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Napetosti v okolici vrha vzdolžne razpoke v cevi uparjalnika
Stresses Around the Tip of an Axial Crack in a Steam Generator Tube

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Prispevek obravnava teorijo in predpostavke elasto-plastične lomne mehanike, ki so bile uporabljene pri določanju kritične dolžine vzdolžne razpoke, ki sega skozi celotno steno cevi uparjalnika. Zaradi več specifičnih predpostavk je uporabnost opisane teorije omejena le na kritične razmere. Za boljše poznavanje napetostnega polja v okolici vrha razpoke v podkritičnih razmerah smo uporabili numerično analizo — nelinearno metodo končnih elementov. V raziskavi smo posebno pozornost posvetili razvoju deformacij, izbočenju in odpiranju razpoke ter razvoju plastične cone pri naraščajočem notranjem tlaku. Rezultate numerične analize smo primerjali z objavljenimi eksperimentalnimi podatki, pri čemer smo dosegli razmeroma zelo dobro ujemanje.

A short overview of elasto-plastic fracture mechanics theories and assumptions, applied to determination of the critical length of a through-wall axial crack in a steam generator tube is given in the paper. The validity of these theories is, due to some specific assumptions, limited to the critical conditions only. To analyse the stresses around the crack tip, a numerical analysis by the means of non-linear finite element method was therefore necessary. Special attention was given to the development of deformations (bulging and crack opening) together with the plastic zone development due to increasing internal pressure. Numerical results are compared with published experimental data with relatively very good agreement.

0. UVOD

Pojav napetostno korozijskih razpok v ceveh uparjalnikov tlačnovodnih jedrskih elektrarn je upravljalce prisilil v raziskave in razvoj novih vzdrževalnih postopkov, ki bodo omogočili varno obratovanje ob čim daljši dobi trajanja [1]. Najbolj so pri tem napredovali belgijski [2], [3], [4] in francoski [5], [6], [7] raziskovalci, ki so vpeljali t.im. dolžinske kriterije čepljenja uparjalnikov.

Osnovna sestavina dolžinskih kriterijev čepljenja je vsekakor določitev dolžine razpoke, pri kateri postane napredovanje nestabilno. Tej dolžini odvzamejo še odstopek merilne metode in predvideno stabilno napredovanje razpoke v naslednjem obdobju med dvema pregledoma [2] in tako dobijo največjo dovoljeno dolžino razpoke, ki jo smejo zaznati ob rednem pregledu uparjalnikov.

Analitični in eksperimentalni postopki, ki so jih belgijski in francoski raziskovalci uporabili kot podlago dolžinskim kriterijem čepljenja (npr. [2] in [5], so, žal, omejeni le na kritične razmere v vrhu razpoke. Povedano drugače, taki postopki sicer dovolj zanesljivo napovedujejo, npr. tlak razpočenja cevi (kritična dolžina razpoke), niso pa primerni za obravnavanje razmer pri normalnem obratovalnem tlaku, ki je navadno dosti nižji od tlaka razpočenja.

0. INTRODUCTION

The appearance of stress corrosion cracks in the steam generator tubes of pressurized water reactor nuclear power plants forced the utilities into research and development of new maintenance procedures to enable safe operation over the longest possible life time [1]. Major advances have been achieved by Belgian [2], [3], [4] and French [5], [6], [7] researchers, who have proposed the so called crack length plugging criteria.

The basis of the crack length plugging criteria is the determination of the critical crack length, which causes unstable crack propagation. The measurement error and predicted stable crack propagation during the period between two inspections [2] are then substracted from the critical crack length to yield the maximum allowable crack length to be detected during regular steam generator inspection.

Unfortunately, the analytical and experimental procedures being applied by Belgian and French researchers as the basis of the crack length plugging criteria [2], [5] are restricted to the critical crack tip conditions. In other words, such procedures are reliable enough to predict, for example, the tube bursting pressure (critical crack length), but hardly suitable for analyses of normal operating pressure conditions, which are usually far below bursting pressure.

Namen pričujočega prispevka je prikazati uporabnost analitičnega načina pri obravnavi kritičnih razmer. Podkritične razmere pa bomo raziskali z nelinearno metodo končnih elementov (računalniški program PAFEC-FE [8], [9]). Posebej se bomo posvetili analizi deformacij v bližini korena razpoke, za katere imamo na voljo tudi eksperimentalne podatke [2]. Z analizo razvoja napetostnega polja in plastične cone pa bomo preverili vpliv upogibnih napetosti in plastifikacije na stabilnost razpoke. Hkrati pa bomo pokazali še zmogljivost in uporabnost metode končnih elementov pri reševanju takih problemov.

The present paper demonstrates the applicability of the analytical approach in relation to critical conditions. Subcritical conditions are investigated by means of the non-linear finite element method (computer code PAFEC - FE [8], [9]). Special attention is paid to the analysis of deformations around the crack tip, which are also available as experimental results [2]. The impact of bending stresses and plastification on crack stability are verified by the analysis of stress field and plastic zone development. The potential and applicability of the finite element method in solving this class of problems are shown.

1. DOLOČANJE KRITIČNE DOLŽINE RAZPOKE

1. CRITICAL CRACK LENGTH DETERMINATION

Obravnavamo le vzdolžne razpoke v ceveh, ki so obremenjene z notranjim tlakom. Take razpoke so vedno obremenjene na odpiranje. Faktor intenzivnosti napetosti pri odpiranju razpoke K_I bomo v nadaljevanju zapisovali kot K.

Only axial cracks in tubes loaded by internal pressure are considered. Such cracks are always subjected to opening mode loading. The stress intensity factor K_I is written as K throughout this paper.

1.1 Možnosti lomne mehanike

1.1 Fracture mechanics possibilities

Analiziramo vzdolžno razpoko dolžine $2a$ v valjasti lupini s srednjim polmerom R in debelino stene t. Obremenitev z notranjim tlakom p povzroča obročno napetost pravokotno na smer razpoke:

An axial through wall crack of length $2a$ in a cylindrical shell with mean radius R and tube wall thickness t is analyzed. Internal pressure p loading induces hoop stress perpendicular to the crack direction:

$$\sigma_\varphi = p\left(\frac{R}{t} - \frac{1}{2}\right) \qquad (1).$$

V literaturi dobro uveljavljen način [10], [11], [12] v takih primerih priporoča uporabo prirejene definicije faktorja intenzivnosti napetosti K:

In such cases, a well recognized approach suggested in the literature [10], [11], [12] upgrades the stress intensity factor definition:

$$K = m\,\sigma_\varphi\,\sqrt{\pi a\,\Phi} \qquad (2).$$

Korekcijski faktor m upošteva povečanje obročne membranske napetosti σ_φ, nastalega zaradi izbočenja sten cevi ob razpoki, ki je posledica notranjega tlaka. Faktor m je prvi teoretično ovrednotil Folias [13], zato je v literaturi zanj najti ime Foliasov faktor oz. faktor izbočenja:

The correction factor m describes the increase of the hoop membrane stress due to tube wall bulging along the crack, which is caused by internal pressure. Factor m was first theoretically evaluated by Folias [13] and is usually referred to as the Folias or bulging factor:

$$m = \sqrt{1.0 + 1.61\,\frac{a^2}{R\,t}} \qquad (3).$$

Najti je tudi drugačne korelacije, npr. Erdoganovo [12], ki se v našem primeru tudi najbolje ujema z eksperimentalnimi rezultati [2]:

Other correlations may also be found, such as, for example, Erdogan's [12], which also provides the best fit to the experimental results [2] in our case:

$$m = 0.614 + 0.386\exp(-1.25\,\lambda) + 0.481\,\lambda \qquad (4),$$

$$\lambda = \sqrt[4]{\left[12\,(1-\nu^2)\right]}\,\frac{a}{\sqrt{R\,t}} \qquad (5).$$

Faktor m velja le za obročno membransko napetost. V literaturi [11] je najti tudi korekcijski faktor za upogibne napetosti, vendar je njihov vpliv na kritičnost razpoke zanemarljiv. Faktor φ pomeni vpliv plastične cone v okolici vrha razpoke. Zopet je v literaturi [11] mogoče najti različne faktorje, ki so seveda posledica različnih predpostavk oz. uporabljanih elasto-plastičnih teorij. Zapisali bomo le tistega, ki se najbolje ujema z eksperimentalnimi rezultati [2]:

Factor m is only valid for hoop membrane stress correction. Corrections for the bending stresses have been reported [11], although they have negligible influence on crack criticality. The effect of the plastic zone at the crack tip is described by factor φ. Again, different proposals following different elastic-plastic theories and assumptions are available in the literature [11]. Only the correlation offering the best fit to the experimental results [2] is given here:

$$\Phi = 2\left(\frac{\pi\sigma}{2\sigma_y}\right)^{-2} \ln \sec\left(\frac{\pi\sigma}{2\sigma_y}\right) \qquad (6).$$

Korekcijski faktor (6) je pravzaprav posledica Dugdaleove rešitve za CTOD (Crack Tip Opening Displacement) v idealno plastičnem materialu z mejo plastičnosti σ_y [10]:

The correction factor in eq. (6) actually follows from Dugdale's Crack Tip Opening Displacement solution (CTOD) in ideally plastic material with yield stress σ_y [10]:

$$\mathrm{CTOD} = \frac{K^2}{E\sigma_y} = \frac{8}{\pi}\frac{\sigma_y a}{E} \ln \sec \frac{\pi\sigma}{2\sigma_y} \qquad (7).$$

Utrjanje materiala v literaturi navadno upoštevamo z računsko mejo plastičnosti, imenovano tudi meja tečenja (flow stress) σ_f [2], [11], s katero nadomestimo dejansko mejo plastičnosti v enačbi (6) in (7). Ta je navadno med dejansko mejo plastičnosti in natezno trdnostjo σ_M, kar lahko popišemo [2] kot:

Material hardening is usually accounted for by effective yield stress, also called flow stress σ_f [2], [11], which replaces the yield stress in eqs. (6) and (7). Its value is usually between the yield stress and ultimate tensile stress σ_M and can be written as [2]:

$$\sigma_f = k(\sigma_y + \sigma_M), \quad k \leq 1{,}0 \qquad (8).$$

Vrednost faktorja k je navadno določena eksperimentalno [2]. Enačbo (2) lahko ob upoštevanju enačb (7) in (8) ponovno zapišemo kot:

The value of factor k is usually experimentally determined [2]. Recalling eqs. (7) and (8), eq. (2) may be rewritten as:

$$K = m\sigma_\varphi \sqrt{\pi a \left[2\left(\frac{2\sigma_f}{\pi m_\varphi}\right)^2 \ln \sec \frac{\pi m \sigma_\varphi}{2\sigma_f}\right]} \qquad (9).$$

Zapišimo še obročno membransko napetost $\sigma_{\varphi C}$, pri kateri se pojavi porušitev. Dobimo jo iz enačb (9) pri pogoju $K = K_C$:

Let us determine the hoop membrane stress $\sigma_{\varphi,C}$ at the tube failure. It can be obtained by setting $K = K_C$ in eq. (9):

$$\sigma_{\varphi C} = \frac{\sigma_f}{m}\frac{2}{\pi} \arccos \exp\left(\frac{\pi K_C^2}{8\sigma_f^2 a}\right) \qquad (10).$$

Očitno je, da smo z uvedbo σ_f omejili uporabnost enačbe (9) le na kritične razmere, torej na napovedovanje začetka nestabilnega napredovanja razpoke. S tem smo izključili možnost analize napetostnega in deformacijskega stanja v okolici razpoke pri celotnem razponu obratovalnih tlakov, ki so praviloma daleč pod kritično vrednostjo.

The introduction of σ_f obviously restricted the validity of eq. (9) to the critical conditions, thus the prediction of the onset of unstable crack propagation. The possibility of analysing the stress and strain field at the crack tip in the entire range of operational pressures, being usually far below the critical value, was therefore eliminated.

1.2 **Porušitveni zakoni**

V lomni mehaniki dostikrat štejemo, da se (krhki) lom pojavi takrat, ko faktor intenzivnosti napetosti doseže kritično vrednost ($K = K_C$). Že bežna analiza enačbe (10) pa pokaže, da z večanjem razmerja ($\pi K_C^2 / 8\sigma_f^2 a$) vplivnost kritičnega faktorja intenzivnosti napetosti slabi, dokler ne dosežemo pogoja žilave porušitve v obliki $\sigma_{\varphi,C} = m\sigma_f$. Do tega sklepa sta najprej prišla Dowling in Townley v svojem predlogu dveh kriterijev [14]. Prehod med obema mejnima primeroma porušitve pa sta definirala prav z enačbo (9).

Eksperimentalne analize [2] so pokazale, da se INCONEL 600, iz katerega so cevi uparjalnika izdelane, v vseh predvidenih obratovalnih razmerah podreja žilavemu lomu. Porušitev oz. kritično dolžino razpoke lahko torej napovemo s kritično obročno membransko napetostjo:

2. NUMERIČNA ANALIZA NAPETOSTI

Z numerično analizo napetosti v okolici vrha razpoke smo raziskali predvsem razvoj deformacij in plastične cone z naraščanjem notranjega tlaka. S tem smo se izognili pomanjkljivostim analitičnega postopka, predstavljenega v prejšnjem poglavju.

2.1 **Opis uporabljenih modelov**

Cev z razpoko smo modelirali z metodo končnih elementov (program PAFEC-FE [8], [9]). Izdelali smo dva modela aksialne razpoke. Prvi je sestavljen iz prostorskih končnih elementov (sl.1), drugi pa iz lupin (sl. 2). V obeh modelih je bila širina razpoke 0 mm in dolžina $2a$ = 12 mm. Ničelna širina je preprosta za modeliranje, hkrati pa pomeni večje koncentracije napetosti v zelo ostrem vrhu.

1.2 **Failure modes**

In fracture mechanics, a (brittle) fracture is considered to occur when the stress intensity factor reaches its critical value ($K = K_C$). However, a brief analysis of eq. (10) shows that increasing the value of ($\pi K_C^2 / 8\sigma_f^2 a$) decreases the influence of stress intensity factor, until the net section plastic collapse mode in the form of $\sigma_{\varphi,C} = m\sigma_f$ is reached. This conclusion was originally published by Dowling and Townley in their proposal of a two criteria approach [14]. The transition between the two limiting failure modes has been defined by eq. (9).

It has been demonstrated by means of experimental analysis [2], that INCONEL 600 made steam generator tubes fail by net section plastic collapse in all expected operating conditions. The failure, or the critical crack length, can therefore be predicted by means of critical hoop membrane stress:

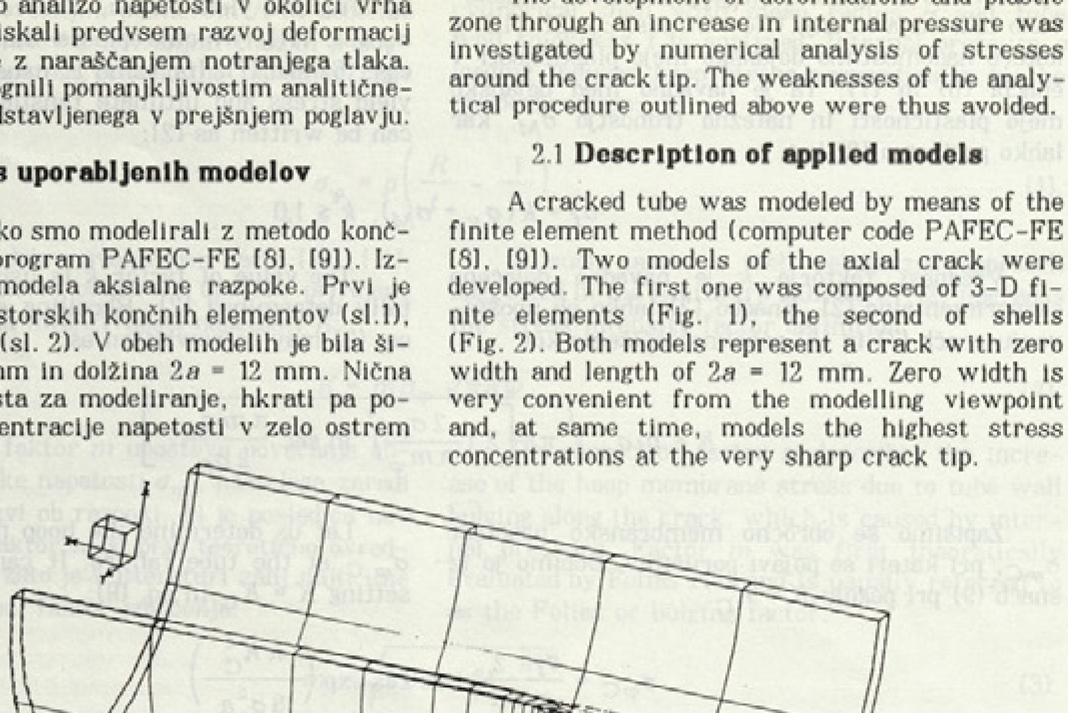
$$\sigma_{\varphi,C} = \frac{\sigma_f}{m} \tag{11}$$

2. NUMERICAL STRESS ANALYSIS

The development of deformations and plastic zone through an increase in internal pressure was investigated by numerical analysis of stresses around the crack tip. The weaknesses of the analytical procedure outlined above were thus avoided.

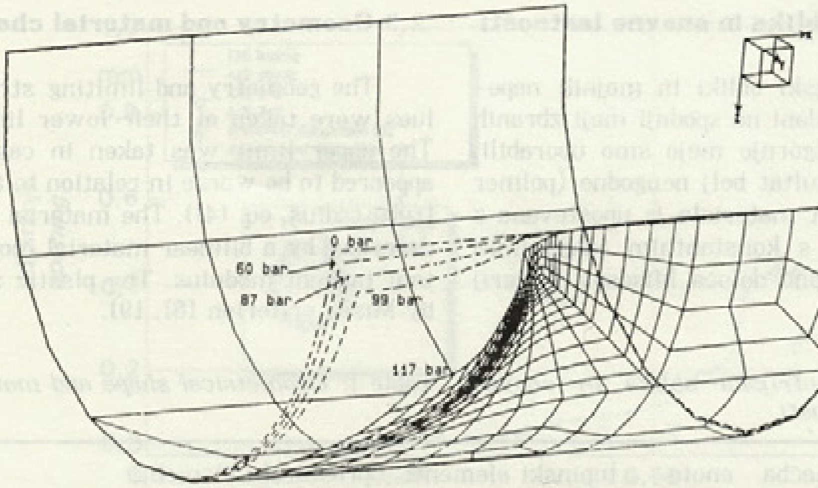
2.1 **Description of applied models**

A cracked tube was modeled by means of the finite element method (computer code PAFEC-FE [8], [9]). Two models of the axial crack were developed. The first one was composed of 3-D finite elements (Fig. 1), the second of shells (Fig. 2). Both models represent a crack with zero width and length of $2a$ = 12 mm. Zero width is very convenient from the modelling viewpoint and, at same time, models the highest stress concentrations at the very sharp crack tip.



Sl. 1. *Deformirana mreža prostorskega modela.*

Fig. 1. *Deformed mesh of the 3-D model.*



Sl. 2. *Deformirana mreža lupinskega modela.*
Fig. 2. *Deformed mesh of the shell model.*

Pri modeliranju smo upoštevali dvojno simetrično naravo problema. Aksialna razpoka v cevi je namreč simetrična glede na svojo lastno ravnino in glede na ravnino, normalno na os cevi, ki gre prav skozi razpolovišče razpoke. Vozlišča, ki so v simetrijskih ravninah nedeformirane mreže, ostanejo v njih tudi po deformaciji. Njihovo gibanje v ravnini je seveda omogočeno.

Drugi konec cevi, kjer ni razpoke, je modeliran v dolžini, ki zagotavlja vzpostavitev napetosti v nemoteni cevi (obročna komponenta membranske napetosti (1)). Cev se končuje s tretjo simetrijsko ravnino, ki simulira vzdolžne napetosti v cevi U.

Model iz lupin (sl. 2) je nastal po rezultatih, dobljenih s prostorskim modelom (sl. 1). Bistvene ugotovitve, uporabljene v ta namen, so:

— vpliv vrha razpoke je za analizirani razpon tlakov manjši od pričakovanega, zato smo zmanjšali aksialno dimenzijo modela;

— gostota mreže okoli vrha razpoke ne daje zanesljivih kolikostnih rezultatov, vendar kakovostno primerno popisuje dogajanje. Mreža lupinskega modela je močno zgoščena, kar omogoča boljšo analizo napetostnega polja z velikimi gradienti;

— numerična natančnost programa PAFEC-FE [8], [9] zadošča do približno 60 odstotkov tlaka razpočenja.

Oba modela sta obremenjena z notranjim tlakom z uporabo interpolacijskih funkcij, vgrajenih v program [8], [9].

2.2 Omejitve

Pri obeh modelih je analiza napetosti potekala po teoriji majhnih deformacij (omejitev programa [8], [9]). Rešitev sicer nelinearnih konstitutivnih enačb zato z naraščajočo deformacijo izgublja natančnost. Zaradi tega je razmeroma velika možnost napake zelo blizu vrha razpoke, kjer tudi pride do največjih deformacij in napetosti.

The double symmetry of the problem was taken into account in the modelling. An axial crack is symmetrical to its own plane and to the plane perpendicular to the tube axis, lying in the middle of the crack. Undeformed mesh nodes which are initially lying in the symmetry planes remain in those planes after deformation. Off course, movements inside those planes are not restricted.

The other tube end (without the crack) is modelled to a length which allows for the development of uncracked tube stresses (hoop membrane stress component, eq. (1)). The tube is closed by a third plane of symmetry, which simulates the U-tube axial stresses.

The model made of shells (Fig. 2) was developed on the basis of 3-D model (Fig. 1) results. The essential conclusions in this context are as follows:

— the effect of the crack tip is lower than expected for the analyzed range of pressures; the axial dimension of the model was thus reduced;

— the crack tip mesh density does not enable reliable quantitative results, allthough qualitative behavior is considered adequate. The shell model mesh density is therefore increased to allow a better analysis of the stress field with large gradients,

— the numerical accuracy of the PAFEC-FE [8], [9] code is adequate up to 60 % of the bursting pressure.

Both models were loaded by internal pressure through the interpolation functions built into the code [8], [9].

2.2 Limitations

Both models were analyzed following the small deformation theory (code limitation [8], [9]). The accuracy of the nonlinear constitutive equations solution thus decreases with increased strain. Consequently, relatively high errors might be expected at the crack tip, where the occurrence of the largest strains and stresses is expected.

2.3 **Geometrijska oblika in snovne lastnosti**

Podatki o geometrijski obliki in mejnih napetostih so praviloma podani na spodnji meji zbranih vrednosti (pregl. 1). Zgornjo mejo smo uporabili, ko je to za končni rezultat bolj neugodno (polmer cevi (4)). Nelinearnost materiala je upoštevana z bilinearnim modelom s konstantnim tangentnim modulom. Plastično cono določa Misesov kriterij [8], [9].

2.3 **Geometry and material characteristics**

The geometry and limiting stresses data values were taken at their lower limits (Table 1). The upper limit was taken in cases where this appeared to be worse in relation to the final result (tube radius, eq. (4)). The material nonlinearity is described by a bilinear material model with constant tangent modulus. The plastic zone is defined by Mises criterion [8], [9].

Preglednica 1: *Geometrijska oblika in snovne lastnosti*

Table 1: *Geometrical shape and material data*

Parameter	oznaka symbol	enota unit	lupinski elementi shell elements	prostorski elementi 3-D elements	
srednji polmer	R	mm	9,12	8,99	mean radius
debelina stene	t	mm	0,91	1,06	wall thickness
meja plastičnosti	σ_y	MPa	255	255	yield stress
natezna trdnost	σ_M	MPa	590	590	ultimate tensile stress
dolžina razpoke	$2a$	mm	12	12	crack lenght
faktor izbočenja	m	-	2,43	2,43	bulging factor
napetosti tečenja	σ_f	MPa	435	435	flow stress
kritični tlak (razpočenje)	p_c	bar	187,5	236	critical pressure (bursting)

3. ANALIZA REZULTATOV

3.1 **Deformacije**

Oba modela sta pokazala izrazito kombinacijo odpiranja in izbočenja razpoke (sl. 1, 2). Na obeh slikah so hkrati prikazane deformirane mreže pri različnih tlakih. Velikosti deformacij pri različnih tlakih so namerno povečane, vendar med sabo sorazmerne. Absolutne vrednosti izbočenja in odpiranja razpoke so skupaj z rezultati preizkusov prikazane na slikah 3 in 4. Opaziti je odlično ujemanje rezultatov lupinskega modela s preizkusom predvsem pri odpiranju (sl. 3). Previsoki rezultati v primeru izbočenja (sl. 4) nastanejo, ker je smer obremenjevanja lupine z notranjim tlakom pri vseh tlakih normalna na neobremenjeno geometrjsko obliko. Tako je bila razpoka med celotnim potekom analize preveč obremenjena na izbočenje in premalo na odpiranje. Zmanjševanje natančnosti prostorskega modela z naraščanjem tlaka smo pričakovali, saj gostota mreže ni zadoščala za popis nastalih gradientov napetosti.

3.2 **Plastična cona**

Na slikah 5 do 8 je prikazan razvoj plastične cone na notranji površini cevi. Pri 60 barih (sl. 5) je poleg plastifikacije vrha razpoke že opaziti začetke natezne plastične cone v področju izbočenja. Obe plastični coni se združita pri 87 bar (sl. 6), kar približno ustreza normalnemu obratovalnemu stanju analizirane cevke. Hitrejše napredovanje

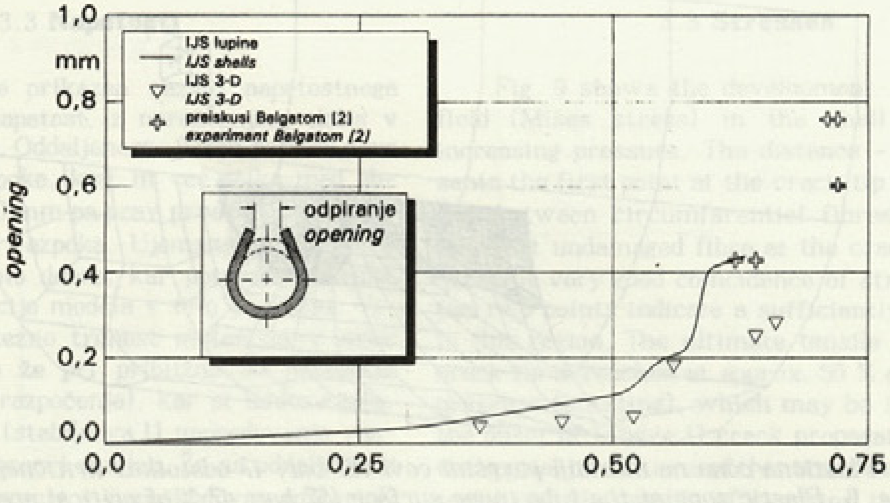
3. ANALYSIS OF RESULTS

3.1 **Deformations**

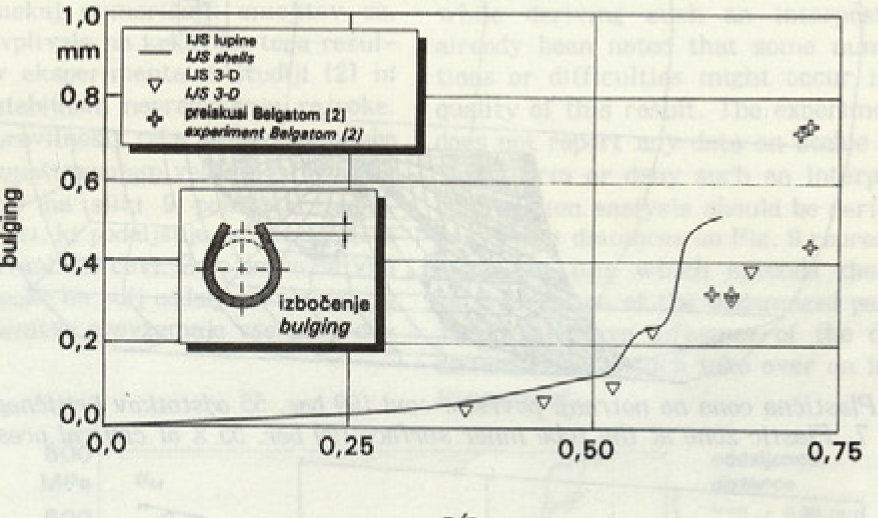
A pronounced combination of crack opening and bulging was shown by both models (Figs. 1 and 2). On both figures, deformed meshes are shown at different pressures. The deformation magnitudes are deliberately magnified but proportional to each other. Absolute values of bulging and opening are shown together with the experimental results on Figs. 3 and 4, respectively. An excellent agreement between shell model and experiment results is shown especially for crack opening (Fig. 3). The overestimated results in the case of bulging (Fig. 4) are caused by a constant shell loading direction based on an undeformed mesh. This caused too high loads in the case of bulging and too low for opening in the entire analysis range. The decrease of the 3-D model accuracy with increased pressure was expected, because of the low mesh density being incapable of describing large stress gradients.

3.2 **Plastic zone**

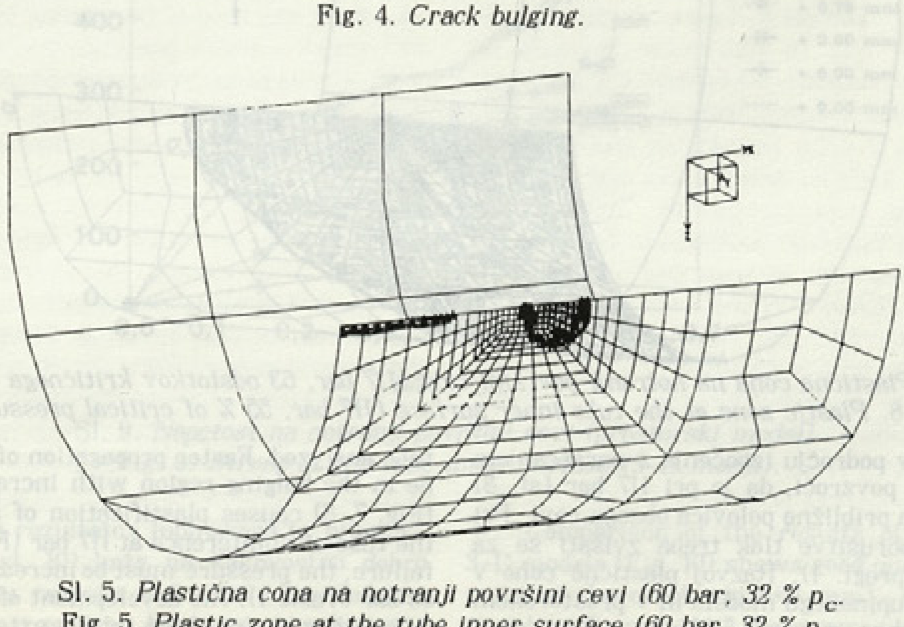
The development of the plastic zone on the inner tube surface is shown on Figs. 5 to 8. At 60 bar (Fig. 5), the first signs of the tensile plastic zone in the bulging region can be observed, in addition to crack tip plastification. Both plastic zones then join at 87 bar (Fig. 6), which approximates to the normal operating conditions of the



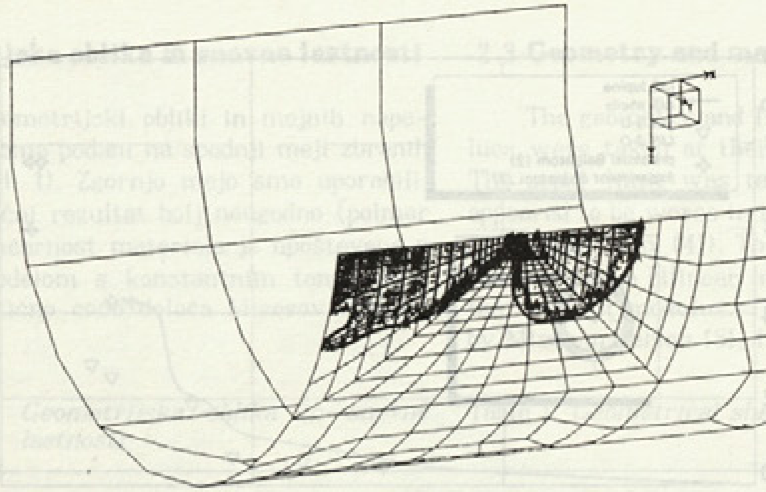
Sl. 3. *Odpiranje razpoke.*
Fig. 3. *Crack opening.*



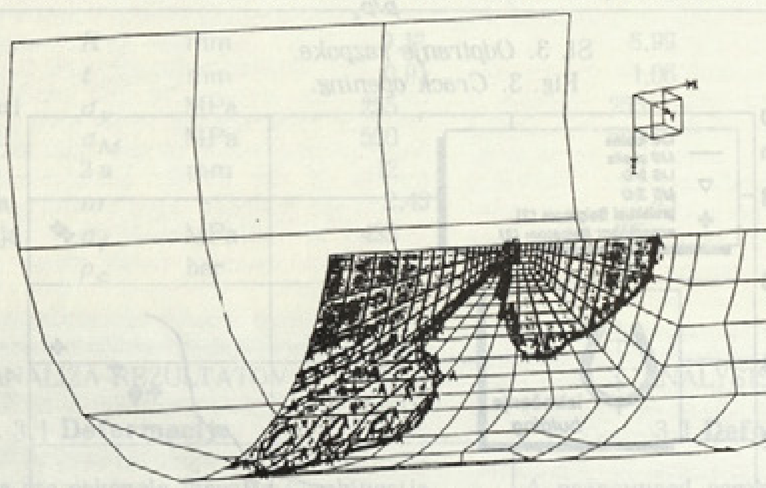
Sl. 4. *Izbočenje razpoke.*
Fig. 4. *Crack bulging.*



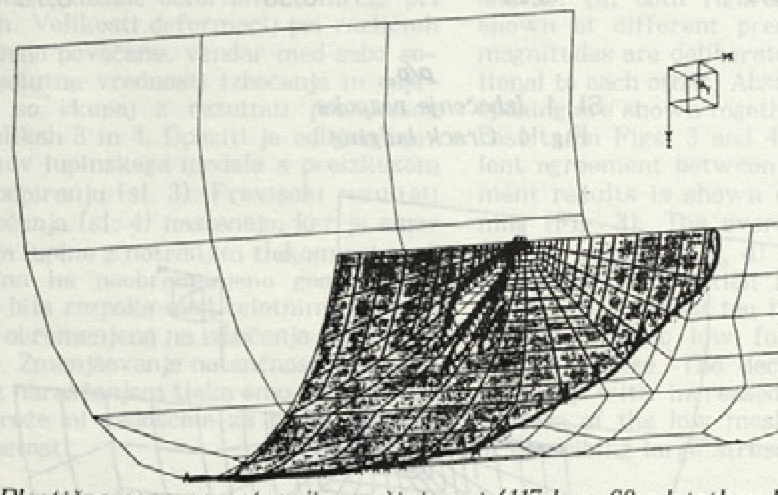
Sl. 5. *Plastična cona na notranji površini cevi (60 bar, 32 % p_c*
Fig. 5. *Plastic zone at the tube inner surface (60 bar, 32 % p_c*



Sl. 6. *Plastična cona na notranji površini cevi (87 bar, 47 odstotkov kritičnega tlaka).*
Fig. 6. *Plastic zone at the tube inner surface (87 bar, 47 % of critical pressure).*



Sl. 7. *Plastična cona na notranji površini cevi (99 bar, 55 odstotkov kritičnega tlaka).*
Fig. 7. *Plastic zone at the tube inner surface (99 bar, 55 % of critical pressure).*



Sl. 8. *Plastična cona na notranji površini cevi (117 bar, 63 odstotkov kritičnega tlaka).*
Fig. 8. *Plastic zone at the tube inner surface (117 bar, 55 % of critical pressure).*

plastične cone v področju izbočenja z naraščanjem tlaka (sl. 7, 8) povzroči, da je pri 117 bar (sl. 8) plastificirana že približno polovica obsega cevi. Pri tem pa je do porušitve tlak treba zvišati še za dobrih 60 bar (pregl. 1). Razvoj plastične cone v drugih plasteh lupinskega modela in v prostorskem modelu je podrobno opisan v [15].

tube analyzed. Faster propagation of the plastic zone in the bulging region with increasing pressure (Fig. 7, 8) causes plastification of approx. half of the tube circumference at 117 bar (Fig. 8). To reach failure, the pressure must be increased by a further 60 bar (Table 1). The development of the plastic zone in other layers of the tube is extensively described in [15].

3.3 Napetosti

Na sliki 9 je prikazan razvoj napetostnega polja, Misesova napetost, z naraščanjem tlaka v lupinskem modelu. Oddaljenost -0 mm pomeni prvo točko v vrhu razpoke, kjer ni več stika med obročnimi vlakni, +0 mm pa prav prvo nepoškodovano vlakno v vrhu razpoke. Ujemanje napetosti v obeh točkah je zelo dobro, kar potrjuje zadostno gostoto diskretizacije modela v tem področju. Vidimo tudi, da natezno trdnost materiala v vrhu razpoke dosežemo že pri približno 55 odstotkih kritičnega tlaka (razpočenja), kar si lahko razlagamo kot začetek (stabilnega !) napredovanja razpoke, saj je pojav precej omejen. Že na oddaljenosti 0,75 mm (v osni smeri v nepoškodovan material) material še vedno lahko prenaša obremenitev, saj so napetosti bistveno manjše. Seveda je pri taki razlagi potrebna določena previdnost. Že prej smo namreč omenili nekaj numeričnih omejitev oz. težav, ki bi lahko vplivale na kakovost tega rezultata. Poleg tega v eksperimentalni študiji [2] ni najti podatkov o stabilnem napredovanju razpoke. Za potrditev (ne)pravilnosti take razlage je treba analizo ponoviti z upoštevanjem velikih deformacij.

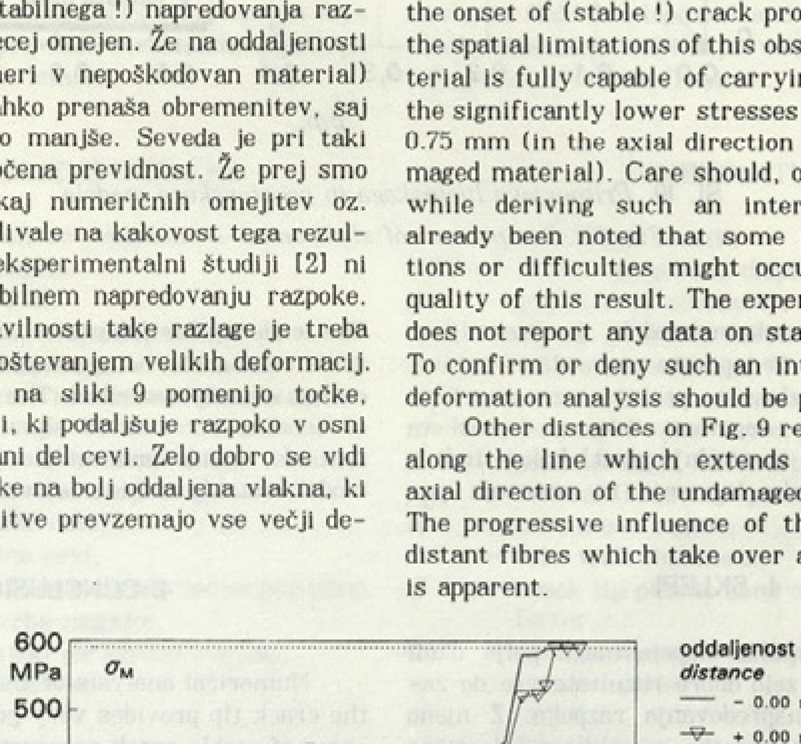
Druge razdalje na sliki 9 pomenijo točke, razmeščene na daljici, ki podaljšuje razpoko v osni smeri v nepoškodovani del cevi. Zelo dobro se vidi širjenje vpliva razpoke na bolj oddaljena vlakna, ki pri večanju obremenitve prevzemajo vse večji delež obremenitve.

3.3 Stresses

Fig. 9 shows the development of the stress field (Mises stress) in the shell model with increasing pressure. The distance -0 mm represents the first point at the crack tip without contact between circumferential fibres and +0 mm the first undamaged fibre at the crack tip.

The very good coincidence of stress values in the two points indicate a sufficiently dense mesh in this region. The ultimate tensile stress at the crack tip is reached at approx. 55 % of the critical pressure (bursting), which may be interpreted as the onset of (stable !) crack propagation, recalling the spatial limitations of this observation. The material is fully capable of carrying the load due to the significantly lower stresses at the distance of 0.75 mm (in the axial direction toward the undamaged material). Care should, of course be taken while deriving such an interpretation. It has already been noted that some numerical limitations or difficulties might occur influencing the quality of this result. The experimental study [2] does not report any data on stable crack growth. To confirm or deny such an interpretation, large deformation analysis should be performed.

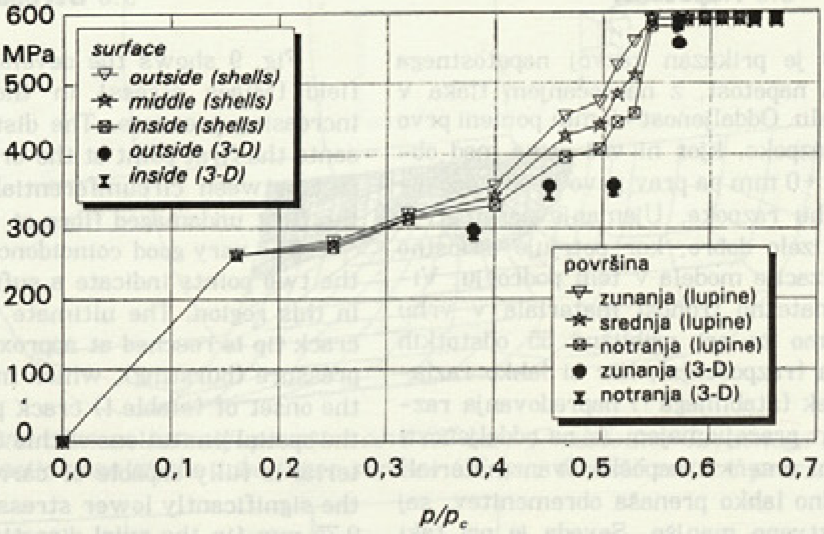
Other distances on Fig. 9 represent the points along the line which extends the crack in the axial direction of the undamaged part of the tube. The progressive influence of the crack on more distant fibres which take over an increasing load, is apparent.



Sl. 9. *Napetost na notranji površini cevi (prostorski model).*
Fig. 9. *Stress at the tube inner surface (3-D model).*

Primerjava rezultatov lupinskega in prostorskega modela (sl. 10) kaže na kakovostno dobro ujemanje v vrhu razpoke (+0 mm), kar dodatno potrjuje uspešnost analize. Nagnjenje k zamujanju

Comparison of the results of the shell and 3-D models (Fig. 10) shows good qualitative agreement at the crack tip (+0 mm), which is additional confirmation of the success of the analysis.



Sl. 10. *Primerjava lupinskega in prostorskega modela.*

Fig. 10. *Comparison of shell and 3-D model.*

napetosti v prostorskem modelu je razumljivo, saj ga povzročajo že opisane numerične težave. S slike 10 lahko razberemo praktično zanemarljivo velikost upogibnih napetosti tako v lupinskem (zunanja, notranja in srednja plast) kakor tudi v prostorskem modelu (zunanja in notranja površina).

4. SKLEPI

Numerična analiza napetostnega polja okoli vrha razpoke daje zelo dobre rezultate vse do začetka stabilnega napredovanja razpoke. Z njeno uporabo smo dobili podatke o velikosti plastične cone in ocenili tlak, pri katerem začne razpoka stabilno napredovati. Ta tlak znaša približno 55 odstotkov tlaka razpočenja. Močan argument za zanesljivost numeričnega modela je zelo dobro ujemanje napetosti v vrhu razpoke ne glede na lego opazovalca, kar kaže na dovolj gosto diskretizacijo v tem področju (lupinski model). Žal belgijski eksperimentalni rezultati eksplicitno ne omenjajo stabilnega napredovanja razpoke pred razpočenjem cevi. Ker smo lahko z numerično analizo zelo dobro sledili deformacijam v okolici razpoke, je začetek stabilnega napredovanja razpoke edino resno razhajanje z eksperimentalnimi rezultati. Vzrok je lahko numerične narave, saj so bile obremenitve okoli 60 % tlaka razpočenja na meji zmogljivosti računalniškega programa PAFEC-FE. Potrditev teze o numeričnem pogrešku je mogoča s predelavo računalniškega programa, ki bo omogočila spreminjanje geometrijske oblike med obremenjevanjem.

The tendency for delayed stresses in the 3-D model is reasonable, being caused by numerical difficulties already described. The negligible magnitude of bending stresses is shown both in the shell (outside, inside and middle layer) and the 3-D model (outside and inside surface).

4. CONCLUSIONS

Numerical analysis of the stress field around the crack tip provides very good results up to the onset of stable crack propagation. It also provides data about the size of the plastic zone and enables an estimation of the pressure which causes stable crack propagation. This pressure is about 55 % of the bursting pressure. A strong argument in favour of numerical model reliability is the very good agreement of stresses at the crack tip, regardless of the obvserver's position, showing appropriate mesh density in this region (shell model). Unfortunately, the Belgian experimental results do not explicitly report stable crack propagation before tube bursting. Since the simulation of the deformations in the vicinity of crack was very good, this is the only serious disagreement with the experimental results. The cause might be numerical difficulties, provided that the loading of 60 % of bursting presure represented the limit of the PAFEC-FE code capabilities. Confirmation of the numerical error thesis is possible via computer code upgrade, allowing for changes of geometry during loading.

Numerični model je bil potrjen tudi s primerjavo rezultatov obeh uporabljenih modelov z deformacijami cevi z razpoko, ki jih je izmeril Frederick s sodelavci [2]. Previsoki numerični rezultati pri izbočenju so posledica ohranjanja prvotne smeri delovanja tlaka, kar povzroča obremenitev, večjo od dejanske. V smeri odpiranja razpoke pa je iz istega razloga obremenitev manjša od dejanske. Kljub temu sta obe izračunani vrednosti zadovoljivo blizu izmerjenim.

Analiza je potrdila tudi obe glavni domnevi, uporabljeni pri določanju kritične dolžine razpoke; zanemarljiv vpliv upogibnih napetosti v vrhu razpoke na razvoj napetostnega polja in s tem na kritičnost razpoke ter prevlado mehanizma plastične porušitve nad krhkim lomom.

The quality of the numerical model was confirmed by a comparison of the results of the two models with experimental results reported by Frederick et al. [2]. Slight numerical overestimates of bulging are caused by the conservation of the initial pressure direction, generating overestimated loading. An underestimate of loading in the crack opening direction had a similar cause. However, both calculated values are in adequate agreement with the experiment.

Both major assumptions of the critical crack length determination were also confirmed: the negligible influence of crack tip bending stresses on stress field development and, consequently, the crack criticality, and the prevalence of net section collapse over brittle fracture.

5. UPORABLJENE OZNAČBE

a — polovična dolžina razpoke,
CTOD — odpiranje razpoke,
E — elastični modul,
K — faktor intenzivnosti napetosti,
k — faktor meje tečenja,
K_C — kritični faktor intenzivnosti napetosti,
m — faktor izbočenja (Foliasov faktor),
p — notranji (tudi diferenčni) tlak,
p_c — kritični tlak (tlak razpočenja),
R — srednji polmer cevi,
t — debelina stene cevi,
Φ — korekcijski faktor zaradi vpliva plastične cone okoli vrha razpoke,
λ — brezdimenzijski parameter razpoke,
ν — Poissonovo število,
σ — napetost,
σ_f — meja tečenja,
σ_M — natezna trdnost,
σ_y — meja plastičnosti,
σ_φ — obročna membranska napetost,
$\sigma_{\varphi,C}$ — kritična obročna membranska napetost.

5. NOMENCLATURE

a — crack half length,
CTOD — crack tip opening displacement,
E — modulus of elasticity,
K — stress intensity factor,
k — flow stress factor,
K_C — critical stress intensity factor,
m — bulging (Folias) factor,
p — internal (also differential) pressure,
p_c — critical (bursting) pressure,
R — tube mean radius,
t — tube wall thickness,
Φ — crack tip plastic zone correction factor,
λ — nondimensional crack parameter,
ν — Poisson ratio,
σ — stress,
σ_f — flow stress,
σ_M — ultimate tensile stress,
σ_y — yield stress,
σ_Φ — membrane hoop stress,
$\sigma_{\Phi,C}$ — critical membrane hoop stress.

6. ZAHVALA

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