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ODREĐIVANJE STEPENA SIGURNOSTI I FAKTORA POUZDANOSTI KOTLOVSKIH CEVI SA POVRŠINSKOM PRSLINOM

DETERMINATION OF SAFETY MARGIN AND RELIBILITY FACTOR OF BOILER TUBE WITH SURFACE CRACK

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Ključne reči
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- greška
- dijagram za procenu otkaza (FAD dijagram)
- SINTAP

Keywords
- pipe
- defect
- failure assessment diagram
- SINTAP

Izvod

U radu je korišćen postupak SINTAP nivo 1 za određivanje stepena sigurnosti i faktora pouzdanosti na cevima parnog kotla kod kojih je otkrivena uzdužna prslina u zavarenom spoju. Ovi stepeni su dobijeni pomoću metode verovatnoće SORM/FORM. Razmatra se i uticaj temperature na stepen sigurnosti i faktor pouzdanost.

Abstract

In this paper SINTAP Level 1 procedure has been used to determine the safety factor and the reliability factor for a boiler tube exhibiting a longitudinal defect inside the tube weld. These factors are obtained using probabilistic FORM/SORM methods. The influence of temperature on the safety and reliability of factors is discussed.

UVOD

Parni kotlovi, gasne turbine i peći su neki od sistema koji su u radu izloženi puzanju. Puzanje je proces koji se javlja na visokim temperaturama. Poznavanje ponašanja materijala na visokim temperaturama je od koristi u oceni ovog tipa otkaza sistema. Otkaz izazvan puzanjem uglavnom je lako identifikovati zahvaljujući deformaciji koja pri tom nastaje. Otkaz može biti duktilan ili krt. Prsline mogu da se šire transgranularno ili intergranularno. Ispitivanje puzanjem se izvodi pri konstantnoj temperaturi i konstantnom pritisku, dok se oštećenja komponente sistema mogu javljati pri različitim uslovima temperature i pritiska.

Premda je krajem 19. veka bilo mnogo otkaza parnih kotlova, nijedna država u to vreme nije imala propise za parne kotlove. Nesumnjivo jedan od najvažnijih otkaza na parnim kotlovima, koji je pokazao da je neophodno doneti zakon u toj oblasti, se dogodio 10. marta 1905. u fabrici obuće u Broktonu, Masačusets. Eksplozija je ubila 58 ljudi i povredila 117, a fabriku potpuno razorila. Ta katastrofa je pokrenula vlasti Masačusets da oforme telo od 5 članova za Pravila o kotlovima, čiji je zadatak bio da napišu Pravilnik o parnim kotlovima, koji su objavili 1908. godine. Država Ohajo je 1911. godine prihvatila taj pravilnik. Prvi Propis o

INTRODUCTION

Boilers, gas turbine engines and ovens are some of the systems which have components exposed to creep. Creep occurs under load at high temperature. An understanding of high temperature material behaviour is beneficial in evaluating these types of system failures. Failures involving creep are usually easy to identify due to the deformation that occurs. Failures may appear ductile or brittle. Cracking may be either transgranular or intergranular. While creep testing is done at constant temperature and constant load, system components may experience damage at various temperatures and loading conditions.

Although there were numerous boiler failures in the late 19^{th} century, there were no legal codes for boilers in any state at this time. Undoubtedly, one of the most important failures that proved the need for developing boiler laws was the boiler failure in Brockton, Massachusetts, on March 10, 1905, at the Brockton Shoe Factory. An explosion resulted in 58 deaths and 117 injuries, and completely destroyed the factory. It was this catastrophe that gave Massachusetts the impetus in 1906 to establish a five-man Board of Boiler Rules, whose charge was to write a boiler law; and they published it in 1908. In 1911, the State of Ohio accepted a parnim kotlovima i posudama pod pritiskom (izdanje 1914) je izdat 1915; to je knjiga od 114 strana dimenzija 5×8 inča. Danas postoji 28 knjiga, uključujući desetak posvećenih izgradnji i inspekcijama u radu komponenti nuklearnih postrojenja, kao i dve knjige nazvane Knjige pravila. Propis o parnim kotlovima i posudama pod pritiskom, izdanje iz 1998. ima preko 14 000 strana.

U uslovima kada je neophodno kritički ispitati integritet nove ili postojeće konstrukcije primenom metoda ispitivanja bez razaranja, neophodno je ustanoviti i nivo prihvatljivosti otkrivenih grešaka. U Postupku za ocenu integriteta konstrukcija (SINTAP), /1/, nivo prihvatljivosti grešaka baziran je na konceptu "pogodnosti za upotrebu". Po tom konceptu, svaka pojedinačna konstrukcija se smatra pogodnom za namenu ako se nisu stekli uslovi koji bi doveli do otkaza, dozvoljavajući u izvesnoj meri nenormalnu eksploataciju ili degradaciju. Potrebno je napraviti razliku između prihvatljivosti zasnovane na kontroli kvaliteta i prihvatljivosti zasnovane na pogodnosti za upotrebu. Postupak SINTAP se zasniva se na postupcima za ocenu integriteta konstrukcije tehnikama koje se koriste da bi se pokazala pogodnost za upotrebu opterećenih komponenti konstrukcija. One su od koristi u fazi projektovanja da bi se dala garancija za nove konstrukcije, naročito ako su uvedene inovacije u izboru materijala ili načinu izrade, kao i u fazi eksploatacije da bi se obezbedila sigurnost tokom veka konstrukcije. Značajan je i uticaj na ekonomski razvoj, osiguranjem kvaliteta tehničkih proizvoda i usluga. Ako se pravilno primene, mogu da povećaju efikasnost prikladnom konstrukcijom izbegavanjem predimenzionisanja i nepotrebnih inspekcija i popravki, ali isto tako mogu i da obezbede ravnotežu između ekonomskih interesa i brige za bezbednost pojedinca i zaštitu okoline tamo gde na to utiče otkaz komponente.

Mehanizmi otkaza koji se razmatraju su lom i plastični kolaps i kombinacija ova dva načina otkaza. Filozofski pristup sastoji se u tome da se kvalitet svih ulaznih podataka odražava na složenost i preciznost rezultujuće analize. Na raspolaganju je nekoliko nivoa, svaki sledeći sve složeniji i manje konzervativan od nižeg nivoa koji mu prethodi. Zbog hijerarhijske strukture podataka i nivoa procene, izbor puta kroz postupak je zasnovan na relativnom stepenu udela krtog loma i plastičnog kolapsa u ukupnom otkazu. Određene su kvalitativne i kvantitativne smernice, koje korisnika vode u pravcu koji će doneti najveću korist u pogledu poboljšanja podataka. Osnova za to je položaj početne tačke analize s obzirom na krti lom i plastični kolaps. Ovo se može proceniti ili pomoću dijagrama za procenu otkaza (FAD) ili pomoću dijagrama sile razvoja prsline (CDF). Ove metode se mogu primeniti pri određivanju prihvatljivosti datog skupa uslova, za određivanje vrednosti kritičnog parametra, za procenu stepena sigurnosti od otkaza ili za određivanje verovatnoće otkaza.

U ovom radu nivo 1 SINTAP postupka koristi se za određivanje stepena sigurnosti i stepena pouzdanosti kod kotlovskih cevi (sl. 1) sa podužnom greškom u zavarenom spoju korišćenjem determinističke i probabilističke metode. Razmotren je i uticaj temperature.

boiler law. The first Boiler and Pressure Vessel Code (1914 Edition) was published in 1915; it consisted of a 114-page book, measuring 5×8 inches. Today there are 28 books, including a dozen dedicated to the construction and in-service inspection of nuclear power plant components, and two Code Case Books. The 1998 edition of the Boiler and Pressure Vessel Code contains more than 14 000 pages.

In circumstances where it is necessary to examine critically the integrity of new or existing structures by use of non-destructive testing methods, it is also necessary to establish acceptance levels for the detected flaws. In Structural Integrity Assessment Procedure (SINTAP), /1/, acceptance levels for flaws are based on the concept of "fitness-for-purpose." According to this concept, a particular structure is considered adequate for its purpose, provided the conditions to cause failure are not reached, after allowing for some measure of abnormal use or degradation in service. A distinction has to be made between acceptance based on quality control and acceptance based on fitness-for-purpose. Procedure SINTAP is based on structural integrity assessment by the techniques used to demonstrate the fitness-for purpose of loaded engineering components. They are of value at the design stage to provide assurance for new constructions, particularly where these may be innovative in the choice of materials or fabrication methods, and at the operation stage to provide assurance throughout the life of the structure. They have important implications for economic development in assuring the quality of engineered goods and services. Used correctly, they can increase efficiency by preventing oversizing in design and unnecessary inspection and repair, but can also provide a balance between economy and concern for individual safety and environmental protection, where this is affected by component failure.

The failure mechanisms considered are fracture and plastic collapse, together with combinations of these failure modes. The philosophy of the approach is that the quality of all input data is reflected in the sophistication and accuracy of the resulting analysis. A series of levels is available, each of increasing complexity and each being less conservative than the preceding lower level. Due to the hierarchical structure of data and assessment levels, the selection path through the procedure is made based on the relative levels of contribution of brittle fracture and plastic collapse towards the overall failure. Qualitative and quantitative guidance is provided for the user in the most beneficial direction in data improvement terms. The basis for this is the location of the initial analysis point in terms of brittle fracture and plastic collapse. Either the Failure Assessment Diagram (FAD) or the Crack Driving Force (CDF) curve can assess this. The methods can be applied to determine the acceptability of a given set of conditions, determine the value of a critical parameter, assess the safety margins against failure or determine the probability of failure.

In this paper SINTAP Level 1 procedure has been used to determine the safety factor and the reliability factor for a boiler tube (Fig. 1) exhibiting a longitudinal defect inside the tube weld, applying deterministic and probabilistic methods. The influence of temperature is discussed.

METODA MONTE KARLO, FORM I SORM

Monte Karlo (MC) je jednostavna metoda koja koristi činjenicu da se integral verovatnoće otkaza može tumačiti kao srednja vrednost u stohastičkom eksperimentu. Ocena se daje usrednjavanjem odgovarajućeg velikog broja nezavisnih ishoda (simulacija) eksperimenta.

METHODS MONTE-CARLO, FORM AND SORM

Monte Carlo (MC) is a simple method that uses the fact that the failure probability integral can be interpreted as a mean value in a stochastic experiment. An estimate is therefore given by averaging a suitably large number of independent outcomes (simulations) of this experiment.

Slika 1. Primer kotla sa različitim cevima
Figure 1. Example of a boiler with different tubes.

Glavni aspekt ovog uzorkovanja je generisanje slučajnih brojeva po ravnomernoj raspodeli (između 0 i 1). Ovaj slučajan broj može da se koristi za dobijanje vrednosti željene proizvoljne promenljive za datu raspodelu. Ako se primeni funkcija kumulativne raspodele $F(X)$, slučajna promenljiva bi tada bila data kao:

The basic aspect of this sampling is the generation of random numbers from a uniform distribution (between 0 and 1). This random number can be used to generate a value of the desired random variable with a given distribution. Using the cumulative distribution function $F(X)$, the random variable would then be given as:

$$X = F_X^{-1}(u) \tag{1}$$

Zatim, za izračunavanje verovatnoće otkaza morao bi da se proceni multidimenzionalni integral:

Then, to calculate the probability of failure, a multi-dimensional integral has to be evaluated:

$$P_F = P_r\left[g(X) < 0\right] = \int\limits_{g(X)<0} f_x(x)dx \tag{2}$$

gde je $g(X)$ funkcija graničnog stanja, a $f_x(x)$ je poznata funkcija gustine verovatnoće slučajnog vektora X.

Da bi se izračunala verovatnoća otkaza, izvodi se N determinističkih simulacija i određuje da li je ispitivana komponenta otkazala (tj. da li je $g(X) < 0$) posle svake simulacije. Za izračunavanje broja otkaza N_F, procena srednje verovatnoće otkaza je:

where $g(X)$ is a limit state function and $f_x(x)$ is a known probability density function of the random vector X.

To calculate the failure probability, one performs N deterministic simulations and determines whether the component analysed has failed (i.e. if $g(X) < 0$) after every simulation. For a count of the number of failures, N_F, an estimate of the mean probability of failure is:

$$P_F = \frac{N_F}{N} \tag{3}$$

Prednost MC metode je u tome što je robusna, lako se uvodi u softver i za veličinu uzorka $N \to \infty$ procenjena verovatnoća teži tačnom rezultatu. Dalja prednost je da je MC metoda prikladna za bilo koju raspodelu proizvoljnih promenljivih. Nema ograničenja na funkcije graničnog stanja. Međutim, MC je prilično neefikasna metoda kada se proračunavaju vrlo male verovatnoće otkaza, jer je najveći udeo verovatnoće otkaza P_F u ograničenom delu metode transformacije intervala integraljenja. Ako ima mnogo slučajnih parametara, ovaj integral je teško (nemoguće) proceniti numeričkim integraljenjem.

The advantage with MC is that it is robust, easy to implement into software and for a sample size $N \to \infty$, the estimated probability converges to the exact result. Another advantage is that MC works with any distribution of random variables. There is no restriction on the limit state functions. However, MC is rather inefficient when calculating very low failure probabilities, since most of the contribution to P_F is in a limited part of the integration interval transform method. This integral is very hard (impossible) to evaluate by numerical integration if there are many random parameters.

Metode pouzdanosti prvog (FORM) i drugog (SORM) reda su opšte metode teorije pouzdanosti konstrukcija, /2/. Ove metode zasnivaju se na linearnoj (prvog reda) i kvadratnoj (drugog reda) aproksimaciji površine graničnog stanja $g(X) = 0$ koja tangira najbližu tačku površine na početku prostora. Određivanje ove tačke podrazumeva nelinearno programiranje.

Algoritmi FORM/SORM obuhvataju nekoliko koraka:

– U prvom koraku, prostor neizvesnih parametara x transformiše se u novi N-dimenzionalni u-prostor, koji se sastoji od nezavisnih standardnih Gausovih promenljivih. Prvobitno granično stanje $g(x) = 0$ se tada preslikava na novo granično stanje $g_u(u) = 0$ u u-prostoru.
– U drugom koraku, tačka na graničnom stanju $g_u(U) = 0$ sa najkraćim rastojanjem do početka u-prostora određuje se korišćenjem odgovarajućeg algoritma nelinearne optimizacije. Ova tačka naziva se projektna tačka ili β-tačka, i ima rastojanje β_{HL} do početka u-prostora (sl. 2).

U trećem koraku se granično stanje $g_u(u) = 0$ aproksimira pomoću površinske tangente na njemu u projektnoj tački. Neka su takva granična stanja $g_L(u) = 0$ i $g_Q(u) = 0$, što odgovara aproksimirajućim površinama hiperravni (linearna ili prvog reda) odnosno hiperparaboloida (kvadratna ili drugog reda).

Otuda se verovatnoća otkaza P_F aproksimira pomoću $P_r[g_L < 0]$ u FORM i $P_r[g_Q(u) < 0]$ u SORM postupku. Ove procene prvog i drugog reda $P_{F,1}$ i $P_{F,2}$ date su kao

First (FORM) and Second-Order Reliability Methods (SORM) are general methods of structural reliability theory, /2/. These methods are based on linear (first-order) and quadratic (second-order) approximations of the limit state surface $g(X) = 0$ tangent to the closest point of the surface to the origin of space. The determination of this point involves nonlinear programming.

The FORM/SORM algorithms involve several steps.

– In the first step, the space of uncertain parameters x is transformed into a new N-dimensional space u consisting of independent standard Gaussian variables. The original limit state $g(x) = 0$ then becomes mapped onto the new limit state $g_u(u) = 0$ in the u space.
– In the second step, the point on the limit state $g_u(U) = 0$ having the shortest distance to the origin of u space is determined using an appropriate nonlinear optimization algorithm. This point is referred to as the design or β-point, and has a distance β_{HL} to the origin of the u space (Fig. 2).

In the third step, the limit state $g_u(u) = 0$ is approximated by a surface tangent to it at the design point. Let such limit states be $g_L(u) = 0$ and $g_Q(u) = 0$, which correspond to approximating surfaces of hyperplane (linear or first-order) and hyperparaboloid (quadratic or second-order), respectively.

The probability of failure P_F is thus approximated by $P_r[g_L < 0]$ in FORM and $P_r\ [g_Q(u) < 0]$ in SORM. These first- and second-order estimates $P_{F,1}$ and $P_{F,2}$ are given by

$$
\begin{aligned}
P_{F,1} &= \phi(-\beta_{HL}) \\
P_{F,2} &\approx \phi(-\beta_{HL}) \prod_{i=1}^{N-1} (1-\kappa_i \beta_{HL})^{-1/2}
\end{aligned}
\tag{4}
$$

Ovde je

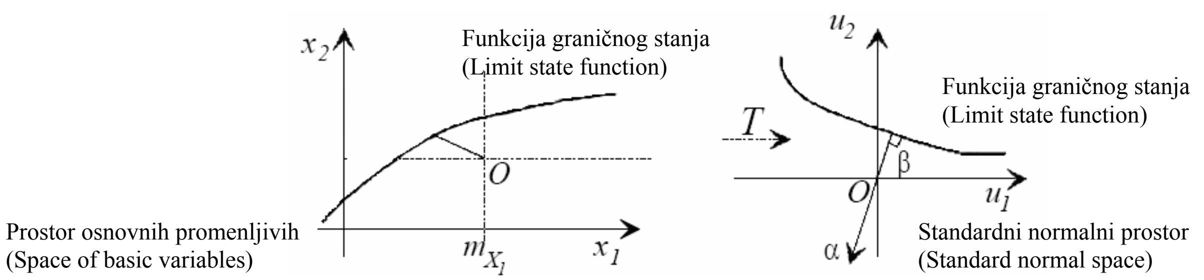
$$\phi(u) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{u} \exp(-\frac{1}{2}\xi^2) d\xi$$

funkcija kumulativne raspodele standardne Gausove slučajne promenljive, a k_i' su glavne krivine na površini graničnog stanja u projektnoj tački. FORM/SORM metode su analitičke metode za izračunavanja verovatnoće. Svaka ulazna slučajna promenljiva i funkcija osobine $g(x)$ mora biti kontinualna.

Here

$$\phi(u) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{u} \exp(-\frac{1}{2}\xi^2) d\xi$$

is the cumulative distribution function of a standard Gaussian random variable, and k_i' are the principal curvatures of the limit state surface at the design point. FORM/SORM are analytical probability computation methods. Each input random variable and the performance function $g(x)$ must be continuous.



Slika 2. Osnovni principi metode pouzdanosti prvog (FORM) i drugog (SORM) reda
Figure 2. Basic principal of the First-(FORM) and Second-Order Reliability Methods (SORM)

SINTAP DIJAGRAM ZA PROCENU OTKAZA (FAD)

U bilo kom dijagramu za procenu otkaza (FAD), svaki vid loma (krti lom, elastoplastični lom ili plastični kolaps) predstavljen je tačkom za procenu čije su koordinate bezdimenzionalne veličine primenjenog opterećenja L_τ i primenjene sile razvoja prsline k_r: $[L_r,k_r]$ na sl. 3.

SINTAP FAILURE ASSESMENT DIAGRAM (FAD)

In any failure assessment diagram (FAD) any kind of rupture (brittle fracture, elastic plastic failure or plastic collapse) is represented by an assessment point with coordinates of non-dimensional values of applied load L_r and of applied crack driving force k_r: $[L_r,k_r]$ in Fig. 3.

Bezdimenzionalna sila razvojne prsline k_r prvobitno je definisana kao odnos faktora intenziteta napona i žilavosti loma materijala K^*_c.

Non-dimensional crack driving force k_r was initially defined as the ratio of applied stress intensity factor over fracture toughness of the material K^*_c.

$$k_\gamma = \frac{K_{app}}{K_c^*} \quad (5)$$

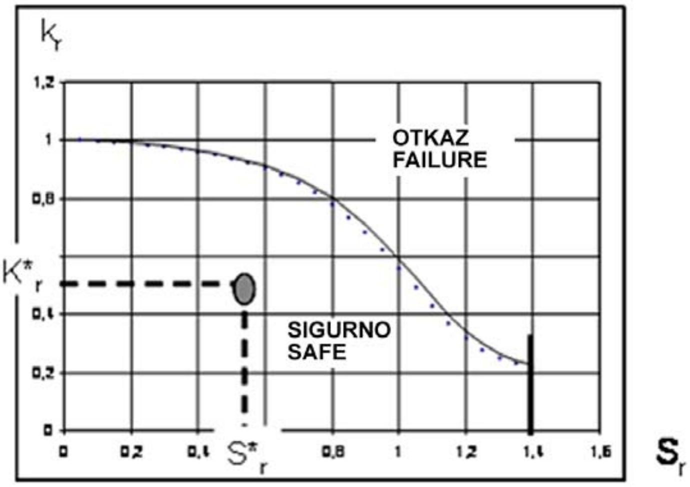
Ako bi se ovaj izraz proširio, može se definisati iz J-integrala ili otvaranja prsline:

In the extended form, this can be defined from the J integral or crack opening displacement:

$$k_r = \sqrt{\frac{J_{app}}{J_{mat}}} \; ; \; k_r = \sqrt{\frac{\delta_{app}}{\delta_c}} \quad (6)$$

u kojoj su J_{app} i δ_{app} veličine primenjenih J-integrala i otvaranja prsline, a J_{mat} i δ_c odgovarajuća žilavost loma materijala.

where J_{app} and δ_{app} are values of the applied J integral and crack opening displacement and J_{mat} and δ_c are corresponding fracture toughness of the material.



Slika 3. Dijagram za procenu otkaza; definisanje sigurne oblasti neke tačke u konstrukciji

Figure 3. Failure assessment diagram; definition of the safe domain and the assessment point of the component or structure.

Bezdimenzionalni napon S_r je odnos ukupnog napona σ_g i napona tečenja R_c (odabranog kao napon tečenja σ_y, zatezna čvrstoća R_m ili napon ojačavanja $R_c = (\sigma_y+R_m)/2$.

Non dimensional stress S_r is the ratio of the gross stress σ_g over flow stress R_c (chosen as yield stress σ_y, ultimate stress R_m or flow stress $R_c = (\sigma_y+R_m)/2$.

$$S_r = \frac{\sigma_g}{R_c} \quad (7)$$

Bezdimenzionalno opterećenje L_r definiše se kako sledi:

Non-dimensional load L_r is defined as follows:

$$L_r = \frac{P}{P_L} \quad (8)$$

P je primenjeno opterećenje, a P_L granično opterećenje.

Kritične tačke za procenu otkaza leže na krivoj interpolacije $k_r = f(S_r)$ između dve tačke koje predstavljaju dva referentna kritična stanja: krti lom [$k_r = 1$; $S_r = 0$]; plastični kolaps [$k_r = 0$; $S_r = 1$].

Tačka procene opterećene komponente predstavljena je tačkom koordinata k_r* i S_r*. Ako je ova tačka ispod krive interpolacije, konstrukcija je sigurna. Ako nije, dolazi do otkaza i radna tačka nalazi se na krivoj interpolacije ili iznad nje.

U literaturi se nude brojne krive interpolacije za FAD. Najširu praktičnu primenu imaju postupci EPRI, R6, SIN–TAP i RCC MR. SINTAP procedura, /1/, je organizovana na hijerarhijski način, i sastoji se od različitih nivoa analize grupisanih na osnovu kvaliteta i kompletnosti zahtevanih ulaznih informacija. Viši nivoi su napredniji od nižih nivoa

P is the applied load and P_L the limit load.

Critical points for failure assessment are located on interpolation curve $k_r = f(S_r)$ between points representing two reference limit states: brittle fracture [$k_r = 1$; $S_r = 0$]; plastic collapse [$k_r = 0$; $S_r = 1$].

The assessment point of a loaded component is represented by a point of coordinates k_r* and S_r*. If this point is below the interpolation curve; the structure is safe. If not, failure occurs, and the working point is situated on the interpolation curve or above it.

Numerous FAD interpolation curves have been proposed in literature. Actually, EPRI, R6, SINTAP and RCC MR methods are the most widely used. The SINTAP procedure, /1/, is structured in a hierarchical manner consisting of various analysis levels constituted by the quality and completeness of the required input information. Higher levels are i zahtevaju složenije ulazne podatke, ali daju manje konzervativne rezultate.

Prvi nivo ili zadati nivo

Traži se samo čvrstoća popuštanja. Žilavost loma može se proceniti na konzervativan način, na osnovu podataka dobijenih na Šarpi klatnu. Kriva interpolacije za bezdimenzionalno opterećenje data je jednačinom

more advanced than lower levels and they need more complex input but lead to less conservative results.

Level 1 or default level

Only the yield strength of the material is required. Fracture toughness can be conservatively estimated from Charpy data. The interpolation curve in terms of non-dimensional load is given by:

$$f\left(L_r\right)=\frac{1}{\sqrt{\left[1+\frac{L_r^2}{2}\right]}}\left[0.3+0.7\exp\left(-0.6L_r^6\right)\right] \;;\; 0\le L_r\le L_{r,\max} \tag{9}$$

$$L_{r,\max}=1+\left[\frac{150}{\sigma_y}\right]^{2.5} \tag{10}$$

Zadati nivo karakteriše činjenica da žilavost loma nije poznata, već se procenjuje na osnovu gornjeg platoa Šarpi energije KV (izražene u J), pomoću sledeće formule:

The default level is characterized by the fact that the fracture toughness is not known but estimated from upper shelf Charpy energy KV (in J) by the following formula:

$$K_{mat}=K_{j,0.2}=\sqrt{\frac{E\left(0.53KV^{1.28}\right)0.2^{0.133KV^{0.256}}}{1000\left(1-\nu^2\right)}} \tag{11}$$

Drugi nivo ili osnovni nivo

Za ovaj nivo traže se žilavost loma, napon tečenja i zatezna čvrstoća materijala.

Level 2 or basic level

Fracture toughness, yield strength and ultimate strength of the material are required for this level.

$$f\left(L_r\right)=\frac{1}{\sqrt{\left[1+\frac{L_r^2}{2}\right]}}\left[0.3+0.7\exp\left(-\mu L_r^6\right)\right] \;;\; 0\le L_r\le 1 \tag{12}$$

$$\mu=\min\left\{\left(0.001\,E/\sigma_y\right),(0.6)\right\} \tag{13}$$

$$f\left(L_r\right)=f\left(L_r=1\right)L_r^{(N-1/2N)} \;;\; 1\le L_r\le L_{r,\max} \tag{14}$$

$$N=0.3\left[1-\frac{\sigma_y}{R_m}\right] \tag{15}$$

$$L_{\max}=\frac{1}{2}\left[\frac{\sigma_y+R_m}{\sigma_y}\right] \tag{16}$$

Treći nivo ili napredni nivo

Za ovaj nivo traže se žilavost loma i kompletna kriva napon-deformacija.

Level 3 or advanced level

The fracture toughness and the complete stress strain curve of the material are required.

$$L_r=\sqrt{\left[\frac{E\varepsilon_{ref}}{\sigma_{ref}}+\frac{1}{2}\frac{L_r^2}{\left(E\varepsilon_{ref}/\sigma_{ref}\right)}\right]} \;;\; 0\le L_r\le L_{r,\max} \tag{17}$$

$$L_{r,\max}=\frac{R_c}{\sigma_y} \tag{18}$$

$$R_c=\frac{\sigma_y+R_m}{2} \tag{19}$$

$f(L_r)$ je neprekidna funkcija, koja sledi krivu stvarni napon-stvarna deformacija kao

$f(L_r)$ is a continuous function which follows the true stress-strain curve as

$$\sigma_{ref}=L_r\sigma_y \tag{20}$$

FAKTORI SIGURNOSTI I POUZDANOSTI

Do 19. veka sve konstrukcije bile su projektovane i izvedene uglavnom na empirijski način. Uvođenje čelične konstrukcije podrazumevao je dalji razvoj čvrstoće materijala. U početku usvojeni princip sigurnosti sastojao se u tome da se osigura da maksimalan napon u najkritičnijem delu konstrukcije bude manji od radnog opterećenja *L*, dobijenog deljenjem otpornosti materijala *R* konvencionalno usvojenim faktorom sigurnosti *K*.

SAFETY AND RELIABILITY FACTORS

Until the 19th century, all structures were conceived and carried out mainly in an empirical way. The introduction of the steel construction required development of strength of materials. The initially adopted principle of safety consisted in making sure that the maximal stress in the most critical section of structure remained lower than the working load *L* obtained by dividing the resistance of the material *R* by conventionally accepted safety factor *K*.

$$F \leq \frac{R}{K} \tag{21}$$

Ovakav pristup utvrđivanja sigurnosti trajao je gotovo ceo jedan vek. Stepen sigurnosti obezbeđuje kvalitativno merenje verovatnoće loma koja se smatra eksperimentalno prihvatljivom.

Inženjeri su postepeno shvatali nedostatke takvog pristupa projektovanju, što je doprinelo razvoju koncepta pouzdanosti na pristupu verovatnoće. Prema novom pristupu, konstrukcija se smatra sigurnom ako je verovatnoća njenog otkaza manja od konvencionalno usvojene vrednosti, vrednosti koja zavisi od mnogih faktora kao što su očekivani vek konstrukcije, posledice koje nastaju njenim otkazom, rizici od zastarelosti, merodavni ekonomski kriterijumi kao što su troškovi zamene, održavanja.

Umesto da se stepen sigurnosti propiše na osnovu čvrstoće materijala ili opterećenja ili veličine greške ili za sve zajedno, pristup verovatnoće uvodi faktor pouzdanosti kao kvantitativni kriterijum male verovatnoće loma.

Stepen sigurnosti dobijen determinističkom metodom

Za determinističku metodu stepen sigurnosti može se definisati na dijagramu analize otkaza (FAD), polazeći od pretpostavke da se greška neće povećavati pod uticajem delujućeg opterećenja. Na sl. 4 je prikazano da se stepen sigurnosti može definisati na radijalnoj pravoj liniji u obliku odnosa F_s = OB/OA.

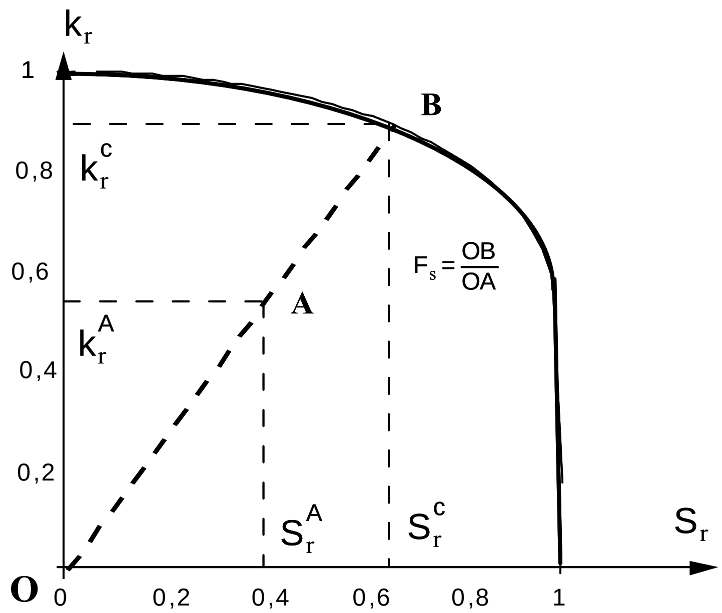
This approach in considering safety lasted nearly a century. The safety factor provides a qualitative measurement of a probability of rupture judged like acceptable by the experiment.

The engineers realized gradually the disadvantage of this design approach and this contributed development of the reliability concept based on a probabilistic approach. According to the new approach, a structure is considered safe if probability of its failure is lower than a conventional accepted value, a value that depends on many factors like the expected life of the structure, consequences generated by its failure, risks of obsolescence, relevant economic criteria like costs of replacement, maintenance costs.

Instead of imposing a safety factor based on the resistance of material, or on load, or on defect size, or all three, the probabilistic approach introduces the reliability factor as a quantitative criterion of low failure probability.

Safety factor obtained by the deterministic method

The safety factor can be defined from the Fracture Analysis Diagram (FAD) for the deterministic method, starting with the assumption that the defect will not extend under applied loading. It is presented in Fig. 4 that the safety factor can be defined on the radial straight line in the form of ratio F_s = OB/OA.



Slika 4. Definisanje faktora sigurnosti u dijagramu analize otkaza (FAD)
Figure 4. Definition of safety factor in failure analysis diagram (FAD).

Faktor pouzdanosti dobijen determinističkom metodom

Oblast pouzdanosti dobija se deljenjem jednačine krive interpolacije sa faktorom sigurnosti čija je vrednost konvencionalna (obično 2). Za opterećenja po radijalnoj pravoj liniji faktor pouzdanosti se definiše kao F_s = OB/OA.

Faktor sigurnosti dobijen probabilističkom metodom

Kriva interpolacije data rutinom nivoa 1 SINTAP-a:

Reliability factor obtained by deterministic method

The reliable domain is obtained by dividing the equation of the interpolation curve by a safety factor whose value is conventional (generally 2). For a radial loading path the reliability factor is defined as F_s = OB/OA.

Safety factor obtained by probabilistic method

The interpolation curve given by SINTAP level 1 routine:

$$f\left(L_r\right) = \sqrt{\left[1+\frac{L_r^2}{2}\right]}\left[0.3+0.7\exp\left(-0.6L_r^6\right)\right] \tag{22}$$

odnosi se na verovatnoću otkaza $P_f = 1$, što odgovara izvesnosti otkaza. Otuda je probabilistički faktor sigurnosti identičan determinističkom.

is related to a failure probability $P_f = 1$, which corresponds to a certainty of failure. The probabilistic safety factor is thus identical to the deterministic safety one.

OSOBINE MATERIJALA I GEOMETRIJSKI OBLIK CEVI I GREŠKE

Cevi su izrađene od čelika za kotlovske cevi čije su zatezne karakteristike (napon tečenja $R_{p0,2}$ i zatezna čvrstoća R_m) i žilavost loma pri ravnoj deformaciji K_{Ic} za 5 različitih temperatura date u tab. 1.

Kotlovska cev ima spoljni prečnik 273 mm i debljinu zida 24 mm. Cev je sučeono zavarena i pretpostavljeno je da se u zavarenom spoju nalazi podužna polueliptična površinska greška (dubina a = 2,25 mm, dužina $2c$ = 15 mm i njihov odnos $a/2c$ = 0,15).

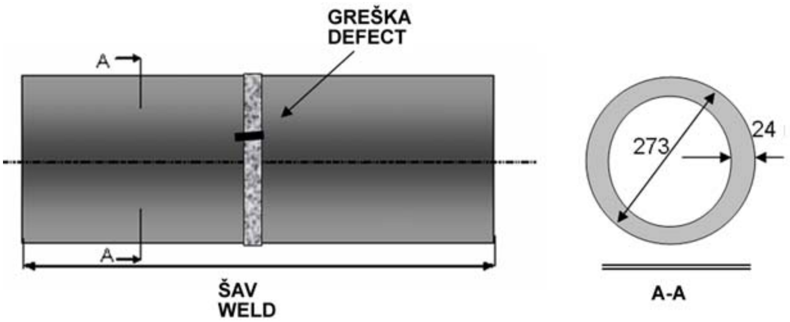
MATERIAL PROPERTIES AND GEOMETRIES OF THE TUBE AND DEFECT

Tubes are made of boiler tube steel with tensile properties (yield strength $R_{p0,2}$ and ultimate tensile strength R_m) and plane strain fracture toughness K_{Ic} at 5 different temperatures, given in Table 1.

The boiler tube has an external diameter of 273 mm and a wall thickness of 24 mm. The tube is butt-welded and it is assumed that the welded joint contains a longitudinal semi-elliptical surface crack (depth a = 2.25 mm, length $2c$ = 15 mm and aspect ratio $a/2c$ = 0.15).

Tabela 1. Mehaničke karakteristike čelika cevi na različitim temperaturama
Table 1. Mechanical properties of tube steel at different temperatures.

Temperatura	Temperature	T	°C	20	400	520	540	560
Napon tečenja	Yield strength	$R_{p0,2}$	MPa	380	275	275	255	240
Zatezna čvrstoća	Ultimate tensile strength	R_m	MPa	500	470	420	400	380
Žilavost loma pri ravnoj deformaciji	Plane strain fracture toughness	K_{Ic}	MPa√m	167.1	160.7	117.9	106.5	94.1



Slika 5. Dimenzije cevi i položaj prsline u zavarenom spoju
Figure 5. Tube dimensions and crack position in welded joint.

Pod dejstvom unutrašnjeg pritiska se u cevi uspostavlja obimni napon od 77 MPa. Faktor intenziteta napona za polueliptičnu površinsku grešku dat je u SINTAP kodu u sledećem obliku:

Under the effect of internal pressure the hoop stress of 77 MPa is produced in the tube. The stress intensity factor for a semi-elliptical surface crack is given in code SINTAP in the following form:

$$K_I = \frac{PR_m}{t}\sqrt{\pi a}\; F\left(\frac{R_i}{t},\frac{2c}{a},\frac{a}{t}\right) \tag{23}$$

R_i je unutrašnji poluprečnik cevi, t je debljina zida cevi i R_m srednji poluprečnik cevi.

Vrednost geometrijske korekcije ove greške jednaka je

R_i is the internal radius; t is the wall thickness of the tube and R_m its mean radius.

The value of geometrical correction for this defect equals

$$F\left(\frac{R_i}{t},\frac{2c}{a},\frac{a}{t}\right) = 1,445 \tag{24}$$

Mala promena a prouzrokuje malu promenu F, i zbog toga se u ovom ispitivanju F smatra konstantom.

PRIMENA SORM I FORM METODA U SINTAP DIJAGRAMU

U okviru odabrane procedure, sledeći parametri smatraju se slučajno raspoređenim:
- žilavost loma,
- napon tečenja,
- zatezna čvrstoća,
- greške, i
- pritisak.

Smatra se da ovi proizvoljni parametri nisu u međusobnoj zavisnosti. Parametri mogu da povinuju normalnu, log-normalnu, Vajbulovu ili neku specijalnu raspodelu (za greške). Koeficijent varijacije CV_x je odličan pokazatelj homogenosti analizirane veličine. Ova će biti homogena ako je $CV < 1/3$, s obzirom na osobine materijala, ako se mehanička ispitivanja pažljivo sprovedu. Koeficijent varijacije je takođe odličan pokazatelj kvaliteta izrade; tako za proizvodnju niskougljeničnog čelika odgovara koeficijent varijacije $CV = 0,1$ za zateznu čvrstoću, napon tečenja i žilavost loma. Raspodela pritiska sledi isti koeficijent varijacije. Treba napomenuti da se za eksponencijalnu raspodelu, koeficijent varijacije obavezno uzima kao jedinica. Metoda će biti prikazana sa odgovarajućom vrednošću koeficijenta varijacije.

Žilavost loma

Pretpostavljeno je da žilavost loma sledi Vajbulovu raspodelu. Vajbulova funkcija gustine verovatnoće ima sledeći oblik:

A small change in a produces only a small change in F, thus considering F a constant in the present study.

THE APPLICATION OF SORM AND FORM METHODS IN SINTAP DIAGRAM

The following parameters are treated as randomly distributed within the chosen procedure:
- fracture toughness,
- yield strength,
- ultimate tensile strength,
- defects, and
- pressure.

These randomly distributed parameters are treated as not correlated with each other. The parameters can follow normal, log-normal, Weibull or some special distribution (for defects). The variation coefficient CV_x is an excellent indicator of homogeneity in the analysed property. It is homogeneous if $CV < 1/3$ regarding material properties, and if mechanical tests are carried out carefully. The variation coefficient is also an excellent indicator of manufacturing quality; thus for manufacturing low carbon steel the corresponding coefficient of variation is $CV = 0.1$ for ultimate strength, yield strength and fracture toughness. The pressure distribution obeys to same variation coefficient. It is to note that for exponential distribution the variation coefficient is necessarily taken as unity. The method will be presented with the corresponding variation coefficient value.

Fracture toughness

The fracture toughness is assumed to obey Weibull's distribution. Weibull's probability density function has the following form:

$$f(K_{Ic}) = C \cdot m \cdot K_{\rho,c}^{m-1} \exp(-CK_{\rho,c}^{m}) \tag{25}$$

gde su C (razmera) i m (oblik) Vajbulovi parametri raspodele. Ulazni podaci za ovaj program su srednje (μ) i standardno (σ) odstupanje i oni su povezani su sa Vajbulovim parametrima raspodele kako sledi:

where C (scale) and m (shape) are the Weibull distribution parameters. Input data for the program are mean (μ) and standard (σ) deviations and they are related to the Weibull distribution parameters as follows:

$$\mu = \frac{C^{-1}}{m\Gamma\left(1+\frac{1}{m}\right)}$$
$$\sigma = C^{\frac{-2}{m}}\left[\Gamma\left(1+\frac{2}{m}\right) - \Gamma^{-2}\left(1+\frac{1}{m}\right)\right] \tag{26}$$

gde je $\Gamma(Z)$ gama funkcija, definisana sledećim integralom:

where $\Gamma(Z)$ is the gamma function, defined by the integral:

$$\Gamma(Z) = \int_0^\infty t^{Z-1} e^{-t} dt \tag{27}$$

Ovaj sistem nelinearnih jednačina rešava se primenom globalno konvergentne metode sa linijskim traženjem i aproksimativnom Jakobijanskom matricom.

Napon tečenja, zatezna čvrstoća i pritisak

Napon tečenja, zatezna čvrstoća i unutrašnji pritisak se uglavnom predstavljaju normalnom raspodelom. Normalna funkcija gustine verovatnoće ima sledeći oblik:

This nonlinear equation system is solved using a globally convergent method with line search and an approximate Jacobean matrix.

Yield strength, ultimate tensile strength and pressure

Yield strength, ultimate tensile strength, and internal pressure are mainly presented as a normal distribution. The normal probability density function has the following form:

$$F(X) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{X-\mu}{\sigma}\right)\right] \tag{28}$$

Veličina greške

Načelno, eksponencijalna raspodela određuje u analizi veličinu greške, pa i njenu dubinu a. Shodno tome, funkcija gustine verovatnoće ima sledeći oblik:

Defect size

The exponential distribution generally governs for defect size analysis, including its depth a. Consequently, the probability density function has the following form:

$$F(X) = \lambda \exp(-\lambda a) \tag{29}$$

gde je λ parametar eksponencijalne distribucije. Srednje (μ) i standardno (σ) odstupanje su povezani sa λ kao:

where λ is the exponential distribution parameter. Mean (μ) and standard (σ) deviations are related to λ as:

$$\mu = \sigma \frac{1}{\lambda} \tag{30}$$

Uzeto je da je veličina koeficijenta varijacije ovog čelika $CV = 0{,}1$. Srednje veličine su date u tab. 1.

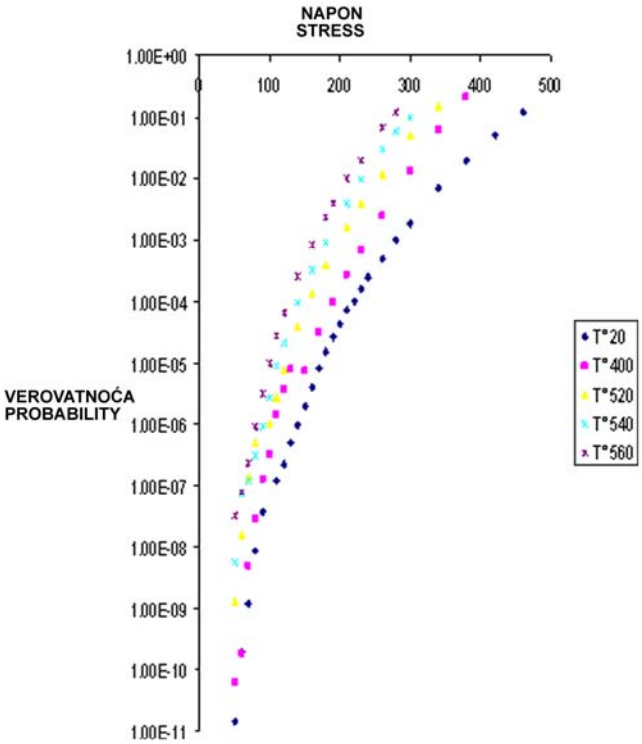
It is assumed that the value of variation coefficient of this steel is $CV = 0.1$. Mean values are given in Table 1.

Rezultati

Verovatnoća loma je proračunata korišćenjem metode FORM/SORM. Na sl. 6 dati su rezultati za verovatnoću loma prema naponima za temperature od 20 do 560°C.

Results

The failure probability is calculated using FORM/SORM methods. Results for failure probability depending on stress for temperatures of 20 to 560°C are given in Fig. 6.



Slika 6. Promena verovatnoće otkaza u zavisnosti od napona za pet različitih temperatura
Figure 6. Evolution of failure probability vs. stress for five different temperatures.

Slika 6 pokazuje da se verovatnoća otkaza smanjuje sa porastom temperature pri konstantnom naponu. Tabela 2 prikazuje napone loma za verovatnoću otkaza 10^{-6} za različite temperature.

Figure 6 shows that the failure probability decreases with increasing temperature at constant stress. Table 2 presents fracture stresses for failure probability of 10^{-6} at different temperatures.

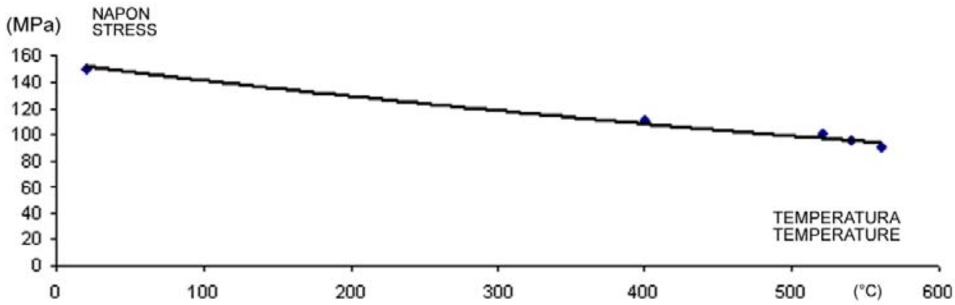
Tabela 2. Veličina napona loma koji odgovara verovatnoći otkaza $P_f = 10^{-6}$ u zavisnosti od temperature
Table 2. The magnitude of fracture stress corresponding to failure probability of $P_f = 10^{-6}$ depending on the temperature.

Napon loma	Fracture stress	MPa	150	110	100	95	90
Temperatura	Temperature	°C	20	400	520	540	560

Promena napona loma sa temperaturom data je na sl. 7. Može se uočiti da se napon loma σ (MPa), koji odgovara verovatnoći loma $P_f = 10^{-6}$, smanjuje sa porastom temperature T (°C):

The evolution of fracture stress with temperature is given in Fig. 7. One can see that the stress fracture σ (MPa) corresponding to failure probability $P_f = 10^{-6}$, decreases with temperature T (°C) increase:

$$\sigma = 153.9e^{-0.0009T} \tag{31}$$



Slika 7. Promena napona loma koja odgovara verovatnoći otkaza $P_f = 10^{-6}$ sa temperaturom
Figure 7. Evolution of fracture stress corresponding to probability of failure $P_f = 10^{-6}$ with temperature.

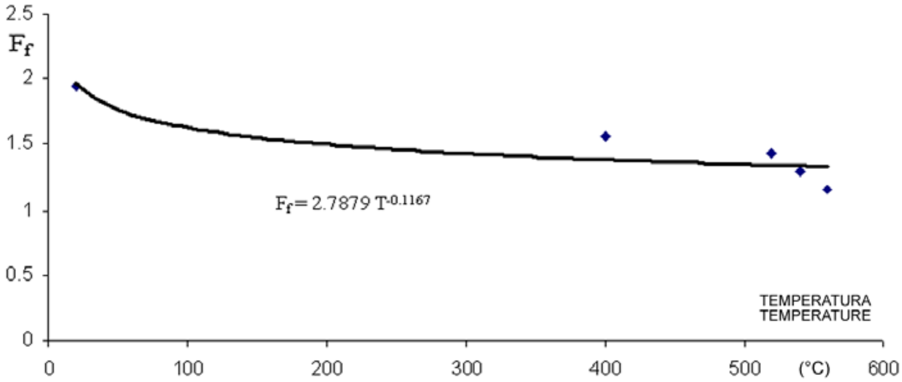
DISKUSIJA

Iz dobijenih rezultata može se odrediti faktor pouzdanosti F_f, koji se smanjuje sa porastom temperature T (sl. 8) prema sledećoj jednačini:

DISCUSSION

From the obtained results it is possible to find the reliability factor F_f which decreases with increasing temperature T (Fig. 8) according to the following equation:

$$F_f = 2.7879T^{-0.1167} \quad (32)$$



Slika 8. Promena faktora pouzdanosti F_f sa temperaturom
Figure 8. Evolution of the reliability factor F_f with temperature.

Promena faktora pouzdanosti F_f za polueliptičnu površinsku grešku u cevi izloženoj unutrašnjem pritisku u zavisnosti od stepena sigurnosti F_s data je jednačinom:

Evolution of the reliability factor F_f for a semi-elliptic surface defect in a tube submitted to internal pressure with the safety factor F_s is given by the equation:

$$F_f = 0.3895e^{0.2604F_s} \quad (33)$$

Faktor pouzdanosti F_f predstavlja poverenje u vrednost veličine greške. Za konvencionalnu verovatnoću otkaza i za srednju vrednost napona σ, dozvoljena veličina greške je a_{ad}. Tačka procene zavisi od raspodele greške sa srednjom vrednošću a^*.

Relativna razlika veličine greške je:

The reliability factor F_f represents the confidence in the defect size value. For a conventional failure probability and for a mean stress value σ, the admissible defect size is a_{ad}. The assessment point is relative to a defect distribution with a mean value of $a*$.

The relative difference of defect size is:

$$\Delta a_{rel} = \frac{|a_{ad} - a*|}{a_{ad}} \cdot 100 \quad (34)$$

Ova razlika je vrlo osetljiva na faktor pouzdanosti f_f i povećava se prema eksponencijalnom zakonu

This difference is very sensitive to reliability factor f_f and increases according to a power law

$$\Delta a_{rel} = 2.4 f_f^{0.2} \quad (35)$$

To znači da je za faktor pouzdanosti f_f manji od 1,5 dozvoljena greška za srednju vrednost veličine greške manja od 10%, da bi se garantovalo da će se dobiti konvencionalna vrednost verovatnoće otkaza. Za kontrolu kvaliteta faktor pouzdanosti je dobro sredstvo kada je povezan sa ispitivanjem bez razaranja (IBR).

This means that for a reliability factor f_f less than 1.5, the admissible error on the mean value of the defect size is less than 10% to guaranty that the conventional value of failure probability is reached. For quality control, the reliability factor is a good tool when associated with non-destructive testing (NDT).

ZAKLJUČAK

Sledeći parametri se tretiraju kao slučajno raspodeljeni kada se razmatraju tokom primene SORM/FORM metoda i postupka SINTAP:
– žilavost loma,
– čvrstoća popuštanja,
– kritična zatezna čvrstoća,
– raspodela grešaka,
– raspodela pritiska.

Oni omogućavaju da se utvrdi odnos verovatnoće otkaza i srednjeg obimnog napona za polueliptičnu površinsku grešku u cevi izloženoj unutrašnjem pritisku.

Srednja vrednost napona otkaza za konvencionalnu verovatnoću otkaza od 10^{-6} smanjuje se sa temperaturom.

Faktori sigurnosti i pouzdanosti dobijeni su prema modifikovanoj SINTAP proceduri. Ovi faktori se takođe smanjuju sa temperaturom.

Faktor pouzdanosti predstavlja poverenje u vrednost veličine greške. On je korisno sredstvo da se proceni osetljivost metode ispitivanja bez razaranja (IBR).

Ovaj rad je u skladu s savremenim trendom da se konstantni i deterministički stepen sigurnosti zameni probabilističkim faktorom sigurnosti koji uzima u obzir kontrolu kvaliteta i bolju procenu opterećenja komponenti.

ZAHVALNOST

Ovaj rad je podržan bilateralnim programom Pavle Savić između Francuske i Srbije N° 07927XE.

CONCLUSION

The following parameters are treated as randomly distributed when considered during application of SORM/FORM methods and SINTAP procedure:
– fracture toughness,
– yield strength,
– ultimate tensile strength,
– defects, and
– pressure.

They allow determining the failure probability versus mean applied hoop stress for a semi-elliptical surface defect in a tube submitted to internal pressure.

The mean value of the fracture stress for a conventional failure probability of 10^{-6} decreases with temperature.

Safety and reliability factors have been obtained according to a modified SINTAP procedure. These factors decrease also with temperature.

The reliability factor represents the confidence in the defect size value. It is a helpful tool to appreciate the sensitivity of the non-destructive testing (NDT) method.

This work is part of the actual trend to replace constant and deterministic safety factor by probabilistic safety factor that takes into account quality control and better estimation of loading of components.

ACKNOWLEDGEMENTS

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