2m} \cdot \left( c \cdot s_h + s \cdot c_h \right) + s \cdot s_h;$$

$$f_{mr} = f_{mr}\left( k_2 \cdot L_2 \right) = f_{1m} \cdot \left( c \cdot s_h - s \cdot c_h \right) + 2 \cdot f_{2m} \cdot c \cdot c_h + c \cdot s_h + s \cdot c_h;$$

$$f_{qr} = f_{qr}\left( k_2 \cdot L_2 \right) = f_{1q} \cdot \left( c \cdot s_h - s \cdot c_h \right) + f_{2q} \cdot \left( c \cdot c_h - s \cdot s_h \right) + f_{3q} \cdot \left( c \cdot c_h + s \cdot s_h \right). \quad (7)$$

$k_j = \sqrt[4]{3 \cdot \left( 1 - \nu^2 \right)} / \sqrt{R_{mj} \cdot \delta_j}$ – attenuation factor, $\left[ N / m^2 \right]$; $j = 1, 2, 3$;

$p_i$ – internal pressure, $\left[ N / m^2 \right]$;

$\delta_j$ – wall thickness of cylindrical elements, $j$, $j = 1, 2, 3$;

$\alpha_T$ – thermal deformation factor, $\left[ 1 / K \right]$;

$E$ – modulus of longitudinal elasticity of the construction material, $\left[ N / m^2 \right]$;

$L_j$ – length of cylindrical elements, $j$ ($j = 1, 2, 3$);

$\overline{P}_1 = 0{,}5 \cdot p_i \cdot R_i^2 / R_{m2}$; $\overline{P}_1^{\bullet} = \overline{P}_1 \cdot R_{m2} / R_{m1}$; $\overline{P}_1^{\bullet\bullet} = \overline{P}_1 \cdot R_{m2} / R_{m3}$ – unit axial forces $\left[ N / m \right]$;

$R_i$ – inner radius of the analyzed cylindrical elements, $\left[ m \right]$; $R_{mj} = R_i + \delta_j / 2$ – average radius $j$ ($j = 1, 2, 3$);

$\Re_j = E \cdot \delta_j^3 / \left[ 12 \cdot \left( 1 - \nu^2 \right) \right]$ – the cylindrical bending rigidity of the constructive elements, $j = 1, 2, 3$;

$\Delta T_j$ – thermal gradient characteristic of the cylindrical element $\left[ K \right]$ $j$ ($j = 1, 2, 3$); for constant internal temperature and different external temperatures, the thermal gradient is different for each section; in the case of constant internal temperature inside and outside, $\Delta T_1 = \Delta T_2 = \Delta T_3 = \Delta T$.

## 4. Stress states

### 4. 1. Cylindrical elements 1 and 3

The axial $\sigma_{1t}(x)$ and annular stresses $\sigma_{2t}(x)$ developed in the cylindrical elements 1 and 3, under the action of external loads - internal pressure and temperature - have the expressions:

$$\sigma_{1t}(x)=\frac{p_i\cdot R_{mt}}{2\cdot\delta_t}\pm\frac{6\cdot M_{ct}(x)}{\delta_t^2}+E\cdot\alpha_T\cdot\Delta T_t\,; \tag{8}$$

$$\sigma_{2t}(x)=\frac{p_i\cdot R_{mt}}{\delta_t}\pm\frac{6\cdot\nu\cdot M_{ct}(x)}{\delta_t^2}+\frac{T_t(x)}{\delta_t}+E\cdot\alpha_T\cdot\Delta T_t\,, \tag{9}$$

where $t$ represents the number of the constructive element ($t=1,3-$ figure 2), respectively $M_t(x)$ - unitary radial bending moment, developed by the unitary force $Q_{0t}$ and the unitary radial bending moment $M_{0t}$ - figure 2:

$$M_t(x)=\left[\frac{1}{k_t}\cdot Q_{0t}\cdot s_{tex}-M_{0t}\cdot\left(c_{tex}+s_{tex}\right)\right]\cdot\frac{R_{m2}}{R_{mt}}\,, \tag{10}$$

$T_t(x)$ - unitary annular force:

$$T_t(x)=2\cdot\left[Q_{0t}\cdot c_{tex}-k_t\cdot M_{0t}\cdot\left(c_{tex}-s_{tex}\right)\right]\cdot k_t\cdot R_{m2}\,, \tag{11}$$

respectively:

$$s_{tex}=exp\left(-k_t\cdot x\right)\cdot sin\left(k_t\cdot x\right);\; c_{tex}=exp\left(-k_t\cdot x\right)\cdot cos\left(k_t\cdot x\right). \tag{12}$$

**<u>Note</u>**:

The current quota, for the cylindrical elements 1 and 3, has every time zero value in the separation plan from cylinder 2. It is measured, further, along the characteristic generator of each long cylinder 1 and 3.

### 4. 2. Cylindrical element 2

The expressions for the radial tension $\sigma_{12}(x)$ and for the annular tension $\sigma_{22}(x)$, corresponding to cylinder 2 (fig. 2), have the forms:

$$\sigma_{12}(x)=\frac{p_i\cdot R_{m2}}{2\cdot\delta_2}\pm\frac{6\cdot M_{2x}\left(x,\,M_{01},M_{02}\right)}{\delta_2^2}\mp\frac{6\cdot M_{2x}\left(x,\,Q_{01},Q_{02}\right)}{\delta_2^2}+E\cdot\alpha_T\cdot\Delta T_2\,; \tag{13}$$

$$\sigma_{22}(x)=\frac{p_i\cdot R_{m2}}{\delta_2}\pm\frac{6\cdot K_{2x}\left(x,\,M_{01},M_{02}\right)}{\delta_2^2}\mp\frac{6\cdot K_{2x}\left(x,\,Q_{01},Q_{02}\right)}{\delta_2^2}+$$

$$+\frac{T_{2x}\left(x,M_{01},M_{02}\right)}{\delta_2}+\frac{T_{2x}\left(x,Q_{01},Q_{02}\right)}{\delta_2}+E\cdot\alpha_T\cdot\Delta T_2\,, \tag{14}$$

where the following notations were used:

$$M_{2x}\left(x,M_{01},M_{02}\right)=M_{01}\cdot\begin{bmatrix}-f_{1m}\cdot s_{k_2x}\cdot s_{hk_2x}+\\+f_{2m}\cdot\left(c_{k_2x}\cdot s_{hk_2x}-s_{k_2x}\cdot c_{hk_2x}\right)+\\+c_{k_2x}\cdot c_{hk_2x}\end{bmatrix}+$$

$$+M_{02}\cdot\left\{-f_{1m}\cdot s_{k_2L_2x}\cdot s_{hk_2L_2x}+f_{2m}\cdot\begin{bmatrix}c_{k_2L_2x}\cdot s_{hk_2L_2x}-\\ -s_{k_2L_2x}\cdot c_{hk_2L_2x}\end{bmatrix}+c_{k_2L_2x}\cdot c_{hk_2L_2x}\right\};\qquad(15)$$

$$M_{2x}\left(x,Q_{01},Q_{02}\right)=\frac{1}{k_2}\cdot Q_{01}\cdot\left(-f_{1q}\cdot s_{k_2x}\cdot s_{hk_2x}-f_{2q}\cdot s_{k_2x}\cdot c_{hk_2x}+f_{3q}\cdot c_{k_2x}\cdot s_{hk_2x}\right)+$$

$$+\frac{1}{2}\cdot Q_{02}\cdot\left[-f_{1q}\cdot s_{k_2L_2x}\cdot s_{hk_2L_2x}-f_{2q}\cdot s_{k_2L_2x}\cdot c_{hk_2L_2x}+f_{3q}\cdot c_{k_2L_2x}\cdot s_{hk_2L_2x}\right];\qquad(16)$$

$$K_{2x}\left(x,\,M_{01},M_{02}\right)=\nu\cdot M_{2x}\left(x,\,M_{01},M_{02}\right);\qquad(17)$$

$$K_{2x}\left(x,\,Q_{01},Q_{02}\right)=\nu\cdot M_{2x}\left(x,Q_{01},Q_{02}\right);\qquad(18)$$

$$+s_{k_2x}\cdot s_{hk_2x}\Big]+M_{02}\cdot\left[f_{1m}\cdot c_{k_2L_2\cdot x}\cdot c_{hk_2L_2x}+f_{2m}\cdot\begin{pmatrix}c_{k_2L_2\cdot x}\cdot s_{hk_2L_2x}+\\ +s_{k_2L_2\cdot x}\cdot c_{hk_2L_2x}\end{pmatrix}+s_{k_2L_2\cdot x}\cdot c_{hk_2L_2x}\right]\Bigg\};\qquad(19)$$

$$T_{2x}\left(x,Q_{01},Q_{02}\right)=-2\cdot k_2\cdot R_{m2}\cdot\Big[\,Q_{01}\cdot\begin{pmatrix}f_{1q}\cdot c_{k_2x}\cdot c_{hk_2x}+f_{2q}\cdot c_{k_2x}\cdot s_{hk_2x}+\\ +f_{3q}\cdot s_{k_2x}\cdot c_{hk_2x}\end{pmatrix}+$$

$$+Q_{02}\cdot\left(f_{1q}\cdot c_{k_2L_2x}\cdot c_{hk_2L_2x}+f_{2q}\cdot c_{k_2L_2x}\cdot s_{hk_2L_2x}+f_{3q}\cdot s_{k_2L_2x}\cdot c_{hk_2L_2x}\right)\Big];\qquad(20)$$

$$s_{k_2x}=sin\left(k_2\cdot x\right);\;c_{k_2x}=cos\left(k_2\cdot x\right);\;s_{hk_2x}=sh\left(k_2\cdot x\right);\;c_{hk_2x}=ch\left(k_2\cdot x\right);\qquad(21)$$

$$s_{k_2L_2x}=sin\left[k_2\cdot\left(L_2-x\right)\right];\;\;s_{hk_2L_2x}=sh\left[k_2\cdot\left(L_2-x\right)\right];\qquad(22)$$

$$c_{k_2L_2x}=cos\left[k_2\cdot\left(L_2-x\right)\right];\;\;c_{hk_2L_2x}=ch\left[k_2\cdot\left(L_2-x\right)\right].\qquad(23)$$

**<u>Note</u>:** In equations (13) and (14) the plus sign for the radial unit bending moments $M_{2x}\left(x,\,M_{01},M_{02}\right)$ and $K_{2x}\left(x,\,M_{01},M_{02}\right)$ is characteristic of the inner surface of the cylindrical element 2. In the case of the radial unit bending moments $M_{2x}\left(x,\,Q_{01},Q_{02}\right)$and $K_{2x}\left(x,\,Q_{01},Q_{02}\right)$ the plus sign corresponds to the outer surface of the short cylinder 2 (fig. 2). In the case of the same equalities (13) and (14), the annular unitary forces have a plus sign for $T_{2x}\left(x,M_{01},M_{02}\right)$, respectively a minus sign for $T_{2x}\left(x,Q_{01},Q_{02}\right)$, as shown by the equalities (19) and (20). The $x$ quota has its origin in the separation plane of elements 1 and 2 and its maximum value ($x=L_2$), in the separation plane of components 2 and 3.

## 5. Conclusions

In this paper, the connection between two long cylindrical elements and a short, intermediate cylindrical element is considered. The continuity equations of the radial and angular deformations are established, so that based on the linear algebraic system, the expressions of the connection loads - unit bending moments and unit shear forces - are deduced. With their help, the expressions of the radial and annular stresses (plane stress state), dependent on a current quota, expressed in the context, are described. For the accepted resistance theory (usually the IV or V theory [25]), the maximum equivalent stresses are established on the internal and external surface of the analyzed constructive element Such a value is compared with the admissible resistance of the construction material, under the specific conditions of application. As a result, the bearing capacity of the construction can be appreciated, for safe operating conditions. In the case of designing structures with discontinuities, the above data allow the modification of the geometry to ensure safe conditions of use. The previous calculation methodology can also be used if the transitions from one structure to another will be with a connection or with a linear transition.

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