

Analiza i optimizacija T-poprečnog preseka dizalične kuke razmatrane kao krivolinijski štap

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U ovom istraživanju predstavljene su analiza i optimizacija geometrijskih parametara T-poprečnog preseka dizalične kuke. Smanjenje površine poprečnog preseka dizalične kuke postavljeno je kao glavni cilj ovog istraživanja. Kao funkcije ograničenja uzeti su dozvoljeni naponi u karakterističnim tačkama poprečnog preseka dizalične kuke na najkritičnijem mestu konstrukcije kuke. Takođe, uzeta su i određena geometrijska ograničenja u drugom delu analize i optimizacije. Maksimalni naponi u karakterističnim tačkama računati su prema Vinkler-Bakovoj teoriji, gde je konstrukcija kuke tretirana kao krivolinijski štap.

Postupak optimizacije sproveden je korišćenjem pet algoritama optimizacije, primenom metode generalizovanog redukovano gradijenta (GRG2) i evolucionog algoritma (EA) u modulu Analysis, u Ms EXCEL softverskom paketu, kao i MATLAB softverskog paketa, primenom funkcija fmincon u okviru modula Optimization Toolbox i genetskog algoritma (GA), i korišćenjem algoritma optimizacije roja čestica (PSO).

Ključne reči: Kuka, Optimalno projektovanje, Naponi, Vinkler-Bakova teorija

1. UVOD

Dizalične kuke predstavljaju sredstva za vešanje i podizanje tereta velikih nosivosti, i sastavni su deo različitih tipova vitala. Dizalične kuke su jako odgovorne komponente i najčešće se primenjuju za manipulacijom teretom u industriji. Zbog svoje odgovornosti, dizalične kuke su adekvatno spojene za noseće sredstvo (uže ili lanac), tako da ispunjavaju sve potrebne uslove što se tiče zdravlja i bezbednosti na radu.

Manipulacija materijalom i teretima velike nosivosti je uglavnom prisutno na gradilištima, fabrikama i drugim industrijskim postrojenjima. Pravilnim korišćenjem opreme se može efikasno manipulirati teretima velike nosivosti i smanjiti operacije ručnog rukovanja. Nepravilnim korišćenjem opreme i dizaličnih kuka neadekvatne geometrije i karakteristika može da dovode do otkaza funkcije i velikih nesreća. Zato je pravilan izbor ove opreme od velikog značaja.

Optimizacija predstavlja proceduru gde se dobijaju najbolje vrednosti varijabli na osnovu zadatih funkcija ograničenja, za posmatranu funkciju cilja (objekta). Najzastupljenije su procedure optimizacije koje imaju za cilj da minimizuju ukupnu masu, površinu ili neki drugi specifični cilj (objekat).

Zbog svega gorenavedenog, prisutan je veliki broj radova koji se bave problematikom analize i optimizacije poprečnih preseka dizaličnih kuka.

Prilikom analize i optimizacije konstrukcije kuke, posmatraju se u svim slučajevima naponska stanja, dok se u određenim slučajevima uzimaju u obzir i deformacije, kao i zamor materijala.

Analiza naponskih stanja se najčešće vrši primenom MKE. U radu [1] izvršena je analiza naponskih stanja kuke tipičnog trapeznog poprečnog preseka primenom IDEAS softverskog paketa. Ovi rezultati su poređeni sa analitičkim, pri čemu je kuka posmatrana kao krivolinijski štap, pri čemu se dokazala opravdanost primene ovakvog analitičkog modela.

U radovima [2], [3] i [4] analizirani su različiti oblici punih poprečnih preseka, pri čemu je 3D model kuke generisan primenom softverskog paketa CREO, dok je analiza naponskih stanja izvršena primenom softverskog paketa ANSYS. U radu [5] analizirani su pravougaoni, trapezni, trougaoni i kružni poprečni presek konstrukcije kuke takođe primenom ANSYS softverskog paketa, dok je 3D model generisan primenom primenom softverskog paketa CATIA.

Slično prethodnom radu, primenom softverskih paketa CATIA i ANSYS, pored različitih punih poprečnih preseka, razmatran je i T-poprečni presek nosača kuke, [6]. U ovom radu su posmatrani i različiti materijali u analizi. T-poprečni presek je takođe razmatran i u radovima [7], [8], [9] i [10] korišćenjem softverskog paketa ANSYS za analizu naponskih stanja.

U radu [8] je izvršena komparativna analiza naponskih stanja za standardni trapezni poprečni presek nosača kuke, kao i za T i I poprečni presek. Modeliranje ovih nosača je izvršeno primenom softverskog paketa CATIA. Komparacija između T i I poprečnih preseka nosača kuke izvršena je u radu [10], pri čemu su 3D modeli generisani u SOLIDWORKS softverskom paketu. Slično prethodnom radu, u [9] je izvršena komparacija T-profila u odnosu na trapezni i kružni profil, a takođe su posmatrani i različiti materijali.

T-poprečni presek je optimizovan u radu [11], pri čemu je optimizacija izvršena sa stanovišta optimizacije oblika (shape optimization), pri čemu je ovde korišćen PSO metod optimizacije (metod roja čestica). Pomenuti PSO metod je uspešno primenjen i u radu [12], gde je izvršena strukturalna analiza i optimizacija jedne dizalične kuke.

Vrlo često se u kombinaciji sa MKE analizom kombinuju numerički metodi optimizacije, što je prikazano u prethodnom radu [12], a takođe i u radu [13]. U radu [13] je korišćen genetski algoritam (GA) u MATLAB softverskom paketu za optimizaciju geometrijskih parametara trapeznog poprečnog preseka kuke, dok je

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verifikacija dobijenih parametar izvršena u softverskom paketu ANSYS.

U radovima [7] i [14] je izvršena optimizacija poprečnih preseka konstrukcije kuke korišćenjem analitičkog postupka i određenih algoritama optimizacije. U radu [7] je izvršeno poređenje trapeznog poprečnog, koji je najčešće zastupljen, u odnosu na kružni, pravougaoni, trougaoni, T i I poprečni presek. Autori su prikazali algoritamsku šemu po kojoj je izvršena optimizacija.

U radu [14] je izvršena komparativna analiza i optimizacija različitih punih oblika poprečnog preseka na primeru jedne dizalične kuke. Posmatran je najkritičniji poprečni presek kuke u analizi. Pored tipičnih poprečnih preseka koji su zastupljeni, analizirani su parabolični i eliptični poprečni presek. Kao metodi optimizacije korišćen je metod Lagranževog množitelja sprovedena u MATHCAD softverskom paketu, kao i GRG2 metod optimizacije, u Ms EXCEL softverskom paketu. Ostvarena je znatna ušteda u poređenju sa standardnim rešenjem.

Potrebno je spomenuti da se pored uobičajnih metoda analize i optimizacije, u zadnje vreme koristi sve više i topološka optimizacija kod ovakvih tipova struktura, što je prikazano u radu [15].

Konačno, imajući u vidu sve gore navedeno, rezultate i značaj optimizacije ovih vrsta konstrukcija, glavni cilj ovog rada je analiza i optimizacija geometrijskih parametara T-poprečnog preseka dizalične kuke na njenom najkritičnijem mestu, na osnovu Vinkler-Bakove teorije.

2. ALGORITMI OPTIMIZACIJE

Procesi postupka optimizacije za ovakav inženjerski problem izvršen je primenom različitih numeričkih metoda (algoritama) optimizacije, korišćenjem programa Ms EXCEL i MATLAB.

GRG metod je jedan od klase tehnike nazvana generalizovani redukovani gradijent ili gradijent projekcija koji je zasnovan na proširenju metode za linearna ograničenja na primenu na nelinearna ograničenja. Ovim se podešavaju varijable tako da su aktivna ograničenja i dalje zadovoljena, i postupak se pomera od jedne tačke do druge. Metoda GRG se bazira na ideji eliminacije varijabli koristeći jednakost ograničenja. Ideja metoda generalisanog redukovanog gradijenta je da se pretvoriti problem ograničenja u jedan bez ograničenja korišćenjem direktne zamene. Ms EXCEL Solver Tool koristi metod generalisanog redukovanog gradijenta (GRG2 algoritam) za optimizaciju nelinearnih problema.

Evolucionni algoritam (EA) primenjuje principe evolucije koji se nalaze u prirodi na probleme pronalaženja optimalnog rešenja za datu funkciju cilja (objekat). U evolucionom algoritmu projektne varijable i problemske funkcije se koriste direktno. Kao i u prethodnom slučaju, Ms EXCEL Solver Tool koristi ovaj algoritam za optimizaciju nelinearnih problema.

$$[X, fval, exitflag, output, lambda, grad, hessian] = fmincon(fun, X0, A, b, Aeq, beq, lb, ub, nonlcon) \quad (5)$$

$$[X, fval, exitflag, output] = ga(fun, n, A, b, Aeq, beq, lb, ub, nonlcon) \quad (6)$$

gde su prikazana pojašnjenja MATLAB funkcija:
fval - vrednost funkcije cilja pri rešavanju,
exitflag - pokazuje razlog prekida izvršavanja rešavanja,
fun - funkcija cilja,

MATLAB Optimization Toolbox se može koristiti kako za linearne, tako i za nelinearne inženjerske probleme. Optimizacija parametara se vrši korišćenjem funkcije *fmincon*, [16].

Slično prethodnom, korišćen je u MATLAB-u i genetski algoritam (GA), primenom funkcije *ga*, [17]. Prednosti genetskog algoritma su jednostavni proračun, jaka robusnost, slučajnost i celovitost. Ovaj algoritam optimizacije ima veliku primenu u inženjerskoj praksi.

Metod optimizacija roj čestica (PSO), [18] je bio globalni stohastički algoritam i njegova ideja zasnivala se na simulaciji pojednostavljenih društvenih modela. PSO je nezavisan od matematičkih karakteristika problema objekta (funkcije cilja) i uspešno se primenjuje u različitim oblastima, uglavnom zbog neograničenih kontinualnih problema optimizacije, jednostavnog koncepta, jednostavne implementacije i brze konvergencije.

3. MATEMATIČKA FORMULACIJA OPTIMIZACIONOG PROBLEMA

Zadatak optimizacije za ovaj problem je određivanje optimalnih geometrijskih parametara T-poprečnog preseka konstrukcije dizalične kuke koji će dovesti do minimizacije njegove površine.

Optimizacioni problem se matematički definiše na sledeći način:

$$\text{minimizacija funkcije cilja} \quad f(X) \quad (1)$$

$$\text{u odnosu na funkcije ograničenja:} \quad g_i(X) \leq 0, \quad i = 1, \dots, m \quad (2)$$

$$\text{pri čemu je ispunjeno:} \quad X_j \geq 0 \quad (3)$$

$$\text{i} \quad l_i \leq X_i \leq u_i, \quad i = 1, \dots, n \quad (4)$$

gde su:

f(X) - funkcija cilja,

$g_i(X) \leq 0, \quad i = 1, \dots, m$ - funkcije ograničenja,

l_i, u_i - donje, odnosno gornje ograničenje,

i - broj funkcija ograničenja,

j - broj projektivnih varijabli,

$X = \{x_1, \dots, x_n\}^T$ - projektivni vektor koga čine *n* projektivnih promenljivih; projektivne promenljive su veličine koje treba odrediti tokom optimizacionog postupka (svaka projektivna promenljiva je definisana svojom donjom i gornjom granicom).

GRG2 i EA metode optimizacije se sprovode u Ms EXCEL softverskom paketu, u Analysis modulu, korišćenjem alata Solver Tool.

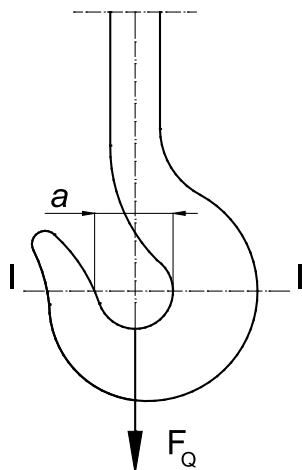
Što se tiče MATLAB softverskog paketa, za korišćenje funkcija *fmincon* i *ga* se koriste izrazi (5) i (6), respektivno:

output - pokazuje izlazne informacije pri optimizaciji,
nonlcon - računa nelinearnu nejednakost,
lambda - Lagranžov množitelj,
grad - gradijent funkcije cilja u tački X,

hessian - Hesianova vrednost funkcije cilja u tački X ,
 X_0 - vektor početnih vrednosti parametara optimizacije,
 b, beq - vektori, A, Aeq - matrice,
 $C(X), Ceq(X)$ - vektorske funkcije.

PSO algoritam optimizacije je definisan prema [18], po čijem se algoritmu određuju optimalne veličine.

Slika 1 prikazuje jednu standardnu dizaličnu kuku prema [19], kao i kritični presek ($I - I$) na čijem se delu posmatra T-poprečni presek (desni deo preseka od ose dejstva sile opterećenja).



Slika 1: Dizalična kuka

Matematička formulacija funkcije cilja prikazana je na sledeći način (Slika 2):

$$f(X) = A_T(X) = A_T(x_1 \ x_2 \ x_3 \ x_4) = A_T(b_t \ t \ h \ d) \quad (7)$$

Vektor ulaznih parametara je:

$$x = (Q, a, \sigma_d) \quad (8)$$

gde su:

Q - nosivost dizalične kuke,

a - prečnik unutrašnjeg dela kuke, [19] (Slika 1),

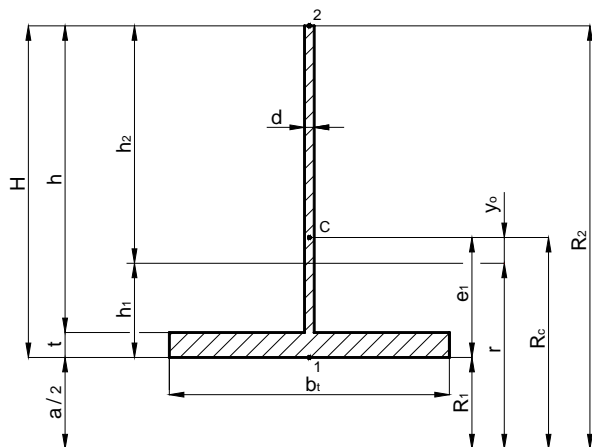
σ_d - kritični napon, [19].

U daljem tekstu će biti prikazane detaljno funkcije cilja i ograničenja.

4. FUNKCIJE CILJA I OGRANIČENJA

4.1. Funkcija cilja

Funkcija cilja predstavlja površinu T-poprečnog preseka dizalične kuke na najkritičnijem mestu konstrukcije kuke (Slika 2).



Slika 2: T-poprečni presek

Površina poprečnog preseka, odnosno funkcija cilja, glasi:

$$A_T = b_t \cdot t + h \cdot d \quad (9)$$

4.2. Funkcije ograničenja

Procesi optimizacije zasnivaju se na dozvoljenim naponima, prema Vinkler-Bakovoj teoriji. Ukupne deformacije vlakana u krivolinijskom štapu su proporcionalne udaljenosti vlakana od neutralne površi (ose). Naprezanja vlakana nisu proporcionalna tim udaljenostima, jer vlakna nisu jednakih dužina, za razliku od pravolinijskog štapa. Kod napona savijanja koji ne prelaze dozvoljeni napon granice tečenja, napon bilo kog vlakna štapa je proporcionalan naprezanju vlakna, tako da elastični naponi u vlaknima krivolinijskog štapa nisu proporcionalna udaljenosti od neutralne površi. Iz istog razloga, neutralna osa u krivolinijskom štapu ne prolazi kroz težište poprečnog preseka.

Matematička formulacija funkcija ograničenja, prema dopuštenim naponima, [20] u karakterističnim tačkama (Slika 2) glasi:

$$g_1 = \sigma_1 = \frac{F_Q}{A_T} + \frac{M_{\max}}{S_x} \cdot \frac{h_1}{R_1} \leq \sigma_d \quad (10)$$

i

$$g_2 = |\sigma_2| = \frac{F_Q}{A_T} - \frac{M_{\max}}{S_x} \cdot \frac{h_2}{R_2} \leq \sigma_d \quad (11)$$

gde su:

$$h_1 = r - R_1 \quad (12)$$

$$h_2 = R_2 - r \quad (13)$$

$$H = h + t = h_1 + h_2 \quad (14)$$

$$R_1 = \frac{a}{2} \quad (15)$$

$$R_2 = \frac{a}{2} + H \quad (16)$$

$$R_c = R_1 + e_1 \quad (17)$$

$$e_1 = \frac{b_t \cdot t^2 + 2 \cdot h \cdot d \cdot t + h \cdot d^2}{2 \cdot A_T} \quad (18)$$

$$y_o = R_c - r \quad (19)$$

$$r = \frac{A_T}{\int_A \frac{dA}{\rho}} \quad (20)$$

$$\int_A \frac{dA}{\rho} = b_t \cdot \ln \frac{a+2 \cdot t}{a} + d \cdot \ln \frac{a+2 \cdot H}{a+2 \cdot t} \quad (21)$$

$$F_Q = Q \cdot g \quad (22)$$

$$M_{\max} = F_Q \cdot R_c \quad (23)$$

$$S_x = A_T \cdot y_o \quad (24)$$

gde su:

R_1 - poluprečnik unutrašnjeg vlakna (Slika 2),

R_2 - poluprečnik spoljašnjeg vlakna (Slika 2),

R_c - poluprečnik težišne ose (Slika 2),

r - poluprečnik neutralne ose (Slika 2),

y_o - rastojanje između težišne i neutralne ose (Slika 2),

F_Q - aksijalna sila (Slika 1),

M_{\max} - maksimalni moment savijanja,

S_x - statički moment površine poprečnog preseka.

5. NUMERIČKI PRIKAZ REZULTATA OPTIMIZACIJE

Optimizacija je sprovedena korišćenjem sledećih algoritama optimizacije: primenom GRG2 algoritma i EA algoritma, korišćenjem alata Solver Tool u modulu Analysis, u Ms EXCEL softverskom paketu; primenom funkcija $fmincon$ prema [16] i ga prema [17], u MATLAB softverskom paketu; primenom algoritma optimizacije za PSO, prema [18], u MATLAB softverskom paketu.

Parametri optimizacije su visina h , debljina d , širina osnove b_t i debljina osnove t , T-poprečnog preseka (Slika 2).

Geometrijski parametar a (Slika 1) uzet je kao ulazna veličina, prema standard [19] i nije predmet optimizacije.

Ulazni parametri optimizacije su: $F_Q=100$ kN, $a=12.5$ cm i $\sigma_d=8$ kN/cm². Posmatran je primer jedne standardne dizalične kuke nosivosti 10 t.

Površina poprečnog preseka dizalične kuke na najkritičnijem mestu, u odnosu na koju se porede optimalni rezultati je: $A_s=109.9$ cm², prema [19].

Za minimalne debljine t i d usvojeno je da njihove vrednost nisu manje od 1 cm.

U narednim tabelama prikazani su rezultati optimizacije (optimalni geometrijski parametri poprečnog preseka, optimalna površina poprečnog preseka i ušteda) prema gorenavedenim algoritmima (Tabela 1÷Tabela 5).

Tabela 1: Optimalne geometrijske vrednosti T-poprečnog preseka prema GRG2 i ušteda

b_t (cm)	22.717	Ušteda (%)
t (cm)	1.000	64.22
d (cm)	1.000	
h (cm)	16.599	
A_T (cm ²)	39.317	

Tabela 2: Optimalne geometrijske vrednosti T-poprečnog preseka prema EA i ušteda

b_t (cm)	20.139	Ušteda (%)
t (cm)	1.000	63.68
d (cm)	1.001	
h (cm)	19.755	
A_T (cm ²)	39.913	

Tabela 3: Optimalne geometrijske vrednosti T-poprečnog preseka prema $fmincon$ i ušteda

b_t (cm)	22.717	Ušteda (%)
t (cm)	1.000	64.22
d (cm)	1.000	
h (cm)	16.600	
A_T (cm ²)	39.317	

Tabela 4: Optimalne geometrijske vrednosti T-poprečnog preseka prema ga i ušteda

b_t (cm)	19.718	Ušteda (%)
t (cm)	1.000	63.15
d (cm)	1.000	
h (cm)	20.779	
A_T (cm ²)	40.501	

Tabela 5: Optimalne geometrijske vrednosti T-poprečnog preseka prema PSO i ušteda

b_t (cm)	22.717	Ušteda (%)
t (cm)	1.000	64.22
d (cm)	1.000	
h (cm)	16.599	
A_T (cm ²)	39.317	

Takođe, posmatran je i slučaj kada su debljine d i t jednake (Tabela 6÷Tabela 10).

Tabela 6: Optimalne geometrijske vrednosti T-poprečnog preseka istih debljina prema GRG2 i ušteda

b_t (cm)	22.712	Ušteda (%)
$t=d$ (cm)	1.000	64.22
h (cm)	16.605	
A_T (cm ²)	39.317	

Tabela 7: Optimalne geometrijske vrednosti T-poprečnog preseka istih debljina prema EA i ušteda

b_t (cm)	22.184	Ušteda (%)
$t=d$ (cm)	1.000	64.20
h (cm)	17.154	
A_T (cm ²)	39.339	

Tabela 8: Optimalne geometrijske vrednosti T-poprečnog preseka istih debljina prema $fmincon$ i ušteda

b_t (cm)	22.717	Ušteda (%)
$t=d$ (cm)	1.000	64.22
h (cm)	16.600	
A_T (cm ²)	39.317	

Tabela 9: Optimalne geometrijske vrednosti T-poprečnog preseka istih debljina prema ga i ušteda

b_t (cm)	21.033	Ušteda (%)
$t=d$ (cm)	1.001	64.00
h (cm)	18.495	
A_T (cm ²)	39.561	

Tabela 10: Optimalne geometrijske vrednosti T-poprečnog preseka istih debljina prema PSO i ušteda

b_t (cm)	22.718	Ušteda (%)
$t=d$ (cm)	1.000	64.22
h (cm)	16.599	
A_T (cm ²)	39.317	

Ono što se vidi na osnovu prethodnih tabela (Tabela 1÷Tabela 10) je da su dosta velike vrednosti za optimalne parametre h i b_t .

Iz tog razloga uvedena su dodatna geometrijska ograničenja tako širina b_t i visina profila H budu manje od standardne vrednosti $h_s=14$ cm, prema [19], tako da je:

$$b_t, H \leq h_s \quad (25)$$

Na osnovu relacije (25) i ponavljanjem postupaka optimizacije, kao što je sprovedeno za prethodne tabele (Tabela 1÷Tabela 10), dobijaju se sledeće tabele sa rezultatima (Tabela 11÷Tabela 20):

Tabela 11: Optimalne geometrijske vrednosti T-poprečnog preseka sa ograničenjem prema GRG2 i ušteda

b_t (cm)	14.000	Ušteda (%)
t (cm)	2.547	41.91
d (cm)	2.461	
h (cm)	11.453	
A_T (cm ²)	63.840	

Tabela 12: Optimalne geometrijske vrednosti T-poprečnog preseka sa ograničenjem prema EA i ušteda

b_t (cm)	13.999	Ušteda (%)
t (cm)	2.526	41.89
d (cm)	2.485	
h (cm)	11.471	
A_T (cm ²)	63.867	

Tabela 13: Optimalne geometrijske vrednosti T-poprečnog preseka sa ograničenjem prema $fmincon$ i ušteda

b_t (cm)	14.000	Ušteda (%)
t (cm)	2.547	41.91
d (cm)	2.461	
h (cm)	11.453	
A_T (cm ²)	63.840	

Tabela 14: Optimalne geometrijske vrednosti T-poprečnog preseka sa ograničenjem prema ga i ušteda

b_t (cm)	13.999	Ušteda (%)
t (cm)	2.602	41.87
d (cm)	2.408	
h (cm)	11.398	
A_T (cm ²)	63.881	

Tabela 15: Optimalne geometrijske vrednosti T-poprečnog preseka sa ograničenjem prema PSO i ušteda

b_t (cm)	14.000	Ušteda (%)
t (cm)	2.561	41.91
d (cm)	2.446	
h (cm)	11.439	
A_T (cm ²)	63.843	

Tabela 16: Optimalne geometrijske vrednosti T-poprečnog preseka istih debljina, sa ograničenjem prema GRG2 i ušteda

b_t (cm)	14.000	Ušteda (%)
$t=d$ (cm)	2.505	41.89
h (cm)	11.495	
A_T (cm ²)	63.862	

Tabela 17: Optimalne geometrijske vrednosti T-poprečnog preseka istih debljina, sa ograničenjem prema EA i ušteda

b_t (cm)	13.998	Ušteda (%)
$t=d$ (cm)	2.506	41.88
h (cm)	11.494	
A_T (cm ²)	63.876	

Tabela 18: Optimalne geometrijske vrednosti T-poprečnog preseka istih debljina, sa ograničenjem prema $fmincon$ i ušteda

b_t (cm)	14.000	Ušteda (%)
$t=d$ (cm)	2.505	41.89
h (cm)	11.495	
A_T (cm ²)	63.862	

Tabela 19: Optimalne geometrijske vrednosti T-poprečnog preseka istih debljina, sa ograničenjem prema ga i ušteda

b_t (cm)	13.955	Ušteda (%)
$t=d$ (cm)	2.519	41.70
h (cm)	11.479	
A_T (cm ²)	64.075	

Tabela 20: Optimalne geometrijske vrednosti T-poprečnog preseka istih debljina, sa ograničenjem prema PSO i ušteda

b_t (cm)	14.000	Ušteda (%)
$t=d$ (cm)	2.505	41.89
h (cm)	11.495	
A_T (cm ²)	63.862	

Na sledećim slikama prikazani su dijagrami konvergencije za optimizacioni metod roja čestica (PSO) iz MATLAB softverskog paketa za sve varijante, što se tiče geometrijskih uslova optimizacije.

6. ZAKLJUČAK

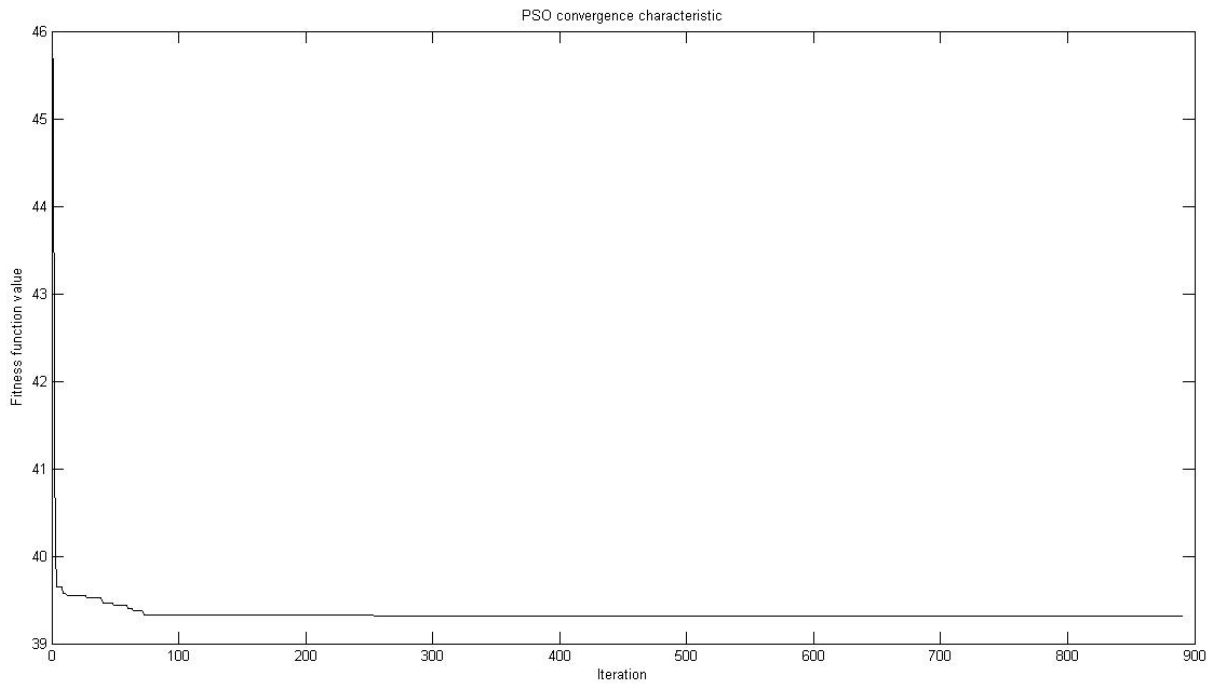
U radu su sračunati optimalni geometrijski parametri T-poprečnog preseka dizalične kuke na najkritičnijem mestu konstrukcije kuke, na jednom primeru za nosivost od 10 t, pri čemu je konstrukcija kuke tretirana kao krivolinijski štap. Kao funkcija cilja posmatrana je površina poprečnog preseka na najkritičnijem mestu konstrukcije kuke, pri čemu su ograničenja u vidu maksimalnih napona zadovoljena. Optimizacija je sprovedena korišćenjem Ms EXCEL softverskog paketa, primenom GRG2 algoritma i EA algoritma optimizacije, kao i korišćenjem MATLAB softverskog paketa, primenom funkcija $fmincon$ i ga (genetski algoritam) i primenom algoritma roja čestica (PSO).

Postavljeni zadatak optimizacije, smanjenje površine poprečnog preseka je uspešno realizovan, što se vidi na osnovu rezultata u prethodnim tabelama (Tabela 1÷Tabela 20).

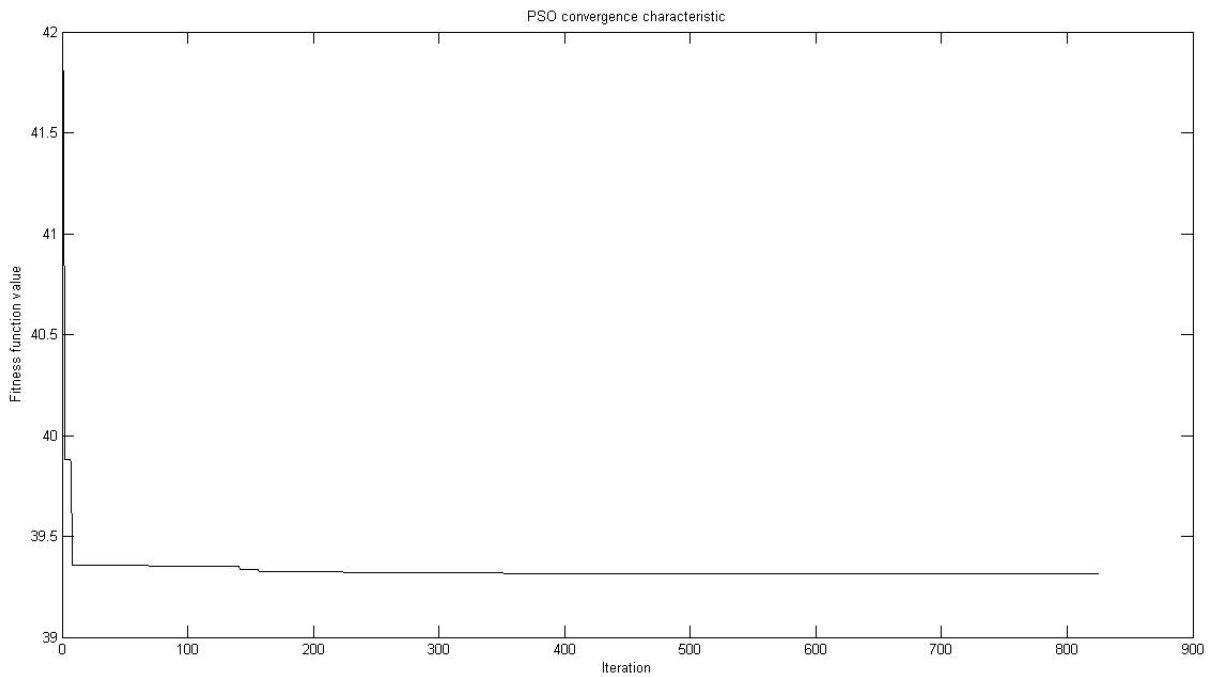
Izbor odgovarajućih metoda optimizacije pokazuje njihovu opravdanost, jer je ostvarena ušteda i do 64.22 %. Sa geometrijskim ograničenjem ostvaruje se ušteda do 41.91 %.

Geometrijsko ograničenje znatno utiče na rezultate optimizacije i ostvarenu uštedu, što se vidi na osnovu dobijenih rezultata. Za varijantu bez ograničenja dobijaju se velike vrednosti za h i b_t . Pokazalo se takođe da za varijante i sa i bez ograničenja, uslov jednakosti debljina ne utiče na vrednost optimalne površine poprečnog preseka.

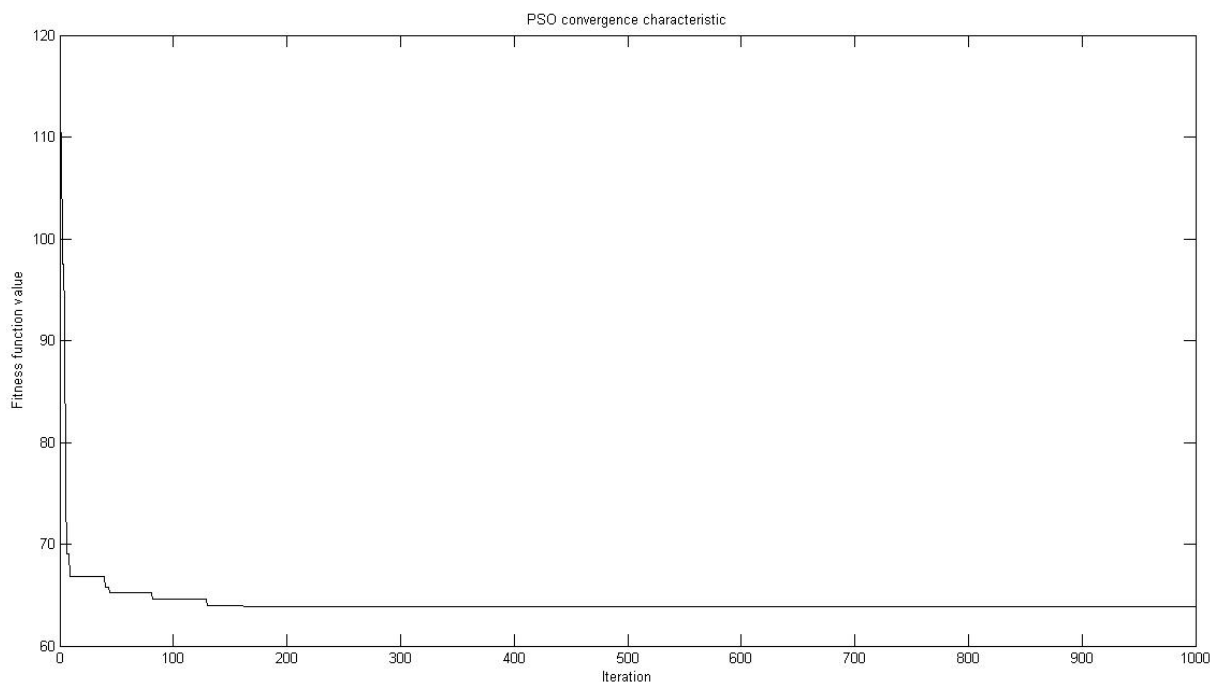
U procesu optimizacije bez geometrijskog ograničenja, kao optimalne debljine su dobijene minimalno postavljene debljine od 1 cm u svim slučajevima (Tabela 1÷Tabela 10). Kod varijante sa ograničenjem, kao optimalne širine i visine dobijene su granične vrednosti, odnosno vrednosti jako bliske graničnim vrednostima (Tabela 11÷Tabela 20). U ovoj varijanti sa geometrijskim ograničenjem, optimalne vrednosti za debljine t su nešto veće od debljine d (Tabela 11÷Tabela 15), za varijantu kada debljine t i d nisu jednake.



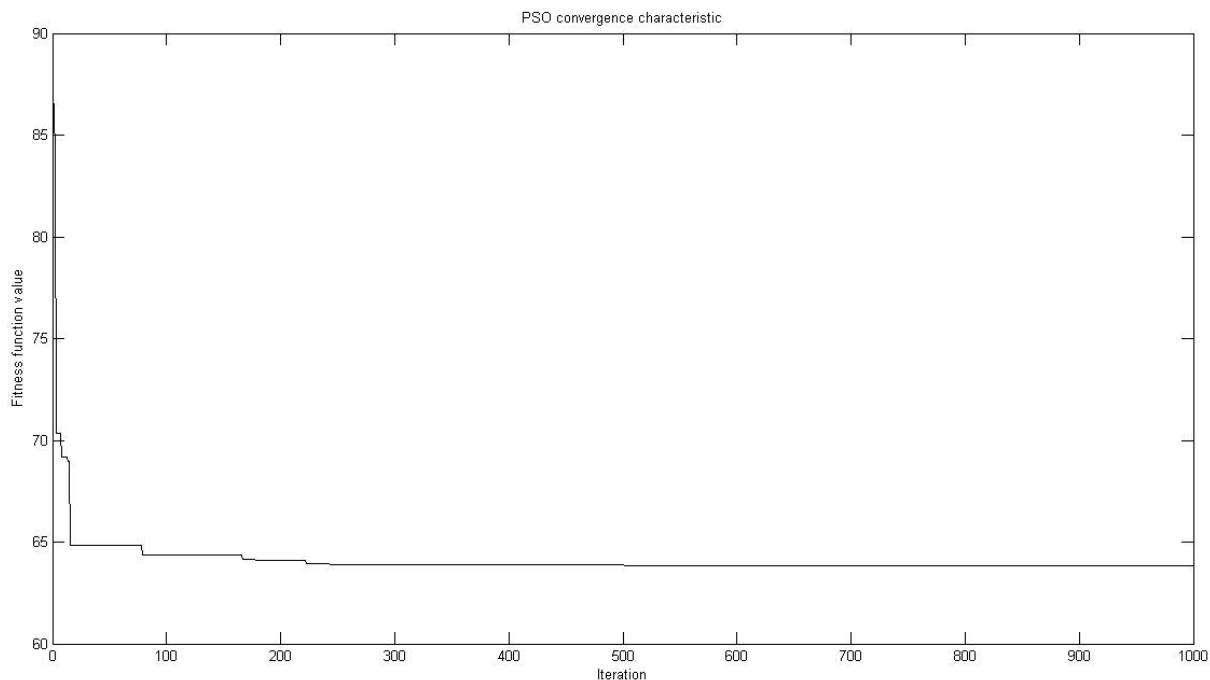
Slika 3: Dijagram konvergencije za PSO za T-poprečni presek



Slika 4: Dijagram konvergencije za PSO za T-poprečni presek sa jednakim debljinama



Slika 5: Dijagram konvergencije za PSO za T-poprečni presek, sa ograničenjem



Slika 6: Dijagram konvergencije za PSO za T-poprečni presek sa jednakim debljinama, sa ograničenjem

Što se tiče primenjenih algoritama optimizacije, najbolje rezultate daju GRG2 i PSO algoritam, kao i primena funkcije *fmincon*. Nešto veće vrednosti daju GA i EA algoritam optimizacije.

Glavni zaključak na osnovu sprovedene analize i optimizacije je da posmatrani T-poprečni presek daje značajne uštede u materijalu u odnosu na standardno izvođenje dizalične kuke sa trapeznim poprečnim presekom. Takođe, geometrijsko ograničenje je vrlo bitno u procesu optimizacije i neophodno je uvesti sva neophodna ograničenja u daljim analizama, što se tiče funkcionalnosti dizalične kuke, kao i tehnološkičnosti.

Za dalja istraživanja u ovoj oblasti, neophodno je uključiti i druge geometrijske parametre strukture dizalične kuke, a takođe posmatrati i ostala karakteristična

mesta i segmente strukture kuke značajne za analizu. Pored naponskih stanja, mogu se analizirati i deformacije kuke, kao i zamor materijala. Takođe, potrebno je analizirati i sve potencijalne druge oblike poprečnih preseka koji mogu doći u obzir, i izvršiti njihovu komparaciju, kao i tipove materijala koji mogu doći u obzir.

Pored analitičkog rešenja problema, dobijeni rezultati se mogu verifikovati i porediti sa onim rezultatima dobijenim na osnovu MKE, u nekom od softverskih paketa, kako bi se izveli određeni zaključci i dale smernice kod analize i optimizacije ovakvog tipa konstrukcija.

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Analysis and Optimization of T-cross section of Crane Hook Considered as a Curved Beam

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This study presents analysis and optimization of the geometric parameters of T-cross section of crane hook. The reduction of the cross-sectional area of the hook is set as the main objective of this research. The permissible stresses in the crane hook characteristic points at the most critical place of her construction are taken as the limitation functions. Also, in the second part, analysis and optimization of certain geometric constraints are taken. The maximum stresses in characteristic points are calculated according to Winkler-Bach theory, where the construction of the hook is treated as a curved beam.

The optimization process is performed by using the five optimization algorithms i.e. by using the generalized reduced gradient method (GRG2) and the evolution algorithm (EA) in the Analysis module (Ms EXCEL software package), as well as the MATLAB software package (fmincon functions within the Optimization Toolbox module) and the genetic algorithm (GA) and by using a particle optimization algorithm (PSO).

Keywords: Crane Hook, Optimization, Stresses, Winkler-Bach theory

1. INTRODUCTION

Crane hooks are devices for hanging and lifting of heavy load capacities and they are an integral part of different types of crane hoists. Crane hooks are highly responsible components that are typically used for loads handling in industries. Due to their responsibility, the hoisting hooks are adequately attached to the supporting device (rope or chain), so that they meet all the necessary conditions in terms of health and safety at work.

Generally, the manipulation with materials and heavy loads occurs on construction sites, factories and other industrial facilities. Proper using of the equipment can lead to efficiently manipulation with heavy loads and reduced manual handling operations. Also, improper using of equipment and hoist hooks, which are with inadequate geometry and characteristics, can lead to function cancellation and disastrous accidents. Therefore, the proper design of crane hook is primary aim.

Optimization is a procedure through which the best possible values of decision variables are obtained under the given set of constraint functions and in accordance to objective function. The most common optimization procedure applies to a design that will minimize the total mass, area or any other specific objective.

Having in mind the above mentioned, there are a large number of papers and publications who dealing with the problems of optimization and analysis of crane hooks cross-section.

During the analysis and optimization of the hook construction, the stress conditions are observed in all cases, while in certain cases deformations are taken into account as well as the material fatigue.

The analysis of stress conditions is most often done by using the Finite Element Method (FEM). In the paper [1], the analysis of stress conditions of the typical trapezoidal cross-sectional hook is performed by using IDEAS software

package. These results are compared with analytical, where the hook is observed as a curved beam, so the validity of such model is proven.

In studies [2], [3] and [4] are analyzed a different forms of full cross sections, where the 3D hook model is generated using CREO software package, while the analysis of the stresses is performed using ANSYS software package. In the paper [5], rectangular, trapezoidal, triangular and circular cross-section of the hook structure are analyzed also using ANSYS software package, while the 3D model is generated using CATIA software package.

Similar to the previous work, using CATIA and ANSYS software packages, besides the different full cross-sections, the T-cross section of the hook carrier is considered [6]. In this paper, different materials are analyzed in the analysis. The T-cross section is also discussed in works [7], [8], [9] and [10] using ANSYS software package for the analysis of stress states.

In the paper [8], a comparative analysis of the stress states is performed for the standard trapezoidal cross-section of the hook carrier, as well as for the T and I cross-section. Modeling of these carriers is done using CATIA software package. Comparison between the T and I transverse cross-section of the hook carrier is performed in [10], with 3D models generated in the SOLIDWORKS software package. Similar to the previous paper, in [9] a comparison of the T-profile is made with respect to the trapezoidal and circular profiles and different materials.

The T-cross section is optimized in [11], whereby optimization is performed from the aspect of optimization (shape optimization), using the PSO optimization method (particle digestion method). The aforementioned PSO method is successfully applied in the paper [12], where structural analysis and optimization of an elevator hook is performed.

Very often in combination with FEM analysis, numerical optimization methods are combined, as shown in the previous paper [12], as well as in [13]. In the paper [13], a genetic algorithm (GA) is used in MATLAB software package for optimizing the geometric parameters of the trapezoidal cross-section of the hook, while the verification of the obtained parameters is performed in ANSYS software package.

In works [7] and [14], the optimization of the cross-sections of the hook structure is performed using the analytical procedure and certain optimization algorithms. In the paper [7], a comparison of the most often represented trapezoidal cross-section, in relation to the circular, rectangular, triangular, T and I cross-section is observed. The authors presented an algorithmic scheme for optimization.

In the paper [14], a comparative analysis and optimization of different full cross sectional shapes is performed on the crane hook example. The most critical cross-section of the hook is observed in the analysis. In addition to the typical cross sections that are represented, the parabolic and elliptical cross sections are analyzed. As a method of optimization, the Lagrange multiplier method is implemented in the MATHCAD software package, as well as the GRG2 optimization method (Ms EXCEL software package). Significant savings are made in comparison with the standard solution.

It should be noted that in addition to the usual methods of analysis and optimization, more and more topological optimization has been used in these types of structures, as shown in [15]. Finally, taking into account the above mentioned i.e. the results and significance of optimization of these types of constructions, the main goal of this paper is the analysis and optimization of the geometric parameters of the T-cross section of the crane hook at its most critical place, based on the Winkler-Bach theory.

2. OPTIMIZATION ALGORITHMS

Optimization process for such an engineering problem is performed using different numerical methods (algorithms) of optimization, using the Ms EXCEL and MATLAB programs.

The GRG method is one of the class of the technique called a generalized reduced gradient or projection gradient that is based on the extension of the method for linear constraints to nonlinear constraints. This adjusts the variables so that the active constraints are still satisfied, and the process moves from one point to another. The GRG method is based on the idea of elimination of variables using the equality of constraints. The idea of a generalized reduced gradient method is to convert the constraint problem into one without limitation using a direct substitution. Ms EXCEL Solver Tool uses a generalized reduced gradient method (GRG2 algorithm) to optimize non-linear problems.

The evolutionary algorithm (EA) applies the principles of evolution that are in nature to the problems of finding the optimal solution for the given objective function.

$$[X, fval, exitflag, output, lambda, grad, hessian] = fmincon(fun, X0, A, b, Aeq, beq, lb, ub, nonlcon) \quad (5)$$

$$[X, fval, exitflag, output] = ga(fun, n, A, b, Aeq, beq, lb, ub, nonlcon) \quad (6)$$

The evolutionary algorithm of project variables and problem functions are used directly. As in the previous case, Ms EXCEL Solver Tool uses this algorithm to optimize non-linear problems.

The MATLAB Optimization Toolbox can be used for both linear and non-linear engineering problems. Optimization of the parameters is done using the *fmincon* function, [16].

Similar to the previous one, it is used in MATLAB and the genetic algorithm (GA), using the function *ga*, [17]. The benefits of a genetic algorithm are simple procedure, strong robustness, coincidence and integrity. This optimization algorithm has a great application in engineering practice.

The particle optimization method (PSO), [18] was a global stochastic algorithm and its idea is based on the simulation of simplified social models. The PSO is independent of the mathematical characteristics of the object's problem (object function) and is successfully applied in different areas, mainly due to unlimited continual optimization problems, simple concepts, simple implementation and fast convergence.

3. MATHEMATICAL FORMULATION OF THE OPTIMIZATION PROBLEM

The task of optimization for this problem is to determine the optimal geometric parameters of the T-cross section of crane hook which will lead to the minimization of its cross sectional area.

The optimization problem is defined in following way:

$$\text{minimization of objective function} \\ f(X) \quad (1)$$

$$\text{subject to the constrain function:} \\ g_i(X) \leq 0, \quad i = 1, \dots, m \quad (2)$$

$$\text{where it is fulfilled:} \\ X_j \geq 0 \quad (3)$$

$$\text{and} \\ l_i \leq X_i \leq u_i, \quad i = 1, \dots, n \quad (4)$$

where are:

$f(X)$ - the objective function,

$g_i(X) \leq 0, \quad i = 1, \dots, m$ - the constrain function,

l_i, u_i - lower and upper constraint limit,

i - number of constrains,

j - number of design variables,

$X = \{x_1, \dots, x_n\}^T$ - a project vector of n variables; project variables are the values which should be determined during the optimization process (each project variable is defined by its lower and upper limit).

GRG2 and EA optimization methods are implemented in the Ms EXCEL software package, in the Analysis module, using the Solver Tool tool. As for the MATLAB software package, to use the functions *fmincon* and use the expressions (5) and (6), respectively:

where the explanations of the MATLAB function are shown:

fval - the value of solving target function,

exitflag - shows the reason for the termination of solving execution,

fun - objective function,

output - shows the output information during optimization,

nonlcon - calculating of non-linear inequality,

lambda - Lagrange multiplier,

grad - the gradient of objective function in point X,

hessian - the Hessian value of objective function in point X,

X0 - the vector of initial values of optimization parameters,

b, beq - vectors, *A, Aeq* - matrices,

C(X), Ceq(X) - vector functions.

The PSO optimization algorithm is defined according to [18], and with that algorithm the optimal value are determined.

Figure 1 shows a standard crane hook according to [19], as well as a critical cross section (I - I) on which the T-cross section is viewed (the right part of the section from the axis of loading force).

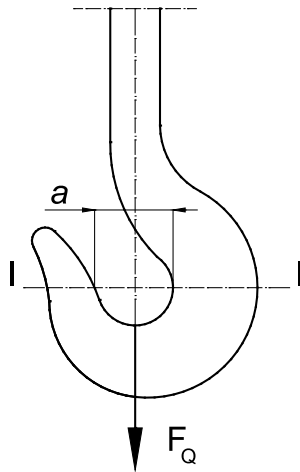


Figure 1: Crane hook

The mathematical formulation of the objective function is shown as follows (Figure 2):

$$f(X) = A_T(X) = A_T(x_1 \ x_2 \ x_3 \ x_4) = A_T(b_t \ t \ h \ d) \quad (7)$$

The input parameters vector is:

$$x = (Q, a, \sigma_d) \quad (8)$$

where are:

Q - load capacity of crane hook,

a - diameter of inner fiber of hook, [19] (Fig. 1),

σ_d - critical stress, [19].

Below text will show detailed objectives and constraints.

4. OBJECTIVE FUNCTIONS AND CONSTRAINTS

4.1. Objective function

The objective function is represented by the area of T-cross section of crane hook at the most critical place. (Figure 2).

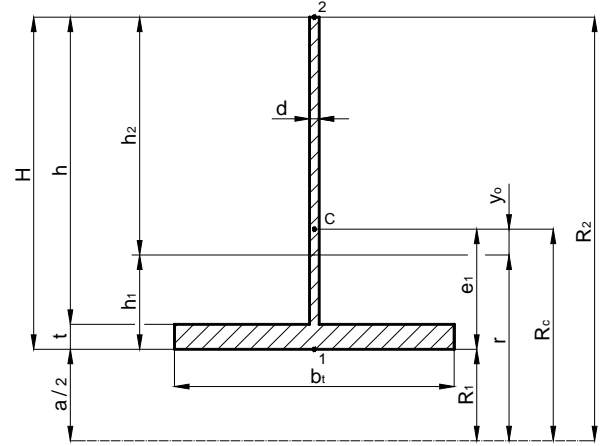


Figure 2: T-cross section

The cross-sectional area, or the objective function, is:

$$A_T = b_t \cdot t + h \cdot d \quad (9)$$

4.2. Constraint functions

Optimization processes are based on permissible stresses, according to Winkler-Bach theory. The total deformation of fibers in the curved beam is proportional to the distance of the fiber from the neutral surface (axis). The strains of the fibers are not proportional to these distances, since the fibers are not equal in length, unlike the straight beam. In the case of bending stress that does not exceed the permitted flow stress limit, the stress of any fiber of the beam is proportional to the stress of the fibers, so that the elastic stresses in the fibers of the curved beam are not proportional to the distance from the neutral surface. For the same reason, the neutral axis in the curved beam does not pass through the center of gravity of the cross-section.

The mathematical formulation of the constrain functions, according to the allowed stresses, [20] in characteristic points (Figure 2) is::

$$g_1 = \sigma_1 = \frac{F_Q}{A_T} + \frac{M_{\max}}{S_x} \cdot \frac{h_1}{R_1} \leq \sigma_d \quad (10)$$

and

$$g_2 = |\sigma_2| = \frac{F_Q}{A_T} - \frac{M_{\max}}{S_x} \cdot \frac{h_2}{R_2} \leq \sigma_d \quad (11)$$

where are:

$$h_1 = r - R_1 \quad (12)$$

$$h_2 = R_2 - r \quad (13)$$

$$H = h + t = h_1 + h_2 \quad (14)$$

$$R_1 = \frac{a}{2} \quad (15)$$

$$R_2 = \frac{a}{2} + H \quad (16)$$

$$R_c = R_1 + e_1 \quad (17)$$

$$e_1 = \frac{b_t \cdot t^2 + 2 \cdot h \cdot d \cdot t + h \cdot d^2}{2 \cdot A_T} \quad (18)$$

$$y_o = R_c - r \quad (19)$$

$$r = \frac{A_T}{\int_A \frac{dA}{\rho}} \quad (20)$$

$$\int_A \frac{dA}{\rho} = b_t \cdot \ln \frac{a+2 \cdot t}{a} + d \cdot \ln \frac{a+2 \cdot H}{a+2 \cdot t} \quad (21)$$

$$F_Q = Q \cdot g \quad (22)$$

$$M_{\max} = F_Q \cdot R_c \quad (23)$$

$$S_x = A_T \cdot y_o \quad (24)$$

where are:

R_1 - radius of inner fiber (Fig. 2),

R_2 - radius of outer fiber (Fig. 2),

R_c - poluprečnik težišne ose (Fig. 2),

r - radius of neutral axis (Fig. 2),

y_o - distance between centroidal axis and neutral axis (Fig. 2),

F_Q - axial force (Fig. 1),

M_{\max} - maximum bending moment,

S_x - static moment of area.

5. NUMERICAL REPRESENTATION OF OPTIMIZATION RESULTS

Optimization is performed using the following optimization algorithms: GRG2 algorithm and EA algorithm, using the Solver Tool tool in the Analysis module in the Ms EXCEL software package; using the *fmincon* functions according to [16] and *ga* according to [17], in MATLAB software package; using the optimization algorithm for the PSO, according to [18], in MATLAB software package.

The optimization parameters are the height h , the thickness d , the width b_t and the thickness of the base t , of T-cross section (Figure 2).

The geometric parameter a (Figure 1) is taken as the input size, according to standard [19] and is not the subject of optimization.

Input optimization parameters are: $F_Q = 100 \text{ kN}$, $a = 12.5 \text{ cm}$ and $\sigma_d = 8 \text{ kN/cm}^2$. A standard crane hook with a load capacity of 10 t is observed.

The cross sectional area of crane hook at the most critical place, in relation to which the optimal results are compared, is: $A_s = 109.9 \text{ cm}^2$, according to [19].

The values of minimum thicknesses t and d are not less than 1 cm .

The following tables show the results of optimization (optimal geometric parameters of the cross-section, optimal cross-sectional area and savings) according to the above algorithms (Table 1 ÷ Table 5).

Table 1: Optimal geometric values of T-cross section to GRG2 and savings

b_t (cm)	22.717	Saving (%)
t (cm)	1.000	64.22
d (cm)	1.000	
h (cm)	16.599	
A_T (cm ²)	39.317	

Table 2: Optimal geometric values of T-cross section to EA and savings

b_t (cm)	20.139	Saving (%)
t (cm)	1.000	63.68
d (cm)	1.001	
h (cm)	19.755	
A_T (cm ²)	39.913	

Table 3: Optimal geometric values of T-cross section to *fmincon* and savings

b_t (cm)	22.717	Saving (%)
t (cm)	1.000	64.22
d (cm)	1.000	
h (cm)	16.600	
A_T (cm ²)	39.317	

Table 4: Optimal geometric values of T-cross section to *ga* and savings

b_t (cm)	19.718	Saving (%)
t (cm)	1.000	63.15
d (cm)	1.000	
h (cm)	20.779	
A_T (cm ²)	40.501	

Table 5 Optimal geometric values of T-cross section to PSO and savings

b_t (cm)	22.717	Saving (%)
t (cm)	1.000	64.22
d (cm)	1.000	
h (cm)	16.599	
A_T (cm ²)	39.317	

Also, the cases where the thickness d and t are equal (Table 6 ÷ Table 10) are observed.

Table 6: Optimal geometric values of T-cross section to GRG2 and savings

b_t (cm)	22.712	Saving (%)
$t=d$ (cm)	1.000	64.22
h (cm)	16.605	
A_T (cm ²)	39.317	

Table 7: Optimal geometric values of T-cross section to EA and savings

b_t (cm)	22.184	Saving (%)
$t=d$ (cm)	1.000	64.20
h (cm)	17.154	
A_T (cm ²)	39.339	

Table 8: Optimal geometric values of T-cross section to *fmincon* and savings

b_t (cm)	22.717	Saving (%)
$t=d$ (cm)	1.000	64.22
h (cm)	16.600	
A_T (cm ²)	39.317	

Table 9: Optimal geometric values of T-cross section to *ga* and savings

b_t (cm)	21.033	Saving (%) 64.00
$t=d$ (cm)	1.001	
h (cm)	18.495	
A_T (cm ²)	39.561	

Table 10: Optimal geometric values of T-cross section to *PSO* and savings

b_t (cm)	22.718	saving (%) 64.22
$t=d$ (cm)	1.000	
h (cm)	16.599	
A_T (cm ²)	39.317	

What is seen from the previous tables (Table 1 ÷ Table 10) is that they are quite large for the optimal parameters h and b_t . For this reason, additional geometric constraints have been introduced such that the width b_t and the height of the profile H are less than the standard value $h_s=14cm$, according to [19], so that:

$$b_t, H \leq h_s \quad (25)$$

Based on the relation (25) and with repeating of the optimization procedures, as carried out for the previous tables (Table 1 ÷ Table 10), the following table of results are obtained (Table 11 ÷ Table 20):

Table 11: Optimal geometric values of T-cross section to *GRG2* and savings

b_t (cm)	14.000	Saving (%) 41.91
t (cm)	2.547	
d (cm)	2.461	
h (cm)	11.453	
A_T (cm ²)	63.840	

Table 12: Optimal geometric values of T-cross section to *EA* and savings

b_t (cm)	13.999	Saving (%) 41.89
t (cm)	2.526	
d (cm)	2.485	
h (cm)	11.471	
A_T (cm ²)	63.867	

Table 13: Optimal geometric values of T-cross section to *fmincon* and savings

b_t (cm)	14.000	Saving (%) 41.91
t (cm)	2.547	
d (cm)	2.461	
h (cm)	11.453	
A_T (cm ²)	63.840	

Table 14: Optimal geometric values of T-cross section to *ga* and savings

b_t (cm)	13.999	Saving (%) 41.87
t (cm)	2.602	
d (cm)	2.408	
h (cm)	11.398	
A_T (cm ²)	63.881	

Table 15: Optimal geometric values of T-cross section to *PSO* and savings

b_t (cm)	14.000	Saving (%) 41.91
t (cm)	2.561	
d (cm)	2.446	
h (cm)	11.439	
A_T (cm ²)	63.843	

Table 16: Optimal geometric values of the T-cross section for same thickness, with *GRG2* and savings

b_t (cm)	14.000	Saving (%) 41.89
$t=d$ (cm)	2.505	
h (cm)	11.495	
A_T (cm ²)	63.862	

Table 17 Optimal geometric values of the T-cross section for same thickness, with *EA* and savings

b_t (cm)	13.998	Saving (%) 41.88
$t=d$ (cm)	2.506	
h (cm)	11.494	
A_T (cm ²)	63.876	

Table 18: Optimal geometric values of the T-cross section for same thickness, according to *fmincon* and savings

b_t (cm)	14.000	Saving (%) 41.89
$t=d$ (cm)	2.505	
h (cm)	11.495	
A_T (cm ²)	63.862	

Table 19: Optimal geometric values of the T-cross section for same thickness, according to *ga* and savings

b_t (cm)	13.955	Saving (%) 41.70
$t=d$ (cm)	2.519	
h (cm)	11.479	
A_T (cm ²)	64.075	

Table 20: Optimal geometric values of the T-cross section for same thickness, according to *PSO* and savings

b_t (cm)	14.000	Saving (%) 41.89
$t=d$ (cm)	2.505	
h (cm)	11.495	
A_T (cm ²)	63.862	

The following figures show the convergence diagrams for the PSO method in the MATLAB software package for all variants, as far as geometric optimization conditions are concerned.

6. CONCLUSION

The optimal geometrical parameters of the T-cross section of the crane hook at the most critical place are calculated for a load capacity of 10 t, where the hook construction is treated as a curved beam. As a objective function, the cross-sectional area is observed at the most critical place of the hook structure, where the maximum stress limitations are satisfied. The optimization is carried out using the Ms EXCEL software package, GRG2 algorithm and EA optimization algorithm, as well as using the MATLAB software package, using the *fmincon* and *ga* function (genetic algorithm) and applying the particle algorithm (PSO).

The optimization task, the reduction of the cross-sectional area, has been successfully implemented, as can be seen from the results in the previous tables (Table 1 ÷ Table 20).

The choice of appropriate optimization methods shows their justification, as savings of up to 64.22% have been achieved. With a geometric limit, savings of up to 41.91% are achieved.

The geometric limit significantly influences the results of optimization and the achieved savings, as can be seen from the results obtained. For a variant without restrictions, high values for h and b_t are obtained. It has also been shown that for variants both with and without limitation, the requirement of equality of thickness does not affect the value of the optimal surface area of the cross

section. In the optimization process without geometric limitations, the minimum thickness of 1 cm in all cases was obtained as optimum thickness (Table 1 ÷ Table 10). With the restriction variant, as the optimal width and height, limit values were obtained, ie values were very close to the limit values (Table 11 ÷ Table 20). In this variant with a geometric limitation, the optimum values for the thickness t are slightly greater than the thickness d (Table 11 ÷ Table 15), for the variant when the thickness t and d are not equal.

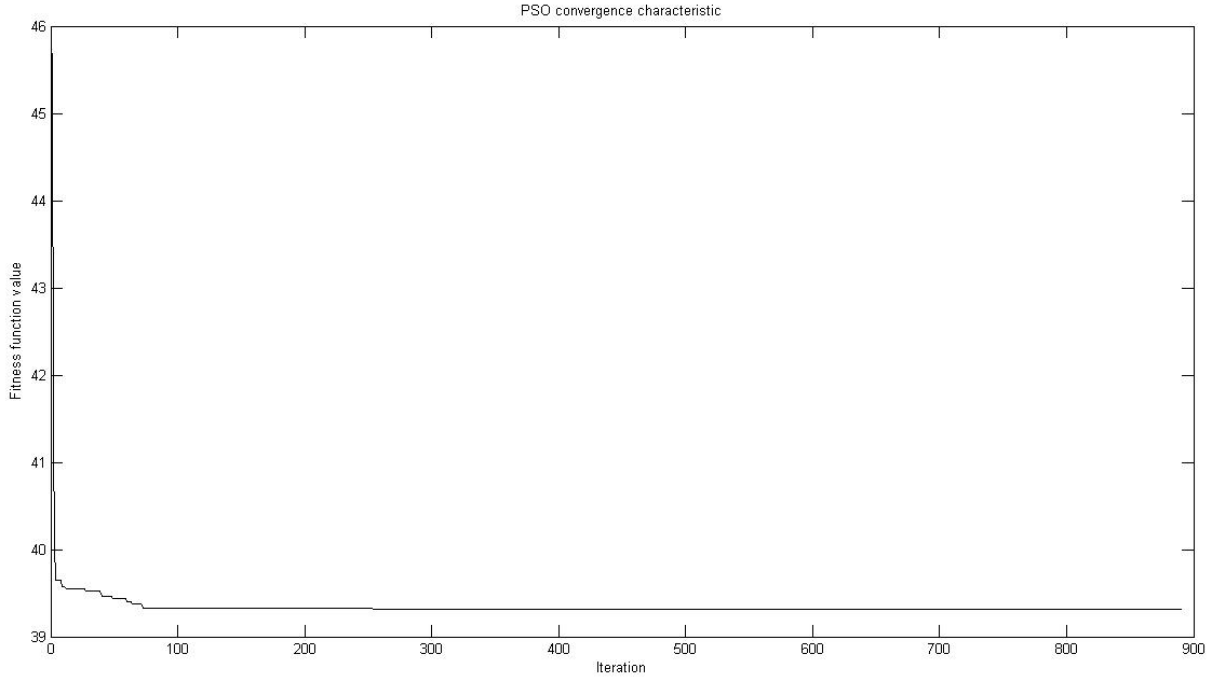


Figure 3: Convergence diagram for PSO and T-cross section

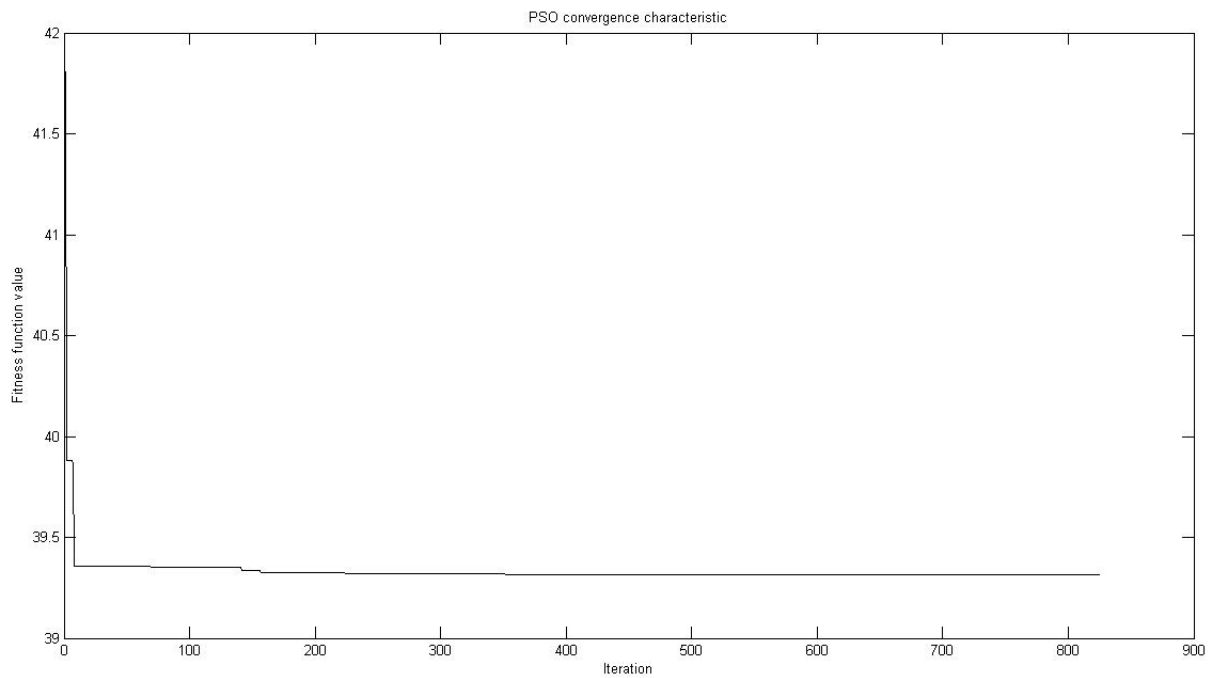


Figure 4: Convergence diagram for PSO and T-cross section with equal thickness

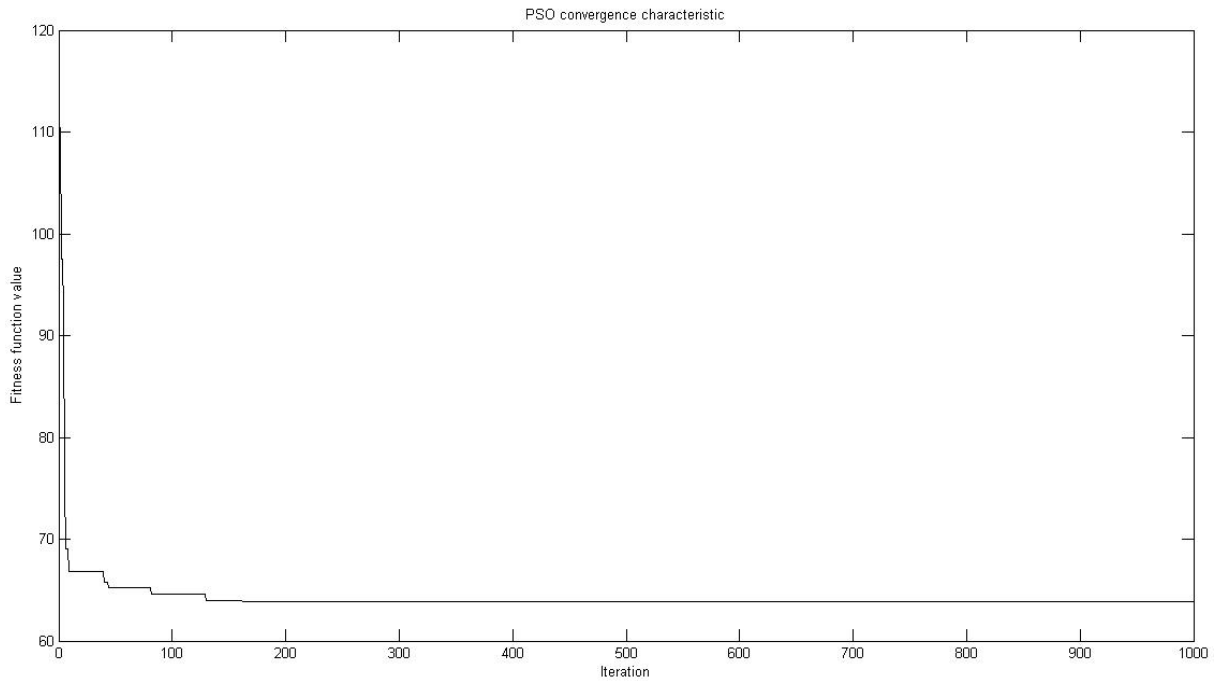


Figure 5: Convergence diagram for PSO and T- cross section, with constraints

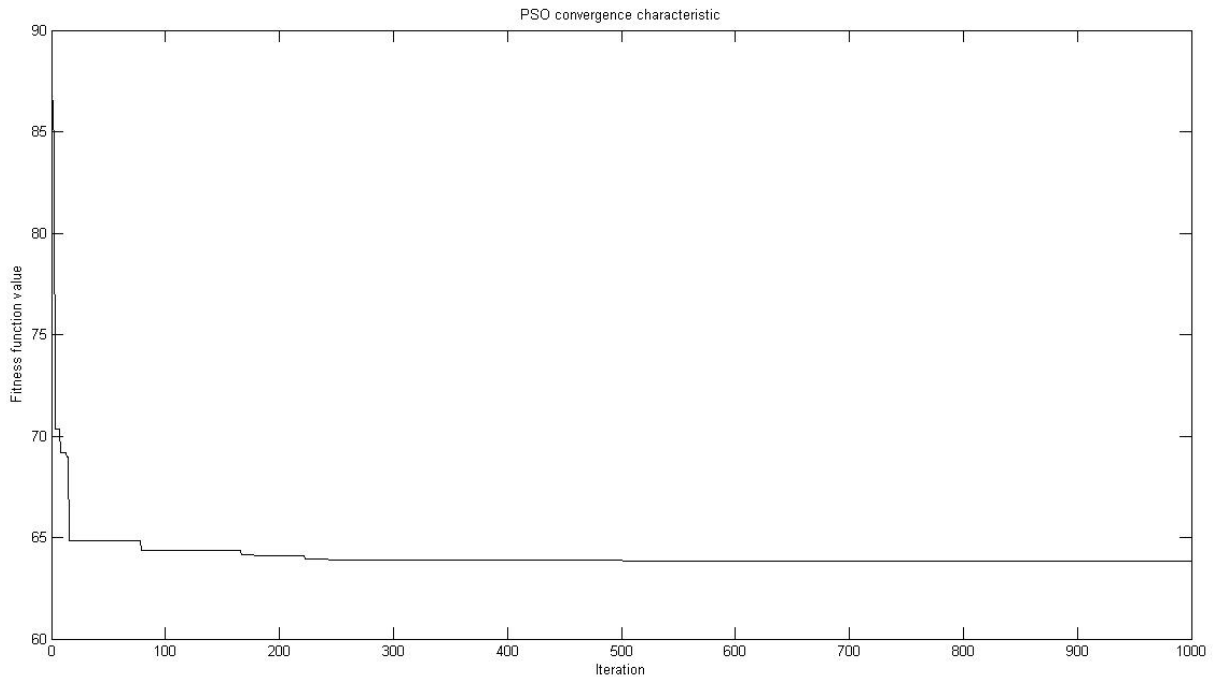


Figure 6: Convergence diagram for PSO and T- cross section, with constraints

As for the applied optimization algorithms, the best results are given by the GRG2 and PSO algorithm, as well as the application of the fmincon function. Something higher values give GA and EA optimization algorithms. The main conclusion based on the analysis and optimization carried out is that the observed T-cross section gives significant savings in the material compared to the standard performance of a crane with a trapezoidal cross-section. Also, the geometric constraint is very important in the optimization process and it is necessary to introduce all the necessary limitations in further analysis, as far as the functionality of the crane hook and the technology are concerned.

For further research in this area, it is necessary to include other geometric parameters of the structure of the crane hook, and also to consider other characteristic sites and segments of the structure of the hook important for analysis. In addition to stress conditions, hook deformation as well as fatigue can be analyzed. It is also necessary to analyze all potential other cross-sectional forms that may be considered, and make their comparison, as well as the types of materials that may be considered. In addition to the analytical solution of the problem, the obtained results can be verified and compared to those obtained on the basis of an FEM in one of the software packages, in order to draw certain conclusions and provide

guidance in the analysis and optimization of this type of construction.

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