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NONLINEAR NUMERICAL ANALYSIS OF TWO-WAY GLOBE VALVE HOUSING

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Preliminary notes

Two-way globe valve housing DN50 PN160 subjected to internal pressure is investigated. Three-dimensional nonlinear finite element analyses are performed to obtain the plastic yield, collapse and instability pressures. For the determination of the plastic collapse pressure, twice-elastic-slope and the tangent-intersection methods are used. The allowable pressure is obtained according to the limit design method. Unlike the previous investigation of the three-way globe valve housing DN100 PN40, it is shown that allowable pressure for the two-way globe valve housing calculated by the application of the EN 12516-2 standard is highly conservative in comparison with the one derived by the application of finite element results for the plastic collapse pressure, in accordance with the limit design method. Additionally, it is shown that the results for the failure pressure can be obtained by a simpler finite element analysis without taking into consideration the material hardening and geometrical nonlinearity.

Keywords: *allowable pressure, finite element analysis, globe valve housing, limit design method, plastic collapse pressure*

Nelinearna numerička analiza kućišta prolaznog ventila

Prethodno priopćenje

Predmet istraživanja je kućište prolaznog ventila oznake DN50 PN160 opterećeno unutarnjim tlakom. Provedene su trodimenzijske nelinearne numeričke analize primjenom metode konačnih elemenata kako bi se odredio tlak plastičnog tečenja, kolapsa i nestabilnosti. Za određivanje tlaka plastičnog kolapsa primijenjena je metoda dvostrukog elastičnog nagiba i metoda sjecišta tangenti, dok je dopušteni tlak dobiven pomoću metode graničnog konstruiranja. Za razliku od prethodno provedenih istraživanja na kućištu troputnog ventila DN100 PN40, u ovom radu pokazano je da je dopušteni tlak kućišta prolaznog ventila dobiven primjenom norme EN 12516-2 izrazito konzervativan u odnosu na isti određen primjenom metode graničnog konstruiranja iz tlaka plastičnog kolapsa dobivenog pomoću metode konačnih elemenata. Osim toga predložen je postupak kojim se pojednostavnjuje dosta složena numerička analiza za dobivanje tlaka sloma kućišta ventila.

Ključne riječi: *dopušteni tlak, analiza konačnim elementima, kućište prolaznog ventila, metoda graničnog konstruiranja, tlak plastičnog kolapsa*

1
Introduction
Uvod

A globe valve is a linear motion valve used to shut off, and regulate fluid flow in pipelines. It is characterized by a baffle or partition separating the two halves of the housing, with an interconnecting part at the centre opened and closed by a disc or plug mounted at right angles to the housing. The name derives from the fact that original housing shapes were spherical, the more usual modern form being semi-spherical or even substantially parallel-sided [1]. Globe valves are very popular throughout the engineering plant. Depending on the number of process connections, they are produced as two- or three way valves. The main valve component carrying the internal pressure is the valve housing [2, 3].

During the design phase, the calculation of its wall thickness, carried out in accordance with standards by means of which the complex three-dimensional geometry, is approximated with two-dimensional one and the equalization of the pressurized surfaces with the supporting surfaces is done. For safe exploitation, the allowable pressure up to which the housing can be pressurized needs to be known. In order to define the allowable load of the pressure vessel components according to the limit design method [4], it is necessary to determine the plastic collapse load due to the static load. Therefore, the plastic collapse load can be predicted by finite element (FE) the limit load analysis which defines two additional characteristic loads, i.e. the plastic yield and the plastic instability load. The plastic yield load is determined on the basis of limit analysis by the application of the small strain theory and elastic–perfectly plastic material assumptions [5, 6]. Unlike the plastic yield load, the determination of the plastic collapse load and the plastic instability load is based on the large strain theory, emphasizing the effect of strain hardening [7-13]. In that case, the plastic collapse load is not a load necessary to cause the physical collapse of the structure; it is rather a load under which significant plastic strain occurs. The commonest methods for the determination of the plastic collapse load used in literature are the twice-elastic-slope (TES) method [4] and the tangent-intersection (TI) method [14]. Both methods are illustrated in Fig. 1a and Fig. 1b. As it can be observed from Fig. 1a and Fig. 1b, the methods define the plastic collapse load by applying a graphical construction to characteristic load–deformation curves. The plastic collapse load calculated in this manner depends on the load and deformation parameters chosen to characterize the structural response. The TES method defines the collapse load as the load at the intersection of a line drawn from the origin of the load-deformation curve, at twice the slope of the linear part of the load-deformation curve (Fig. 1a). For the determination of the collapse load by means of the TI method, it is necessary to draw the tangent line to the linear and nonlinear parts of the load-deformation curve, as shown in Fig. 1b. The load at the intersection of tangent lines defines the plastic collapse load in contrast to the TES method, which gives consistent results, the TI method is sensitive to the selection of the point in which the tangent line is drawn to the nonlinear part of the curve. In contrast to the plastic collapse load, the plastic instability load can be defined as the maximum load which the structural element made of a work-hardening material could withstand (Fig. 1a) [8, 9, 13, 15, 16, 17].

In the previous investigation [16, 17], three-dimensional nonlinear finite element analyses were performed to obtain the plastic yield, collapse and

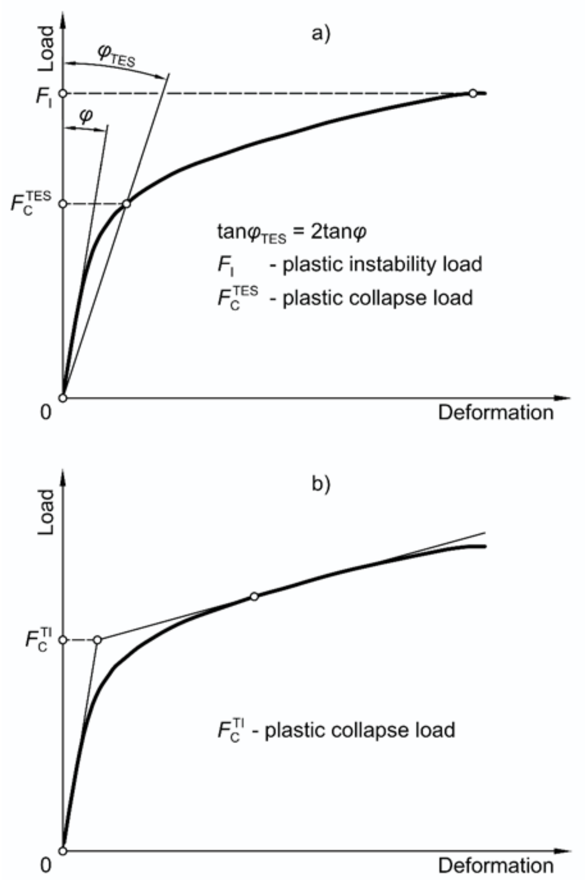

Figure 1 *Definition of the plastic collapse load by: (a) twice-elastic-slope (TES) method, (b) tangent-intersection (TI) method* [17]
Slika1. *Definicija opterećenja plastičnog kolapsa: a) metoda dvostrukog elastičnog nagiba, b) metoda sjecišta tangenti* [17]

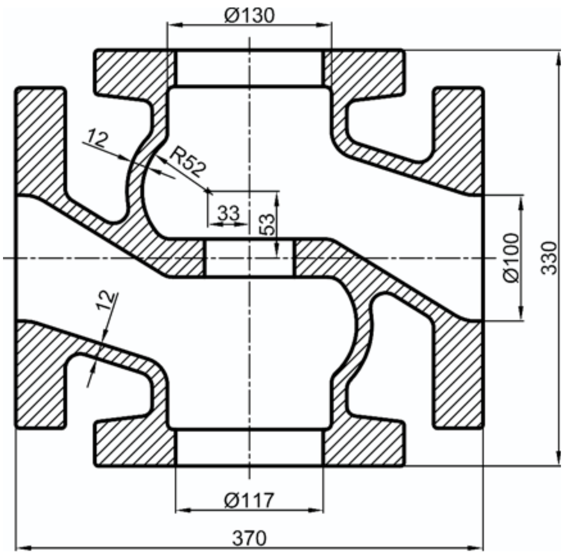

Figure 2 *Layout and dimensions of the three-way globe valve housing DN100 PN40*
Slika 2. *Izgled i dimenzije kućišta troputnog ventila DN100 PN40*

instability pressures for the valve housing under internal pressure and to predict the burst pressure obtained by experimental results. A three-port, globe valve housing DN100 PN40 was analyzed (Fig. 2). It was shown that the plastic collapse pressure results obtained by real strain hardening material model agree well with the experimental ones obtained by strain gauges. Slightly better results correspondence was obtained by the application of the TI method than by the TES method. The results also indicated that the allowable pressure determined by the application of the EN 12516-2 standard [2] was close to FE and experimental results obtained by the application of the limit design method.

The aim of this paper is to determine the allowable and failure pressures of the two-way globe valve housing DN50 PN160. The housing subjected to internal pressure is investigated using FE analysis. The allowable pressure of the housing is compared with the solution obtained by the method proposed in [2]. Here, it is necessary to emphasize that the numerical model applied in this paper is similar to the one used in the previous investigation of the three-way globe valve housing DN100 PN40 [16, 17]. The last one was verified experimentally using strain gauges and pressure transducer. In addition, both housings are made of the same cast steel.

2
Problem description
Opis problema

The housing was made by sand casting. Its complex geometry with basic dimensions is shown in Fig. 3. As may be observed, it is a two-way housing consisting of two lateral flanges and one upper flange. In service, a bonnet is connected to the upper flange, while the valve is connected to the pipeline through the lateral ones.

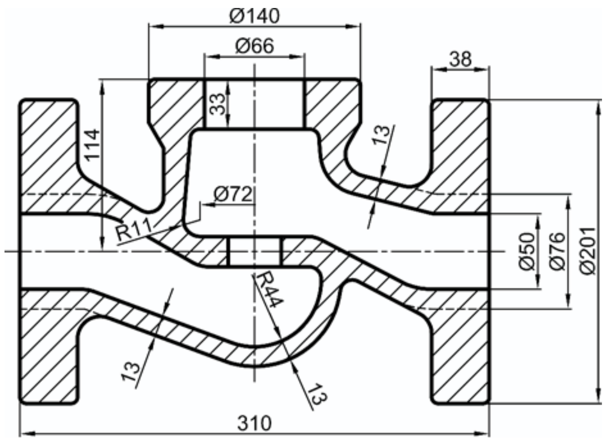

Figure 3 *Layout and dimensions of the two-way globe valve housing DN50 PN160*
Slika 3. *Izgled i dimenzije kućišta prolaznog ventila DN50 PN160*

2.1
Material
Materijal

The housing material is cast steel GS-C25. Its chemical composition is shown in Table 1, and basic material parameters at room temperature are summarized in Table 2. It should be noted that specified values are minimum values for this material. The engineering stress-strain diagram (σ_e, ε_e) determined experimentally in a standard tensile test [16-18] at room temperature is shown in Fig. 4. As evident from the ratio of the ultimate stress and the yield stress σ_u/σ_y, the given material exhibits considerable strain hardening.

Table 1 *Chemical composition of the cast steel GS-C25*
Tablica 1. *Kemijski sastav čeličnog lijeva GS-C25*

	C	Si	Mn	P	S	Cr
%	0,20	0,33	0,80	0,026	0,026	0,03

Table 2 *Mechanical properties of the cast steel GS-C25 at room temperature*
Tablica 2. *Mehanička svojstva čeličnog lijeva GS-C25 pri sobnoj temperaturi*

Modulus E, GPa	Yield stress σ_y / MPa	Ultimate stress σ_u / MPa	Extension strain ε / %	Area reduction, %
205	250	475	30	55

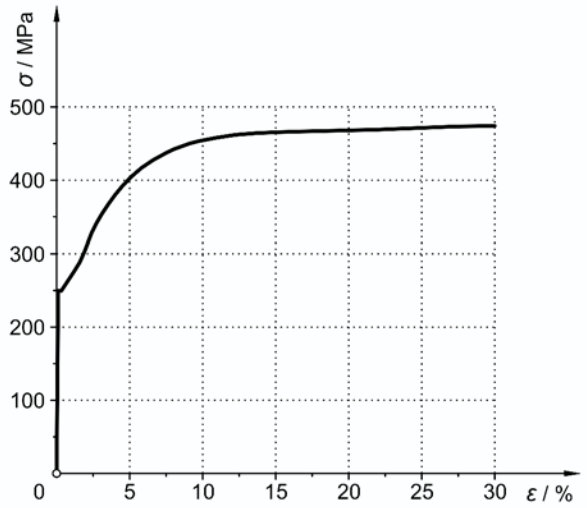

Figure 4 *Engineering stress-strain diagram for cast steel GS-C25* [16, 17]
Slika 4. *Konvencionalni dijagram naprezanje-deformacija za čelični lijev GS-C25* [16, 17]

For the large strain FE analysis, the true stress and strain values (σ_t, ε_t) are determined by the following relationships:

$$\sigma_t = \sigma_e \left(1+\varepsilon_e\right), \tag{1}$$

$$\varepsilon_t = \ln\left(1+\varepsilon_e\right). \tag{2}$$

The values of engineering terms and true terms are shown in Table 3. For the large strain FE analysis, the true stress and strain values are determined up to the ultimate tensile stress level (30 % of strain). After this specified point, the response is assumed to be perfectly plastic.

Table 3 *Material data of the cast steel GS-C25*
Tablica 3. *Podaci za čelični lijev GS-C25*

Engineering stress σ_e /MPa	Engineering plastic strain $\varepsilon_{e,pl}$ / %	True stress σ_t/MPa	True plastic strain $\varepsilon_{t,pl}$ / %
250,0	0,00	250,8	0,00
250,0	0,21	250,8	0,21
285,7	1,35	290,0	1,34
322,7	2,13	330,1	2,10
358,4	3,06	370,0	3,00
393,1	4,35	411,0	4,24
423,6	6,05	450,1	5,85
449,7	8,76	490,1	8,36
457,0	15,79	530,1	14,59
467,9	21,58	570,0	19,45
475,0	29,77	617,5	25,94

3
Finite element analysis
Analiza primjenom metode konačnih elemenata

3.1
Numerical model
Numerički model

The finite element analysis is performed by using the commercial finite element package ABAQUS/Standard [19]. Only one half of the housing is modelled for symmetry purposes. In order to simplify the numerical model and reduce number of finite elements, lateral flanges, due to their large stiffness, are not modelled [16, 17]. Layout and dimensions of the modelled housing are shown in Fig. 3. Dashed lines represent cylindrical surfaces of the lateral flanges removal.

Since this is a case of a very complex geometry, a free-meshing algorithm is applied. For the model discretization, a modified quadratic tetrahedral element (C3D10M) is applied as adequate for both small and large deformations. Several different meshes are analyzed and typical mesh is shown in Fig. 5a. Mesh contains 142 588 tetrahedral elements and 211 892 nodes. Boundary conditions (Fig. 5b) are defined by restraining displacements in all nodes in the symmetry plane in the direction perpendicular to the plane. Additionally, the displacement of all nodes in the cylindrical surfaces of the lateral flanges removal is restrained in radial direction. The housing load is the internal pressure p, which was applied as a distributed load to the internal walls of the FE model. The pressure affecting the upper flange is calculated into the screw force and given as the surface traction, upwards for the upper flange and is assigned to the holes in which the screws are mounted.

Nonlinear material behaviour is modelled using the incremental plasticity with the von Mises yield function, together with the associated flow rule and isotropic hardening. The large strain FE model is employed by invoking the NLGEOM option within ABAQUS.

3.2
Finite element analysis results
Rezultati dobiveni primjenom metode konačnih elemenata

The investigated housing DN50 PN160 nominal pressure at room temperature is 16 MPa. In Fig. 6a, it is shown that zone of equivalent plastic strain distribution did not appear at the nominal pressure, which means that model housing is completely in the elastic area. The first zone of the equivalent plastic strain appears on the inner surface of the model at the pressure of about 25 MPa, as shown in Fig. 6b. The response of the model housing during an incremental increase of the internal pressure is characterized by the spreading of the plastic region. The equivalent plastic strain distribution at the pressure of 47 MPa, which is close to the allowable pressure determined by limit design method (see section 4), is shown in Fig. 6c. With a further pressure increase, larger elastic-plastic strains occur on the model. At the pressure of 159 MPa, the zone of maximum equivalent plastic strain value of 30 % reaches the outer surface of the model housing (Fig. 6d). This value was chosen as it represents the strain at which a fracture of the housing material happens.

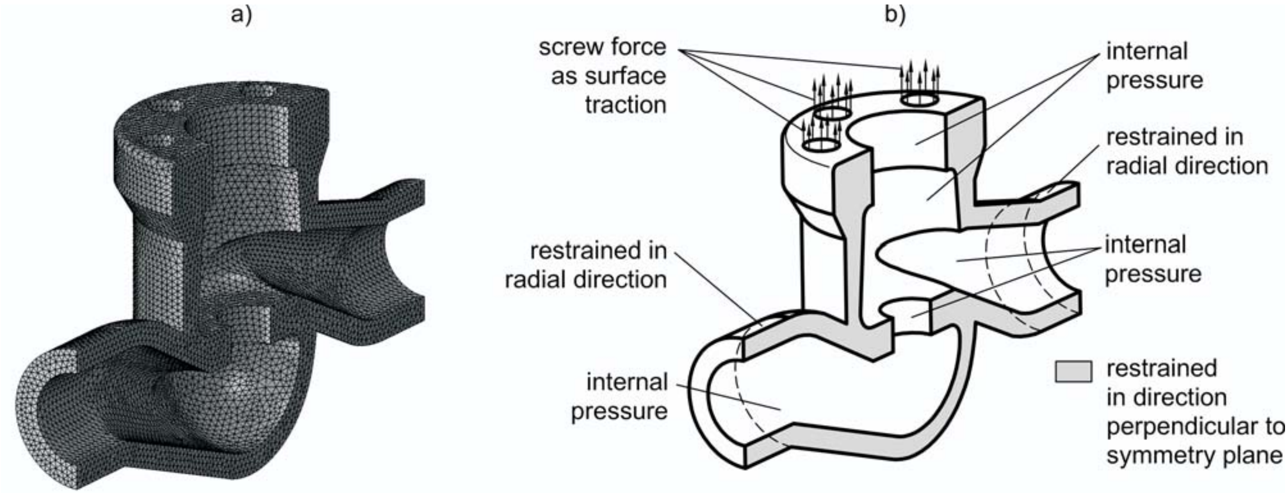

Figure 5 *Numerical model: a) typical FE mesh and b) rubni uvjeti*

Slika 5. *Numerički model: a) tipična mreža konačnih elemenata i b) rubni uvjeti*

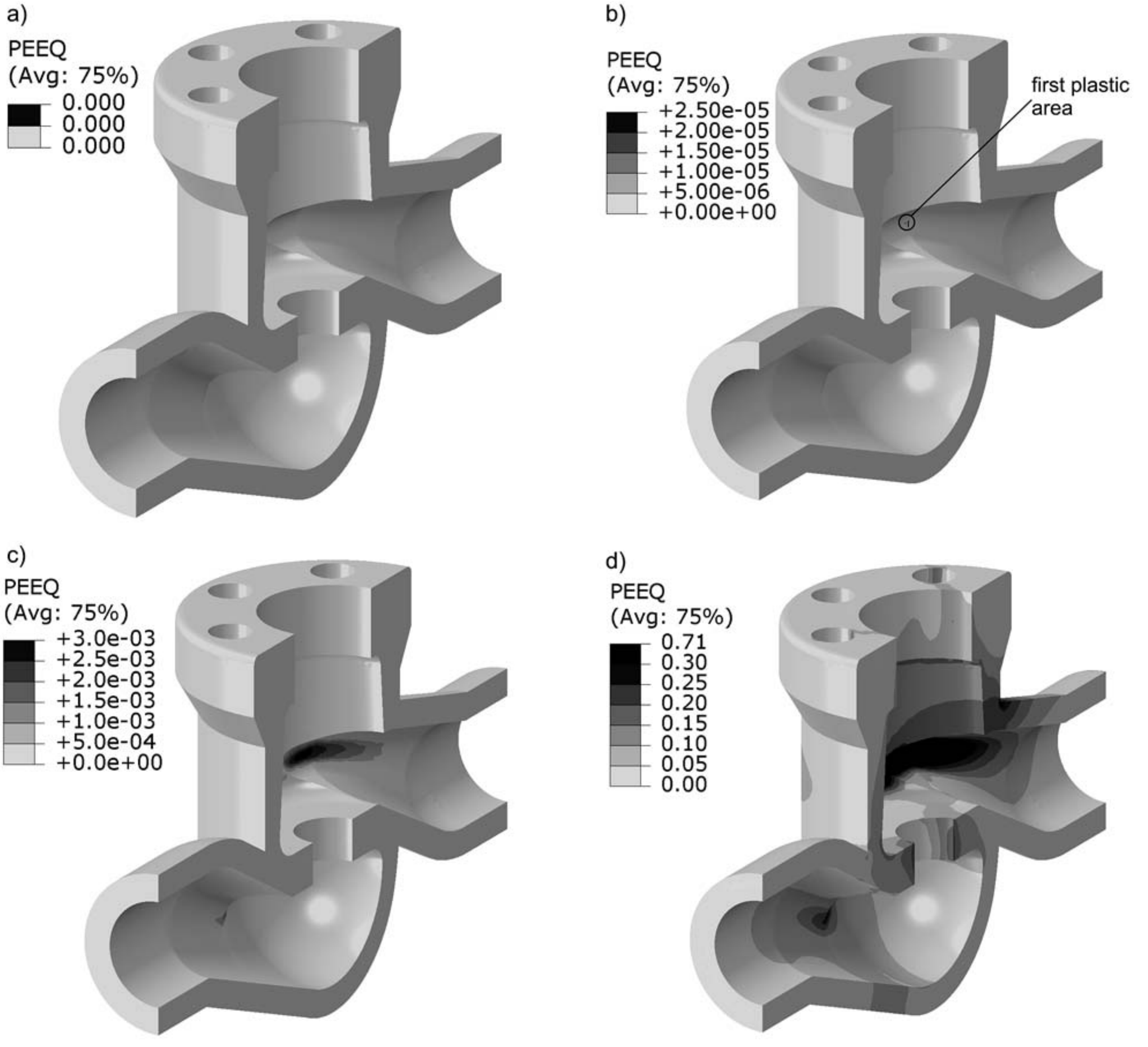

Figure 6 *The equivalent plastic strain distribution at the pressure of: a) 16 MPa, b) 25 MPa, c) 47 MPa i d) 159 MPa*

Slika 6. *Raspodjela ekvivalentne plastične deformacije pri tlaku od: a) 16 MPa, b) 25 MPa, c) 47 MPa i d) 159 MPa*

Spreading of the zones with maximum equivalent plastic strain throughout the housing wall thickness at the critical location where maximum equivalent plastic strain reaches the outer surface of model housing is shown in Fig. 7. It is evident that critical location determined by the nonlinear FE analysis and represented by the point A in Fig. 7 is away from both points S_L and S_R which represent critical locations at the regions proposed by the EN 12516-2 standard.

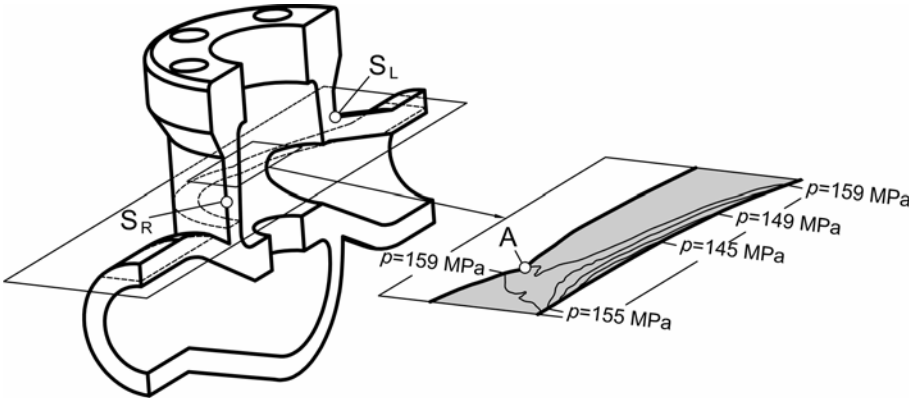

***Figure** 7 Spread of the zones with maximum equivalent plastic strain value of 30 % through the wall thickness for a series of pressure values*
***Slika 7.** Širenje zona ekvivalentne plastične deformaciji u iznosu od 30 % kroz debljinu stijenke kućišta za različite iznose tlaka*

Based on the FE results, the plastic collapse pressures for the housing are determined separately for points S_L and S_R as well as for point A. Fig. 8 shows the values for critical points S_L and S_R, while Fig. 9 shows the values for the point A. Herein p_C^{TES} is the plastic collapse pressure obtained by the TES method and p_C^{TI} is the plastic collapse pressure determined by the TI method. The mean value of the plastic collapse pressure determined by TI and TES method is 95,9 MPa for point S_L, 79,3 MPa for point S_R and 71,3 MPa for the point A.

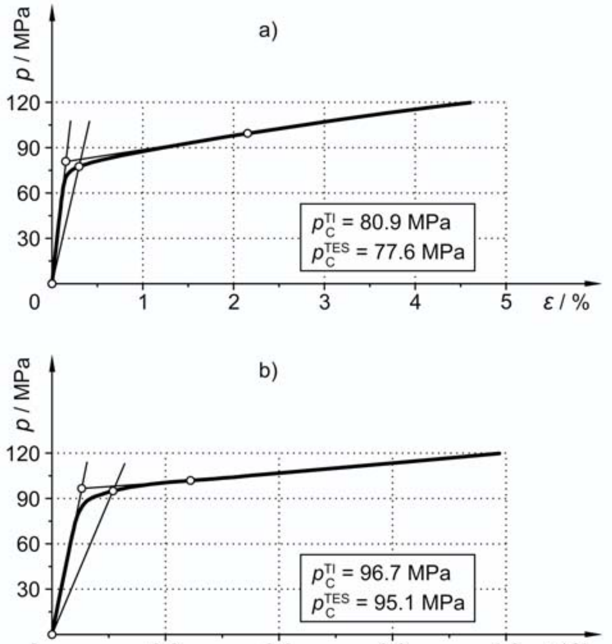

***Figure 8** Variation of pressure with the maximum principal strain with appropriate plastic collapse pressures for points: a) S_R and b) S_L*
***Slika 8.** Promjena tlaka u ovisnosti o najvećim glavnim deformacijama s odgovarajućim tlakovima plastičnog kolapsa za točke: a) S_R i b) S_L*

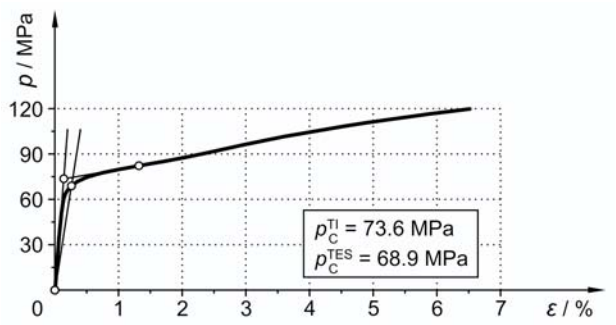

***Figure 9** Variation of pressure with the maximum principal strain of the point A with appropriate plastic collapse pressures*
***Slika 9.** Promjena tlaka u ovisnosti o najvećim glavnim deformacijama s odgovarajućim tlakom plastičnog kolapsa za točku A*

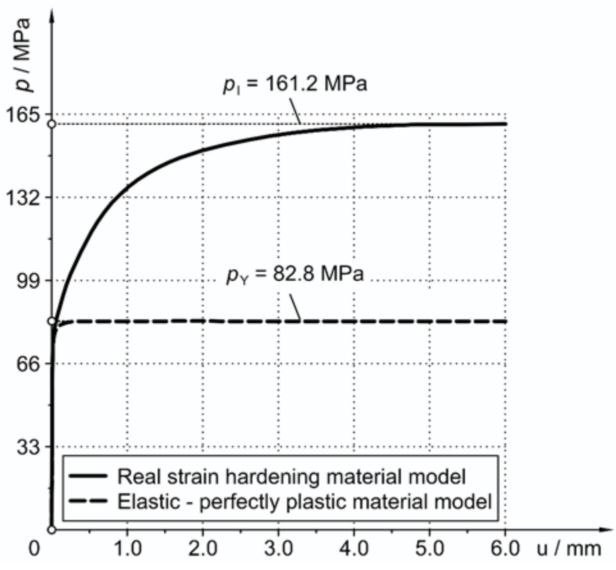

***Figure 10** Variation of pressure with the displacement of the point A. Plastic yield and instability pressure analyses*
***Slika 10.** Promjena tlaka u ovisnosti o pomaku točke A. Analiza tlaka plastičnog tečenja i tlaka plastične nestabilnosti*

Pressure-displacement diagrams for the FE node in the numerical model at the critical point A are shown in Fig. 10. From the pressure-displacement curve, the plastic instability pressure p_I is obtained as the highest point on the curve, i.e. the maximum pressure that could be attained. In the FE analyses it is assumed that the material will fail in a ductile manner so that the plastic instability pressure p_I represents the failure pressure p_F that causes the plastic collapse of the housing. In such a manner, the numerically obtained failure pressure at the point A is 161,2 MPa.

The approximate result for the failure pressure p_F can be obtained by using the reference stress concept [20] without the detailed consideration of the real material hardening and geometrical nonlinearity. The concept can be applied to flawed and unflawed components [21]. In some Failure Assessment Diagram methods [6, 22], the reference stress concept is used to define a parameter L_r, that measures the probability of a ductile failure

$$L_r = \frac{p}{p_Y} = \frac{\sigma_{ref}}{\sigma_y}, \qquad (3)$$

where p_{Y} denotes the plastic yield pressure. When applied to unflawed components, the reference stress, σ_{ref},

$$\sigma_{\mathrm{ref}} = \sigma_{\mathrm{Y}} \frac{p}{p_{\mathrm{Y}}}, \tag{4}$$

can be compared to the material's yield stress, σ_{Y}, for non-work hardening behaviour, or to some flow stress, σ_{f},

$$\sigma_{\mathrm{f}} = k(\sigma_{\mathrm{y}} + \sigma_{\mathrm{u}}), \tag{5}$$

when significant work hardening is exhibited, to estimate the onset of plastic collapse

$$p_{\mathrm{F}} = p_{\mathrm{Y}} \frac{\sigma_{\mathrm{f}}}{\sigma_{\mathrm{y}}}. \tag{6}$$

Herein k stands for the flow stress factor (k = 0,5, recommended for most assessments [15]). For the analyzed housing the plastic yield pressure amounts to 82,8 MPa (see Fig. 10).

If the term σ_{f} is inserted into the previous expression (6) for the mean value between the yield stress and the ultimate tensile stress (k = 0,5), a rather conservative solution for the failure pressure (p_{F} = 120,1 MPa) is obtained. But if the ultimate tensile stress is assumed for the flow stress ($\sigma_{\mathrm{f}} = \sigma_{\mathrm{u}}$), the obtained failure pressure in the amount of 157,3 MPa corresponds well to the numerically determined burst pressure of 161,2 MPa, for real material.

4
Allowable pressure
Dopušteni tlak

In accordance with [4], the allowable pressure $p_{\mathrm{allowable}}$ based on the limit designed method is determined from the plastic collapse pressure p_{C} through the expression

$$p_{\mathrm{allowable}} = \frac{2}{3} p_{\mathrm{C}}. \tag{7}$$

The mean value of the plastic collapse pressures $p_{\mathrm{C}}^{\mathrm{TES}}$ and $p_{\mathrm{C}}^{\mathrm{TI}}$ at the point A obtained from FE results is $p_{\mathrm{C}} = 71{,}3$ MPa. If it is inserted into the previous expression, it follows that the globe valve housing allowable pressure is 47,5 MPa.

In common engineering practice, the calculation of the valve housing wall thickness is done in accordance with the EN 12516-2 standard. The calculation needs two steps: the calculation of the housing main section wall thickness and calculation of wall thickness in the crotch area. Since the wall thickness in the crotch area cannot be calculated directly, the initial wall thickness in this area is assumed from the one calculated in the first step and then incrementally increased until the equilibrium of forces is reached. The investigated valve housing DN50 PN160 wall thickness calculation is, therefore, carried out only in the crotch area. The housing dimensions required for the calculation according to EN 12516-2 standard are shown in Fig. 11 and the calculation method is described in the following section.

Based on the dimensions from Fig. 3 and notation from Fig. 11, the following expression is derived:

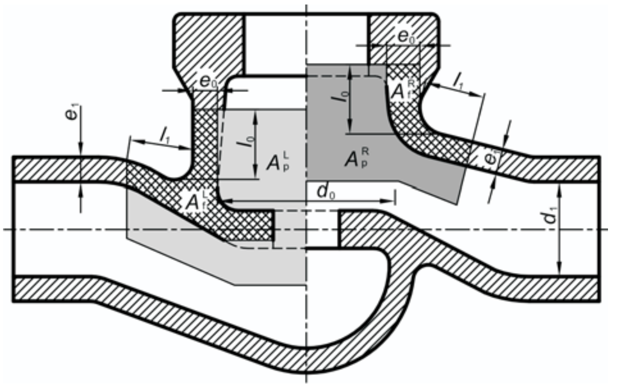

Figure 11 *Illustration of the housing dimensions required for the calculation according to EN 12516-2 standard*
Slika 11. *Prikaz dimenzija koje su potrebne za proračun stjenke kućišta ventila prema normi EN 12516-2*

$$\begin{aligned} l_0 &= \sqrt{(d_0 + e_0)\cdot e_0} = \sqrt{(94+13)\cdot 13} = 37{,}3\ \mathrm{mm}, \\ l_1 &= 1{,}25\cdot\sqrt{(d_1+e_1)\cdot e_1} = 1{,}25\cdot\sqrt{(50+13)\cdot 13} = 32{,}0\ \mathrm{mm}. \end{aligned} \tag{8}$$

For the calculated distances l_0 and l_1, the lined surfaces in Fig. 11 are determined graphically as follows:

$$\begin{aligned} &A_{\mathrm{f}}^{\mathrm{L}} = 1886{,}76\ \mathrm{mm}^2,\ A_{\mathrm{p}}^{\mathrm{L}} = 5070{,}86\ \mathrm{mm}^2, \\ &A_{\mathrm{f}}^{\mathrm{R}} = 1053{,}79\ \mathrm{mm}^2,\ A_{\mathrm{p}}^{\mathrm{R}} = 3511{,}62\ \mathrm{mm}^2, \end{aligned} \tag{9}$$

where the R and L indices mark the right and left side of the housing, respectively. The maximum allowable pressure for the right and the left side of the housing is determined according to the expression

$$p \le \frac{f}{\left[\dfrac{A_p}{k_{\mathrm{C}}\cdot A_f} + \dfrac{1}{2}\right]}, \tag{10}$$

where $f = \sigma_{\mathrm{y}}/1{,}9$ and $k_{\mathrm{C}} = 1$ are used for a non-welded structure. If the surfaces determined in expression (9) are inserted into expression (10), the allowable pressures for the left and right side of the housing are derived as: $p_{\mathrm{allowable}}^{\mathrm{L}}$ = 41,3MPa and $p_{\mathrm{allowable}}^{\mathrm{R}}$ = 34,3MPa. Since the $p_{\mathrm{allowable}}^{\mathrm{R}}$ is lower than the $p_{\mathrm{allowable}}^{\mathrm{L}}$, the maximum allowable pressure of the housing, calculated according to the EN 12516-2 standard, is 34,3 MPa. If results are compared, it is clear that the maximum allowable pressure value calculated by the application of the EN 12516-2 standard is notably lower than the maximum allowable pressure of 47,5 MPa derived by the application of FE results for the plastic collapse pressure, in accordance with the limit design method [4].

Therefore it can be concluded that for the considered two-way globe valve housing geometry, the standard engineering approach [2] is highly conservative. Economically speaking, this may result in an unsatisfactory housing because the material consumption (thicker walls increase material consumption) has a great influence on the product price. On the other hand, the results shown in [16, 17] for the three-way globe valve housing indicate that the allowable pressure determined by the application of the EN 12516-2 standard compare satisfactorily with the FE based solution. In both cases the allowed pressure is much higher than the nominal pressure of valve housing.

5
Discussion and conclusions
Rasprava i zaključak

The present paper is a continuation of the authors' previous work published in [16, 17] where a three-port globe valve housing (designation DN100 PN40) was analyzed in details. The results for the mentioned housing indicate that the allowable pressure determined by the application of the EN 12516-2 standard compare satisfactorily with the experimental and FE based solutions.

Two-way globe valve housing DN50 PN160 subjected to internal pressure is investigated in this paper. Three-dimensional nonlinear FE analyses are performed to obtain the plastic yield, collapse and instability pressures. The real material hardening and geometrical nonlinearity were modelled. The numerical model used in this paper is similar to the one experimentally verified in the previous investigation. Based on the numerical results, the housing plastic collapse pressure was determined by means of two methods: the twice-elastic-slope and the tangent-intersection. It is shown that allowable pressure for the globe valve housing calculated by the application of the EN 12516-2 standard is highly conservative compared with the one derived by the application of FE results for the plastic collapse pressure, in accordance with the limit design method.

As presented in this paper, the wall thickness in the crotch areas of the two-way globe valve housing, according to the EN 12516-2 standard, is calculated only in a symmetry plane. Although critical location obtained by the FEM is located in the crotch area, it is located away from the symmetry plane and thus away from both critical locations proposed by the EN 12516-2 standard. Therefore, it can be concluded that EN 12516-2 standard is not precise enough for designing of the two-way globe valve housing details.

In the FE analyses it is assumed that the material will fail in a ductile manner. In accordance with that, from the pressure-displacement diagram obtained by the FE analysis, the failure pressure, i.e. the plastic instability pressure, was determined as the highest point on the curve. The numerically obtained failure pressure has the value of 161,2 MPa. Additionally, it is shown that the results for the failure pressure can be obtained by a simpler FE analysis without taking into consideration the material hardening and geometrical nonlinearity. Thereby, FE results show that the failure pressures obtained by the limit load analyses give conservative results, except those obtained by using the ultimate tensile stress as the flow stress.

Since the EN 12516-2 standard gives too conservative result for the allowable pressure compared to the FE based solution, additional studies are needed to define more precise method for calculation of two-way globe valve housing wall thickness. It is necessary firstly to carry out an experimental investigation to confirm the numerical prediction presented here. These results represent the content of the paper that is in preparation.

6
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