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Modeliranje dejstava usled kranova prema Evrokodu

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U radu se opisuje način modeliranja dejstava usled kranova prema Evrokod standardima. Ovaj postupak je složeniji i precizniji u odnosu na poznate proračune i u tome je bitna razlika navedenog modeliranja u odnosu na dosadašnje načine proračuna dejstava kranova. Sam način proračuna dejstava ilustrovan je na konkretnom numeričkom primeru dvogredne mosne dizalice za rad sa kukom. Definisana su opterećenja koja deluju tokom njenog rada i na osnovu njihovog karaktera usvojeni odgovarajući dinamički faktori. Proračunom se dalje sprovode dokazi pouzdanosti delova konstrukcije za granično stanje nosivosti, granično stanje upotrebljivosti, kao i procenu zamora.

Ključne reči: kran, nosač, dejstvo, proračun, Evrokod

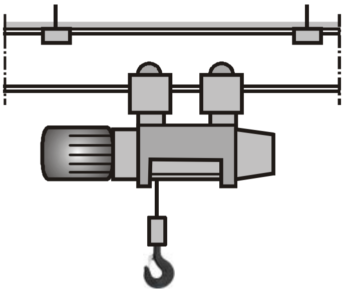
1. UVOD

Problematika dejstava usled kranova je u okviru Evrokoda obrađena u dva dela:

- EN 1991-3: Dejstva na konstrukcije – Deo 3: Dejstva usled kranova i mašina [1],
- EN 1993-6: Proračun čeličnih konstrukcija – Deo 6: Nosači kranskih staza [2].

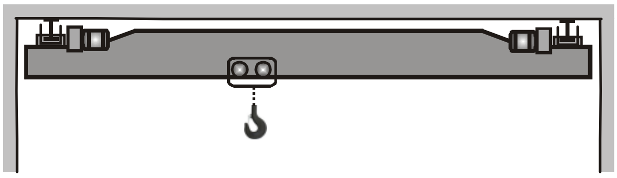
Oba standarda su usvojena kao SRPS EN na engleskom jeziku.

Postoje različite verzije izvođenja samog krana, odnosno načina njegovog povezivanja sa konstrukcijom industrijske hale u kojoj je instaliran. Za lakše terete u upotrebi su monorejl kranovi, slika 1, dok se za veće terete najčešće koriste mosni kranovi kod kojih se konstrukcija krana oslanja preko posebnih nosača (kranskih nosača) na konstrukciju hale.

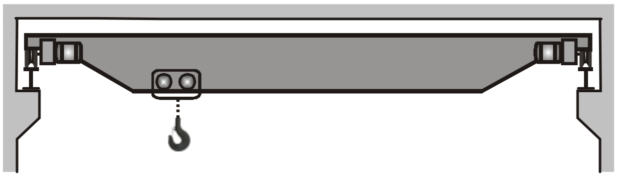


Slika 1: Monorejl dizalica

U primeni su i tzv. obešene dizalice, slika 2, kod kojih su nosači krana obešeni na konstrukciju hale. Često se koriste odozgo postavljeni kranovi, kao što je prikazano na slici 3. Postoje i neke druga izvođenja koja sadrže sopstvenu konstrukciju i sl.



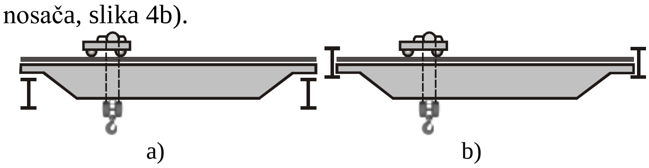
Slika 2: Obešeni kran



Slika 3: Odozgo postavljeni kran

Mosni kranovi se uobičajeno izvode u sledeće dve varijante:

- kranovi koji se kreću po gornjem pojasu kranskih nosača, slika 4a) ili,
- kranovi koji se kreću po donjem pojasu kranskih nosača, slika 4b).



Slika 4: Mosni kranovi

Usled kretanja krana javlja se niz međusobno zavisnih pokretnih sila koje deluju u:

- vertikalnom – gravitacionom pravcu usled sopstvene težine krana i težine tereta kao dominantnog opterećenja,
- podužnom horizontalnom pravcu usled ubrzanja ili kočenja krana, ekscentričnog dizanja tereta, zakošenja krana i udara krana u odbojnik,
- poprečnom horizontalnom pravcu usled ubrzanja ili kočenja, ekscentričnog dizanja tereta, zakošenja krana i udara kolica („mačke") u odbojnik.

Dejstva koja nastaju delovanjem kranova imaju statičku i dinamički komponentu, a obe su u funkciji vremena i menjaju se u zavisnosti od položaja krana i intenziteta tereta koji se prenosi, kao i od položaja tereta na kranskom nosaču. Dinamički uticaji se uzimaju u obzir tako što se poznato statičko opterećenje množi odgovarajućim dinamičkim faktorima. Svakako, treba pomenuti i problem zamora materijala koji je kod kranskih nosača jako značajan s obzirom da su oni izloženi višestrukim ciklusima opterećenja i rasterećenja. U ovom radu je na konkretnom numeričkom primeru prikazan način proračuna dejstava usled kranova.

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2. OPTEREĆENJA USLED DELOVANJA KRANOVA

Deo Evrokoda koji obrađuje opterećenja nastala delovanjem kranova nosi oznaku EN 1991-3 [1]. Dejstva usled kranova se uopšte mogu razmatrati kao:

- **Promenljiva dejstva (Q):**
  - vertikalna opterećenja usled sopstvene težine krana i težine tereta koji se diže,
  - horizontalna (podužna i poprečna) dejstva usled ubrzanja, kočenja ili zakošenja krana pri njegovom kretanju
- **Incidentna dejstva (A):**
  - dejstva usled udara krana ili „mačke" u odbojnik ili udaranja sklopa za podizanje u prepreke.

Promenljive vrednosti dejstva sadrže dinamičku komponentu usled inercijalnih sila ili vibracija koje se javljaju pri kretanju krana. Dinamički uticaji se uzimaju u obzir primenom kvazi-statičkog opterećenja koje se određuje kao proizvod karakteristične vrednosti statičkog opterećenja i dinamičkog faktora:

$$F_{\varphi,k} = \varphi_i \cdot F_k \qquad (1)$$

gde su:

$F_{\varphi,k}$ - karakteristična vrednost opterećenja kranom,

φ_i - dinamički faktor,

F_k - karakteristična vrednost statičkog dejstva.

Vrste i primena dinamičkog faktora u zavisnosti od razmatranog uticaja navedeni su u tabeli 1 [1].

Tabela 1: Dinamički faktor

Dinamički faktor	Uticaji koji se razmatraju	Primenjuje se na
φ_1	Pobuda konstrukcije krana usled vertikalnog podizanja tereta sa tla	Sopstvena težina krana
φ_2 ili φ_3	Dinamički efekti usled vertikalnog podizanja tereta od tla do krana Dinamički efekti usled iznenadnog ispuštanja tereta ako se koristi grabilica ili magnet	Teret koji se diže
φ_4	Dinamički efekti usled kretanja krana po šinama ili kranskoj stazi	Sopstvena težina krana i težina tereta koji se podiže
φ_5	Dinamički efekti usled pogonske sile	Pogonska sila
φ_6	Dinamički efekti usled probnog opterećenja	Probno opterećenje
φ_7	Dinamički efekti usled udara u odbojnik	Sila udara

Mogućnost istovremenog delovanja više nabrojanih opterećenja kranom uzima se u obzir na način da se formiraju određene grupe opterećenja kao što je prikazano u tabeli 2 [1].

Tabela 2: Grupe opterećenja i dinamički faktori

	Dejstvo	Simbol	Grupe opterećenja									
			Granična stanja nosivosti							Probno opt.	Incidentno opterećenje	
			1	2	3	4	5	6	7	8	9	10
1	Sopstvena težina krana	Q_c	φ_1	φ_1	1	φ_4	φ_4	φ_4	1	φ_1	1	1
2	Težina tereta	Q_h	φ_1	φ_3	-	φ_4	φ_4	φ_4	$\eta^{1)}$	-	1	1
3	Ubrzanje i kočenje krana	H_L, H_T	φ_5	φ_5	φ_5	φ_5	-	-	-	φ_5	-	-
4	Zakošenje krana	H_S	-	-	-	-	1	-	-	-	-	-
5	Ubrzanje ili kočenje „mačke" ili uređaja za podizanje tereta	H_{T3}	-	-	-	-	-	1	-	-	-	-
6	Vetar	F_W	1	1	1	1	1	-	-	1	-	-
7	Probno opterećenje	Q_T	-	-	-	-	-	-	-	φ_6	-	-
8	Sila usled udara u odbojnik	H_B	-	-	-	-	-	-	-	-	φ_7	-
9	Sila udara sklopa za podizanje	H_{TA}	-	-	-	-	-	-	--	-	-	1
1)	η deo tereta koji se diže i koji ostaje nakon uklanjanja korisnog tereta, a koji nije uračunat u sopstvenu težinu krana											

Svaka od tih grupa opterećenja može se smatrati jednim karakterističnim opterećenjem krana koje se onda može kombinovati sa ostalim vrstama (nekranskih) opterećenja.

3. NUMERIČKI PRIMER

3.1. Osnovni podaci o kranu

Radi sprovođenja dokaza za granično stanje nosivosti i granično stanje upotrebljivosti nosača kranske staze, kao i proveru zamora, potrebno je sprovesti detaljnu analizu opterećenja za nosač kranske staze, tj. izračunati merodavne uticaje prema [3].

Za opsluživanje hale predviđena je dvogredna mosna dizalica sa jednom kukom. Svaki par točkova ima zaseban pogonski motor. Ležajevi između pogona i nosača su za sva četiri točka izvođenja nepokretno-nepokretno (IFF). Poznati su sledeći podaci krana:

- sopstvena težina mosta, Q_{c1}=60 kN,
- sopstvena težina kolica, Q_{c2}=10 kN,
- nosivost krana, $Q_{h,nom}$=100 kN,

– raspon krana, L=15 m,
– rastojanje točkova, a=2,5 m
– minimalno rastojanje kolica i oslonaca, e_{min}=0 m
– brzina dizanja, $v_{h,nom}$=6 m/min
– klasa uređaja za podizanje: HC 3
– S klasa: S6
– raspon nosača kranske staze između oslonaca: l=7 m

3.2. Određivanje dinamičkih faktora

Dinamički faktor φ_1 usvaja se kao gornja vrednost vibracionog impulsa a prema tabeli 2.4, EN 1991-3 [1]:

$$\varphi_1 = 1,1 \tag{2}$$

Dinamički faktor φ_2 računa se prema tabeli 2.4 [1]. Pošto je kran klasifikovan u klasu HC 3, pri čemu su preporuke za klasifikaciju kranova date u Aneksu B standarda EN 1991-3, proizilazi da je:

$$\varphi_2 = \varphi_{2,\min} + \beta_2 \cdot v_h = 1,15 + 0,51 \cdot \frac{6}{60} = 1,20 \tag{3}$$

Parametri $\varphi_{2,min}$ i β_2 usvajaju se prema tabeli 2.5 [1].

Pod pretpostavkom da nema iznenadnog ispuštanja tereta, prema tabeli 2.4 [1], usvaja se:

$$\varphi_3 = 1,00 \tag{4}$$

Pod pretpostavkom da se tolerancije za šine kranskih staza posmatraju prema EN 1993-6 dinamički faktor φ_4 , prema tabeli 2.4 [2], usvaja se:

$$\varphi_4 = 1,00 \tag{5}$$

Dinamički faktor za horizontalna dejstva φ_5 usvaja se prema tabeli 2.6 [2], pod pretpostavkom da se pogonska sila menja „glatko“:

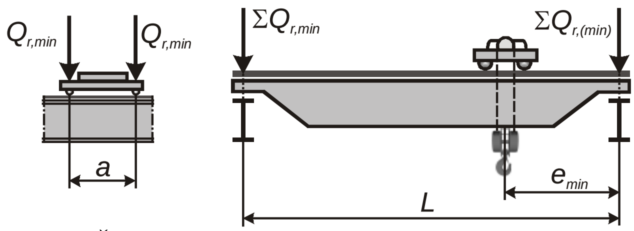
$$\varphi_5 = 1,00 \tag{6}$$

3.3. Određivanje vertikalnih opterećenja

Pri određivanju vertikalnog opterećenja na kranski nosač zbog kretanja „mačke“ po kranskom mostu, potrebno je analizirati različite položaje „mačke“ (sa i bez tereta). Na taj način, moguće je pronaći minimalne i maksimalne vrednosti vertikalnog opterećenja koje se modelira kao koncentrisana sila na mestima točkova. Vertikalna opterećenja potrebno je povećati množenjem odgovarajućim dinamičkim faktorima. Razmatraju se pojedinačna, karakteristična dejstva usled sopstvene težine krana i najnepovoljnijih položaja tereta koji se diže. Takođe, treba voditi računa i o mogućem ekscentričnom delovanju vertikalnog opterećenja. Prema EN 1991-3, nacionalna preporuka je da se ekscentričnost e uzme kao 25% od širine šine b_r.

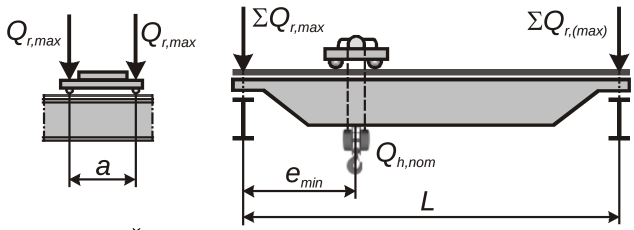
$$e = 0,25 \cdot b_r \tag{7}$$

Minimalni pritisak točka $Q_{r,min}$ bez tereta, sa „mačkom“ u najbližem mogućem položaju uz suprotnu kransku stazu prikazan je na slici 5. Na suprotnoj kranskoj stazi određuje se odgovarajući pritisak točka $Q_{r,(min)}$ [4].



Slika 5: Šema opterećenja za dobijanje minimalnih uticaja

Maksimalni pritisak točka $Q_{r,max}$ pri maksimalnom teretu $Q_{h,nom}$ u najbližem mogućem položaju na posmatranoj kranskoj stazi e_{min}, prikazan je na slici 6. Na suprotnoj kranskoj stazi određuje se odgovarajući pritisak točka $Q_{r,(max)}$ [4],.



Slika 6: Šema opterećenja za dobijanje maksimalnih uticaja

Vertikalna opterećenja (sile) prikazane na šemama opterećenja na slikama 5 i 6 su:
$Q_{h,nom}$ – težina tereta koji se diže,
$Q_{r,max}$ - maksimalna sila u točku (opterećenog krana),
$Q_{r,(max)}$ - odgovarajuća sila (na drugom kraju),
$\Sigma Q_{r,max}$ - suma maksimalnih sila,
$\Sigma Q_{r,(max)}$ - suma odgovarajućih sila (na drugom kraju),
$Q_{r,min}$ - minimalna sila u točku (neopterećenog kraja),
$Q_{r,(min)}$ - odgovarajuća minimalna sila,
$\Sigma Q_{r,min}$ - suma minimalnih sila,
$\Sigma Q_{r,(min)}$ - suma odgovarajućih sila.

Određivanje minimalnih uticaja usled vertikalnih opterećenja vrši se na sledeći način:

a) Grupe opterećenja 1, 2

$$\varphi_1 = 1,1: \ \Rightarrow Q_{c1,k} = 1,1 \cdot 60 = 66 \text{ kN}$$
$$\Rightarrow Q_{c2,k} = 1,1 \cdot 10 = 11 \text{ kN} \tag{7}$$

$$\sum Q_{r,(\min)} = \frac{1}{2} \cdot 66 + 11 = 44 \text{ kN} \ \Rightarrow \ Q_{r,(\min)} = 22 \text{ kN}$$
$$\sum Q_{r,\min} = \frac{1}{2} \cdot 66 = 33 \text{ kN} \ \Rightarrow \ Q_{r,\min} = 16,5 \text{ kN} \tag{8}$$

b) Grupe opterećenja 3, 4, 5, 6

$$\varphi_4 = 1,0: \ \Rightarrow Q_{c1,k} = 1,0 \cdot 60 = 60 \text{ kN}$$
$$\Rightarrow Q_{c2,k} = 1,0 \cdot 10 = 10 \text{ kN} \tag{9}$$

$$\sum Q_{r,(\min)} = \frac{1}{2} \cdot 60 + 10 = 40 \text{ kN} \ \Rightarrow \ Q_{r,(\min)} = 20 \text{ kN}$$
$$\sum Q_{r,\min} = \frac{1}{2} \cdot 60 = 30 \text{ kN} \ \Rightarrow \ Q_{r,\min} = 15,0 \text{ kN} \tag{10}$$

Određivanje maksimalnih uticaja usled vertikalnih opterećenja vrši se na sledeći način:

a) Grupa opterećenja 1

$$\varphi_1 = 1,1: \ \Rightarrow Q_{c1,k} = 1,1 \cdot 60 = 66 \text{ kN}$$
$$\Rightarrow Q_{c2,k} = 1,1 \cdot 10 = 11 \text{ kN} \tag{11}$$
$$\varphi_2 = 1,2: \ \Rightarrow Q_{h,k} = 1,2 \cdot 100 = 120 \text{ kN}$$

$$\sum Q_{r,(\max)} = \frac{1}{2}\cdot 66 = 33\ \text{kN} \Rightarrow Q_{r,(\max)} = 16,5\ \text{kN}$$
$$\sum Q_{r,\max} = \frac{1}{2}\cdot 66 + 11 + 120 = 164\ \text{kN} \Rightarrow Q_{r,\max} = 82\ \text{kN} \qquad (12)$$

b) <u>Grupa opterećenja 2</u>

$$\varphi_1 = 1{,}1: \ \Rightarrow Q_{c1,k} = 1{,}1\cdot 60 = 66\ \text{kN}$$
$$\Rightarrow Q_{c2,k} = 1{,}1\cdot 10 = 11\ \text{kN} \qquad (13)$$
$$\varphi_3 = 1{,}0: \ \Rightarrow Q_{h,k} = 1{,}0\cdot 100 = 100\ \text{kN}$$

$$\sum Q_{r,(\max)} = \frac{1}{2}\cdot 66 = 33\ \text{kN} \ \Rightarrow \ Q_{r,(\max)} = 16,5\ \text{kN}$$
$$\sum Q_{r,\max} = \frac{1}{2}\cdot 66 + 11 + 100 = 144\ \text{kN} \ \Rightarrow \ Q_{r,\max} = 72\ \text{kN} \qquad (14)$$

c) <u>Grupa opterećenja 4, 5, 6</u>

$$\varphi_4 = 1{,}1: \ \Rightarrow Q_{c1,k} = 1{,}0\cdot 60 = 60\ \text{kN}$$
$$\Rightarrow Q_{c2,k} = 1{,}0\cdot 10 = 10\ \text{kN} \qquad (15)$$
$$\varphi_4 = 1{,}0: \ \Rightarrow Q_{h,k} = 1{,}0\cdot 100 = 100\ \text{kN}$$

$$\sum Q_{r,(\max)} = \frac{1}{2}\cdot 60 = 30\ \text{kN} \ \Rightarrow \ Q_{r,(\max)} = 15\ \text{kN}$$
$$\sum Q_{r,\max} = \frac{1}{2}\cdot 60 + 10 + 100 = 140\ \text{kN} \ \Rightarrow \ Q_{r,\max} = 70\ \text{kN} \qquad (16)$$

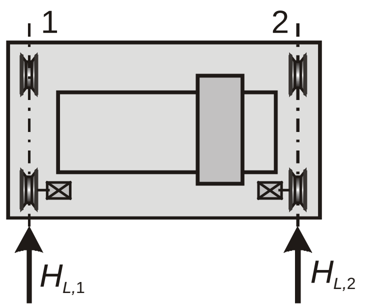
3.4. Određivanje horizontalnih opterećenja

Horizontalna opterećenja koja treba uzeti u obzir su:

- horizontalne sile koje nastaju zbog ubrzanja i kočenja krana,
- horizontalne sile koje nastaju zbog ubrzanja i kočenja „mačke“,
- horizontalne sile koje nastaju zbog zakošenja krana,
- horizontalne sile usled udara krana u odbojnik,
- horizontalne sile usled udara „mačke“ u odbojnik.

a) Podužne horizontalne sile usled ubrzanja i kočenja krana

Podužne horizontalne $H_{L,i}$ sile usled ubrzanja ili kočenja krana, nastaju usled pogonske sile na kontaktnoj površini između šine i pogonskog točka, slika 7.



Slika 7: Podužne horizontalne sile $H_{L,i}$

Podužne sile $H_{L,i}$ primenjene na šinu mogu se izračunati prema:

$$H_{L,i} = H_{L,1} = H_{L,2} = \varphi_5 \cdot K \cdot \frac{1}{n_r} = 1,5\cdot 6\cdot\frac{1}{2} = 4,5\ \text{kN} \qquad (17)$$

gde su:
φ_5 – dinamički faktor,
K – pogonska sila,
n_r – broj nosača kranskih staza, $n_r=2$
i – indeks koji definiše redni broj šine kranske staze, $i=1,2$

Pogonska sila se računa prema:

$$K = K_1 + K_2 = \mu\cdot\sum Q^*_{r,\min} = 0,2\cdot 30 = 6\ \text{kN} \qquad (18)$$

gde su:
μ=0,2 – preporučena vrednost koeficijenta trenja za kontakt površina čelik-čelik. Vrednosti koeficijenta trenja mogu biti date u Nacionalnom aneksu.

Za odvojene pogone točkova:

$$\sum Q^*_{r,\min} = m_w \cdot Q_{r,\min} = 2\cdot 15 = 30\ \text{kN} \qquad (19)$$

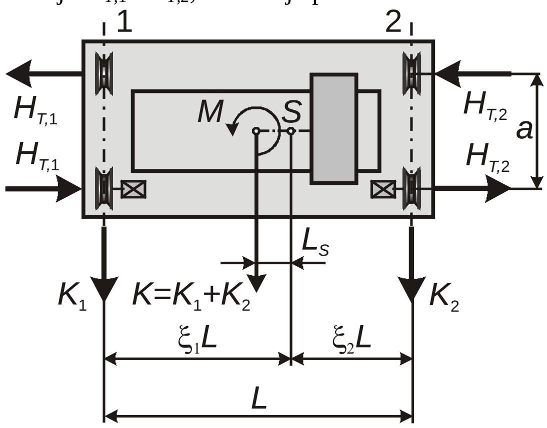
gde je:
m_w=2 – broj pogonjenih točkova

Za centralni pogon:

$$\sum Q^*_{r,\min} = Q_{r,\min} + Q_{r,(\min)} \qquad (20)$$

b) Poprečne horizontalne sile usled ubrzanja i kočenja krana

Rezultujući moment M usled pogonskih sila koji deluje u težištu uravnotežen je poprečnim horizontalnim silama koje deluju $H_{T,1}$ i $H_{T,2}$, kao što je prikazano na slici 8.



Slika 8. Poprečne horizontalne sile $H_{T,i}$

Poprečne horizontalne sile usled ubrzanja i kočenja krana računaju se prema:

$$H_{T1} = \varphi_5 \cdot \xi_2 \cdot \frac{M}{a} = 1,5\cdot 0,18\cdot\frac{29,7}{2,5} = 3,2\ \text{kN} \qquad (21)$$

$$H_{T2} = \varphi_5 \cdot \xi_1 \cdot \frac{M}{a} = 1,5\cdot 0,82\cdot\frac{29,7}{2,5} = 14,6\ \text{kN} \qquad (22)$$

gde su:

$$\xi_1 = \frac{\sum Q_{r,\max}}{\sum Q_r} = \frac{140}{170} = 0,82$$
$$\sum Q_r = \sum Q_{r,\max} + \sum Q_{r,(\max)} = 140 + 30 = 170\ \text{kN}$$
$$\xi_2 = 1 - \xi_1 = 1 - 0,82 = 0,18 \qquad (23)$$
$$M = K\cdot l_S = 6\cdot 4,95 = 29,7\ \text{kN}$$
$$l_S = (\xi_1 - 0,5)\cdot l = (0,83 - 0,5)\cdot 15 = 4,95\ \text{m}$$

c) Podužne i poprečne horizontalne sile usled zakošenja krana

Sila vođenja, S, i horizontalne sile, $H_{S,i,j,k}$, usled zakošenja krana mogu da se izračunaju prema:

$$S = f\cdot\lambda_{S,j}\cdot\sum Q_r = 0,248\cdot 0,5\cdot 170 = 21,1\ \text{kN} \qquad (24)$$
$$H_{S,1,j,L} = f\cdot\lambda_{S,1,j,L}\cdot\sum Q_r \qquad (25)$$
$$H_{S,2,j,L} = f\cdot\lambda_{S,2,j,L}\cdot\sum Q_r \qquad (26)$$
$$H_{S,1,j,T} = f\cdot\lambda_{S,1,j,T}\cdot\sum Q_r \qquad (27)$$

$$H_{S,2,j,T} = f \cdot \lambda_{S,2,j,T} \cdot \sum Q_r \tag{28}$$

gde su:

j - indeks koji se odnosi na pogonski par točkova.

f – faktor koji zavisi od ugla zakošenja α, računa se prema:

$$\begin{aligned} f &= 0,3 \cdot \left(1-\exp\left(-250\cdot\alpha\right)\right) = 0,3\cdot\left(1-\exp\left(-250\cdot 0,007\right)\right) \\ f &= 0,2484 \le 0,3 \end{aligned} \tag{29}$$

Ugao zakošenja α računa se prema:

$$\begin{aligned} \alpha &= \alpha_F + \alpha_V + \alpha_0 = 0,004 + 0,002 + 0,001 = \\ &= 0,007 \le 0,015 \text{ rad} \end{aligned} \tag{30}$$

gde su α_F, α_V, α_0 definisani u tabeli 2.7 standarda EN 1991-3:

$$\alpha_F = \frac{0,75x}{a_{ext}} = \frac{10}{2500} = 0,004 \text{ rad} \tag{31}$$

$$\alpha_V = \frac{y}{a_{ext}} = \frac{0,10b}{a_{ext}} = \frac{0,1\cdot 50}{2500} = 0,002 \text{ rad} \tag{32}$$

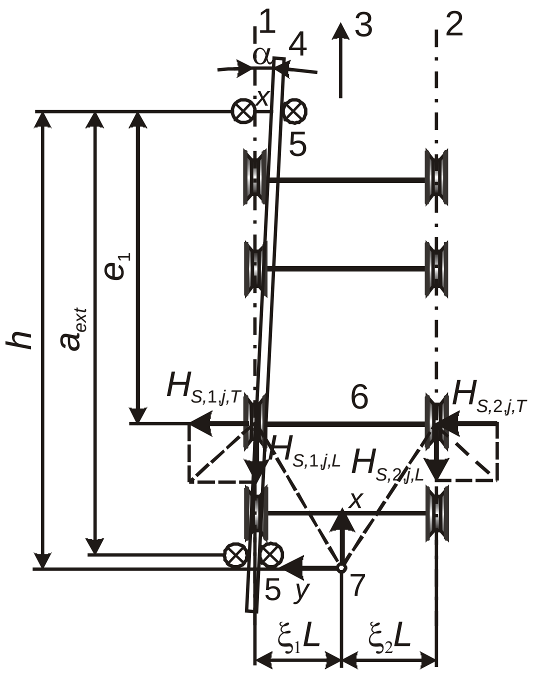
$$\alpha_0 = 0,001 \text{ rad} \tag{33}$$

Faktor sile $\lambda_{S,I,j,k}$ zavisi od kombinacije parova točkova i rastojanja h između trenutnog centra rotacije i odgovarajućeg sredstva vođenja, kao na slici 9, gde su:

i - oznaka za redni broj šine,

j - oznaka za par točkova,

k - pravac sile (L – podužni, T – poprečni).



Slika 9. Definisanje ugla α i rastojanja h

Vrednost rastojanja h može se odrediti prema tabeli 2.8 standarda EN 1991-3, a faktora sile prema izrazima datim u tabeli 2.9. istog standarda.

$$h = \frac{m\cdot\xi_1\cdot\xi_2\cdot l^2 + \sum e_j^2}{\sum e_j} = \frac{0+2,50^2}{2,5} = 2,5 \text{ m} \tag{34}$$

gde su:

m – broj parova spojenih točkova (m=0 za nezavisne parove točkova IFF)

$\xi_1 l$ – rastojanje trenutnog centra rotacije od šine 1,

$\xi_2 l$ – rastojanje trenutnog centra rotacije od šine 2,

L – raspon krana

e_j – rastojanje para točkova j od odgovarajućeg sredstva vođenja.

e_1=0 ako se koriste točkovi sa vencem

e_2=a=2,5 m

$$\lambda_{S,j} = 1 - \frac{\sum e_j}{n\cdot h} = 1 - \frac{2,5}{2\cdot 2,5} = 0,5 \tag{35}$$

$$\lambda_{S,1,L} = \lambda_{S,2,L} = 0 \tag{36}$$

<u>Za par točkova 1</u>:

$$\lambda_{S,1,1,T} = \frac{\xi_2}{n}\left(1-\frac{e_1}{h}\right) = \frac{0,18}{2}\left(1-0\right) = 0,09 \tag{37}$$

$$\lambda_{S,2,1,T} = \frac{\xi_1}{n}\left(1-\frac{e_1}{h}\right) = \frac{0,82}{2}\left(1-0\right) = 0,41 \tag{38}$$

<u>Za par točkova 2:</u>

$$\lambda_{S,1,2,T} = \frac{\xi_2}{n}\left(1-\frac{e_2}{h}\right) = \frac{0,18}{2}\left(1-\frac{2,5}{2,5}\right) = 0 \tag{39}$$

$$\lambda_{S,2,2,T} = \frac{\xi_1}{n}\left(1-\frac{e_2}{h}\right) = \frac{0,82}{2}\left(1-\frac{2,5}{2,5}\right) = 0 \tag{40}$$

Tada su podužne sile:

$$H_{S,1,L} = f \cdot \lambda_{S,1,L} \cdot \sum Q_r = 0 \tag{41}$$

$$H_{S,2,L} = f \cdot \lambda_{S,2,L} \cdot \sum Q_r = 0 \tag{42}$$

Sila vođenja se određuju prema:

$$S = f \cdot \lambda_S \cdot \sum Q_r = 0,248\cdot 0,5\cdot 170 = 21,1 \text{ kN} \tag{43}$$

Poprečne sile za par točkova 1 postaju:

$$\begin{aligned} H_{S,1,1,T} &= f \cdot \lambda_{S,1,1,T} \cdot \sum Q_r = \\ &= 0,248\cdot 0,09\cdot 170 = 3,8 \text{ kN} \end{aligned} \tag{44}$$

$$\begin{aligned} H_{S,2,1,T} &= f \cdot \lambda_{S,2,1,T} \cdot \sum Q_r = \\ &= 0,248\cdot 0,41\cdot 170 = 17,3 \text{ kN} \end{aligned} \tag{45}$$

$$\begin{aligned} &\Rightarrow H_{S,1,T} = S - H_{S,1,1,T} = 17,3 \text{ kN} \\ &\Rightarrow H_{S,2,T} = H_{S,2,1,T} = 17,3 \text{ kN} \end{aligned} \tag{46}$$

Poprečne sile za par točkova 2:

$$H_{S,1,2,T} = f \cdot \lambda_{S,1,2,T} \cdot \sum Q_r = 0,248\cdot 0\cdot 170 = 0 \text{ kN} \tag{47}$$

$$H_{S,2,2,T} = f \cdot \lambda_{S,2,2,T} \cdot \sum Q_r = 0,248\cdot 0\cdot 170 = 0 \text{ kN} \tag{48}$$

Sila usled ubrzanja ili kočenja „mačke“ je:

$$H_{T,3} = 0,1\cdot\left(10+100\right) = 11 \text{ kN} \tag{49}$$

3.5. Dejstvo usled ekscentričnosti točka

Dejstvo usled ekscentričnog položaja točka dizalice na šini, Q_r, treba da bude uzet u zavisnosti od dela širine glave šine b_r.

Nacionalni prilog preporučuje vrednost ekscentriciteta prema slici 10:

$$e = 0,25\cdot b_r = 0,25\cdot 55 = 13,75 \text{ mm} \tag{50}$$

3.6. Zamor opterećenje

Zamor opterećenje za kranske nosače je definisano u EN 1991-3:

$$Q_{e,i} = \varphi_{fat}\cdot\lambda_i\cdot Q_{\max,i} \tag{51}$$

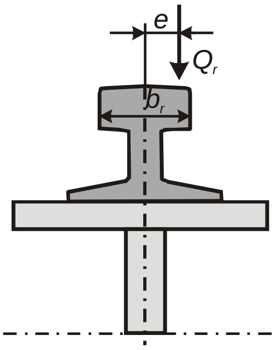
gde su:

φ_{fat} – dinamički faktor koji može da se odredi prema:

$$\varphi_{fat,1} = \frac{1+\varphi_1}{2} = \frac{1+1,1}{2} = 1,05 \tag{52}$$

$$\varphi_{fat,2} = \frac{1+\varphi_2}{2} = \frac{1+1,2}{2} = 1,1 \tag{53}$$

λ_I – faktor ekvivalentnog dinamičkog oštećenja (zavisi od klase krana).



Slika 10. Ekscentričnost opterećenja točka

Pod pretpostavkom da je kran klase S_6 prema EN 13001-1 [5], usvaja se:

$$\lambda_i = 0,794 \text{ za normalni napon} \qquad \lambda_i = 0,871 \text{ za smičući napon} \tag{54}$$

$Q_{max,i}$ – maksimalni pritisak točka i

Za normalne napone:

$$Q_{e,i} = \varphi_{fat} \cdot \lambda_i \cdot Q_{\max,i} = 1,1 \cdot 0,794 \cdot 70 = 61,1 \text{ kN} \tag{55}$$

Za smičuće napone:

$$Q_{e,i} = \varphi_{fat} \cdot \lambda_i \cdot Q_{\max,i} = 1,1 \cdot 0,871 \cdot 70 = 67,1 \text{ kN} \tag{56}$$

U tabeli 3 prikazana su vertikalna i horizontalna dejstva kranova određena prema gore navedenom postupku. U tabeli 4 navedene su vrednosti parcijalnih koeficijenata, dok su u tabeli 5 prikazane vrednosti koeficijenata ψ za kombinaciju dejstava prema EN 1991-3.

Tabela 3: Grupe opterećenja i dinamički faktori za numerički primer

Grupe opterećenja			1	2	3	4	5	6
Faktor uvećanja koji se razmatra za grupu opterećenja			φ_1=1,1 φ_2=1,2 φ_5=1,5	φ_1=1,1 φ_3=1,0 φ_5=1,5	φ_1=1,1 φ_5=1,5	φ_4=1,1 φ_5=1,5	φ_4=1,1	φ_4=1,1
Vertikalna opterećenja	Sopstvena težina karana	$Q_{r,(min)}$	22	22	20	20	20	20
		$Q_{r,min}$	16,5	16,5	15	15	15	15
	Sopstvena težina karana i tereta koji se podiže	$Q_{r,(max)}$	16,5	16,5	-	15	15	15
		$Q_{r,max}$	82	72	-	70	70	70
Horizontalna opterećenja	Ubrzanje krana	$H_{L,1}$	4,5	4,5	4,5	4,5	-	-
		$H_{L,2}$	4,5	4,5	4,5	4,5	-	-
		$H_{T,1}$	3,2	3,2	3,2	3,2	-	-
		$H_{T,2}$	14,6	14,6	14,6	14,6	-	-
	Zakošenje krana	$H_{S1,L}$	-	-	-	-	0	-
		$H_{S2,L}$	-	-	-	-	0	-
		$H_{S1,T}$	-	-	-	-	17,3	-
		$H_{S2,T}$	-	-	-	-	17,3	-
	Ubrzanje mačke	$H_{T,3}$	-	-	-	-	-	11

Tabela 4: Parcijalni koeficijenti sigurnosti za kombinacije dejstva

Dejstva	Oznaka	Proračunske situacije	
		Stalne i prolazne	Incidentne
Stalna dejstva usled krana - nepovoljna - povoljna	 γ_{Gsup} γ_{Ginf}	 1,35 1,00	 1,00 1,00
Promenljiva dejstva usled krana - nepovoljna - povoljna kada je kran prisutan kada kran nije prisutan	 γ_{Qsup} γ_{Qinf}	 1,35 1,00 0,00	 1,00 1,00 0,00
Ostala promenljiva dejstva - nepovoljna - povoljna	γ_Q	 1,50 0,00	 1,00 0,00
Incidentna	γ_A		1,00

Tabela 5: Koeficijenti ψ za kombinacije dejstva

Dejstva	Oznaka	ψ_0	ψ_1	ψ_2
Jedan kran ili grupa opterećenja usled kranova	Q_r	1,0	0,9	Odnos stalnog i ukupnog opterećenja usled krana

Za verifikaciju graničnih stanja nosivosti, treba uzeti u obzir sledeće kombinacije dejstava:

- Za stalne i prolazne proračunske situacije:

$$\sum_{j\geq 1}\gamma_{G,j}\cdot G_{k,j}+\gamma_P\cdot P+\gamma_{Q,1}\cdot Q_{k,1}+\sum_{i>1}\gamma_{Q,i}\cdot\psi_{0,i}\cdot Q_{k,i} \quad (57)$$

- Za incidentne proračunske situacije:

$$\sum_{j\geq 1}G_{k,j}+P+A_d+\left(\psi_{1,1}\text{ ili }\psi_{2,1}\right)Q_{k,i}+\sum_{i>1}\psi_{2,i}\cdot Q_{k,i} \quad (58)$$

4. ZAKLJUČAK

U radu je prikazan sasvim nov pristup određivanja opterećenja usled dejstva kranova prema savremenom evropskom standardu, Evrokodu. Opisani postupak je daleko složeniji i precizniji u odnosu na dosadašnje poznate i korišćene proračune. Prikazane su sve vrste opterećenja koja mogu nastati prilikom dejstva krana u toku njegove eksploatacije. U numeričkom primeru obrađene su sve potrebne analize dejstava prema navedenom standardu. Za dobijena merodavna opterećenja određeni su skupovi opterećenja kao karakteristične vrednosti jednog delovanja na kranski nosač kao deo konstrukcije hale sa kojom je kran u interakciji. Zbog obimnosti celog proračuna u radu su obrađena samo dejstva čijim izračunavanjem se dalje sprovode dokazi pouzdanosti delova konstrukcije hale ili krana za granično stanje nosivosti, granično stanje upotrebljivosti, kao i procenu zamora.

ZAHVALNICA

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Modelling of Actions Induced by Cranes According to Eurocodes

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This paper describes the method of modelling of actions due to the operation of cranes according to Eurocode standards. This procedure is more complex and more precise in relation to the known calculations of the crane actions. The procedure of calculation of the crane actions is illustrated on the concrete numerical example of double girder crane with a hook. Loads that act during crane operation were defined and appropriate dynamic factors were adopted based on their character. These actions induced by crane should be taken into account for the further proof of the ultimate limit state, serviceability limit state and fatigue verification.

Keywords: crane, girder, action, design, Eurocode

1. INTRODUCTION

The problems of the cranes' actions have been processed within the Eurocodes in two parts:

- EN 1991-3: Actions on structures – Part 3: Actions induced by cranes and machinery [1],
- EN 1993-6: Design of steel structures – Part 6: Crane supporting structures [2].

Both standards have been adopted as SRPS EN in English.

There are different versions of the crane installation, i.e. the ways of its connection with the construction of the industrial building in which it is installed. For lighter loads, monorail cranes are used as shown in figure 1, while bridge cranes are mostly used for larger loads where the construction of the crane lies on the construction of the building by special supports (crane supports).

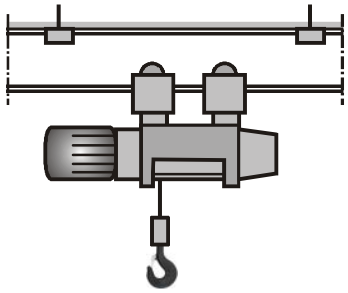


Figure 1: Runway beam with hoist block

The underslung crane with hoist block is shown in figure 2, in which the crane carriers are hanged on the construction of the building. Overhead travelling crane that is supported on the top of the crane runway beam is shown on figure 3. There are some other installations that contain their own construction, etc.

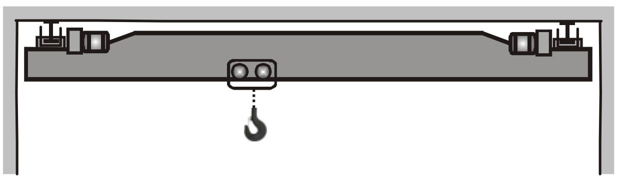


Figure 2: Underslung crane with hoist block

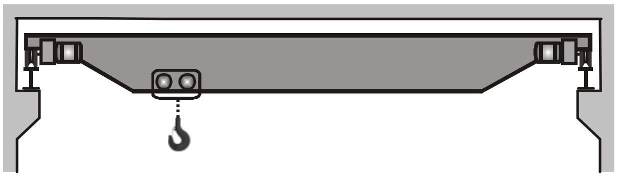
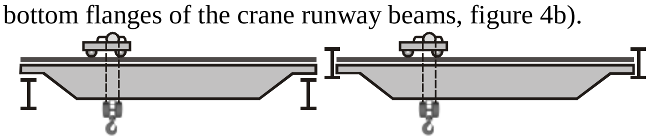


Figure 3: Overhead travelling crane

Overhead bridge cranes are usually designed in the following two variants:

- overhead travelling crane that is supported at the top of the crane runway beam, figure 4a) or,

- overhead travelling crane that is supported at the bottom flanges of the crane runway beams, figure 4b).



a) b)

Figure 4: Overhead bridge cranes

Due to the travelling of the crane, there are series of moving forces that act in:

- vertical – gravity direction caused by the self-weight of the crane and the hoist load as dominant loads,
- longitudinal horizontal direction due to acceleration or deceleration of the crane, eccentric load lifting, skewing of the crane and impact of the crane on the buffer,
- transversal horizontal direction due to acceleration or deceleration of the crane, eccentric load lifting, skewing of the crane and impact of the crab on the buffer.

Actions induced by cranes are composed of a static and a dynamic component. Both are functions of time and they vary depending on the position of the crane and the intensity of the hoist load, as well as the position of the load on the crane girder. Dynamic influences are taken into account in such a way that the known static load is multiplied by the corresponding dynamic factors. Certainly, the problem of fatigue which is very important in cranes should be mentioned, since they are exposed to multiple cycles of loading and unloading. In this paper, the concrete

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numerical example shows the method of calculating the actions induced by cranes.

2. ACTIONS INDUCED BY CRANES

The part of the Eurocode that deals with the actions caused by the operation of the cranes is EN 1991-3 [1]. Actions induced by cranes are generally classified as:

- **Variable actions (Q):**
  - variable vertical crane actions caused by the self-weight of the crane and the hoist load,
  - variable horizontal (longitudinal or transversal) crane actions caused by acceleration or deceleration or by skewing or other dynamic effects.
- **Accidental actions (A):**
  - accidental actions due to collision of crane or crab with buffers (buffer forces) or collision of lifting attachments with obstacles (tilting forces).

Variable actions are composed of dynamic components induced by inertial forces or vibrations during crane travelling. Dynamic effects are taken into account by using a quasi-static load that is determined by multiplication of characteristic value of the static load and dynamic factors φ_i:

$$F_{\varphi,k} = \varphi_i \cdot F_k \quad (1)$$

where:
$F_{\varphi,k}$ - is the characteristic value of a crane action,
φ_i - is the dynamic factor,
F_k - is the characteristic static component of a crane action.

The various dynamic factors and their application are listed in table 1 [1].

Table 1: Dynamic factors φ_i

Dynamic factors	Effects to be considered	To be applied to
φ_1	Excitation of the crane structure due to lifting the hoist load off the ground	Self-weight of the crane
φ_2 or φ_3	Dynamic effects of transferring the hoist load from the ground to the crane Dynamic effects of sudden release of the payload if for example grabs or magnets are used	Hoist load
φ_4	Dynamic effects induced when the crane is travelling on rail tracks or runways	Self-weight of the crane and hoist load
φ_5	Dynamic effects caused by drive forces	Drive forces
φ_6	Dynamic effects of a test load moved by the drives in the way the crane is used	Test load
φ_7	Dynamic elastic effects of impact on buffers	Buffer loads

The simultaneity of the crane load components may be taken into account by considering groups of loads as identified in table 2 [1].

Table 2: Groups of loads and dynamic factors

	Action	Symbol	Groups of loads									
			Ultimate Limit State							Test load	Accidental load	
			1	2	3	4	5	6	7	8	9	10
1	Self-weight of crane	Q_c	φ_1	φ_1	1	φ_4	φ_4	φ_4	1	φ_1	1	1
2	Hoist load	Q_h	φ_1	φ_3	-	φ_4	φ_4	φ_4	η 1)	-	1	1
3	Acceleration of crane bridge	H_L, H_T	φ_5	φ_5	φ_5	φ_5	-	-	-	φ_5	-	-
4	Skewing of crane bridge	H_S	-	-	-	-	1	-	-	-	-	-
5	Acceleration or braking of crab or hoist block	H_{T3}	-	-	-	-	-	1	-	-	-	-
6	In-service wind	F_W	1	1	1	1	1	-	-	1	-	-
7	Test load	Q_T	-	-	-	-	-	-	-	φ_6	-	-
8	Buffer force	H_B	-	-	-	-	-	-	-	-	φ_7	-
9	Tilting force	H_{TA}	-	-	-	-	-	-	--	-	-	1

1) η is the proportion of the hoist load that remains when the payload is removed, but is not included in the self-weight of the crane.

Each of these groups of loads should be considered as one characteristic crane action which may be combined with other non-crane loads.

3. NUMERICAL EXAMPLE

3.1. Basic crane data

For the purpose of proof of the ultimate limit state, the serviceability limit state and fatigue verification, a detailed load analysis for the crane should be carried out, i.e. calculation of the relevant effects induced by cranes shall be determined for each design situation identified in accordance with [3].

Double girder overhead crane with one hook is designed to serve the industrial building. Each pair of wheels has a separate drive motor. The bearings between the drive and the carrier are fixed for all four wheels (IFF). The following properties are assumed in the design example of the crane:

- Self-weight of the crane, Q_{c1}=60 kN,
- Self-weight of the crab, Q_{c2}=10 kN,
- Hoist load, $Q_{h,nom}$=100 kN,
- Span length of the crane bridge, L=15 m,
- Wheel spacing, a=2,5 m
- Min. spacing between crab and support, e_{min}=0 m
- Lifting speed, $v_{h,nom}$=6 m/min
- Hoisting class of the crane: HC 3
- S class: S6
- Span of the crane supporting structure: l=7 m

3.2. Determination of the dynamic magnification factors

The magnification factor φ_1 has to be upper value of the vibrational pulses according to the table 2.4, EN 1991-3 [1]:

$$\varphi_1 = 1,1 \tag{2}$$

The magnification factor φ_2 is also determined according to the table 2.4 [1]. Since the crane is classified as the HC 3 class, where the recommendations for the classification of cranes are given in Annex B of EN 1991-3, it follows that:

$$\varphi_2 = \varphi_{2,\min} + \beta_2 \cdot v_h = 1,15 + 0,51 \cdot \frac{6}{60} = 1,20 \tag{3}$$

The parameters $\varphi_{2,min}$ and β_2 were obtained from the table 2.5 [1].

In the design example, it is assumed that no part of the payload may be suddenly released or dropped, so the following value was adopted according to the table 2.4 [1]:

$$\varphi_3 = 1,00 \tag{4}$$

Assuming that the tolerances for rail tracks are specified in EN 1993-6 [2] the magnification factor φ_4 is, according to the table 2.4 [2]:

$$\varphi_4 = 1,00 \tag{5}$$

The dynamic factor φ_5 is, according to the table 2.6 [2], for the smoothly change of the drive force:

$$\varphi_5 = 1,00 \tag{6}$$

3.3. Determination of the vertical wheel loads

In determining the vertical load due to the movement of the crab on the crane bridge, it is necessary to analyze the different positions of the crab (with and without hoist load). In this way, it is possible to find the minimum and maximum values of the vertical load that are modelled as a concentrated force at wheel points. Vertical loads should be increased by multiplying by appropriate dynamic factors. For normal service conditions, the vertical load should be taken as composed of the self-weight of the hoist block, the hoist load and the dynamic factor. Also, the eccentricity of application of a vertical wheel load should be taken in consideration. The recommended value of eccentricity according to the National Annex is:

$$e = 0,25 \cdot b_r \tag{7}$$

The minimum vertical wheel load $Q_{r,min}$ when the crane is unloaded, with a crab at the minimum possible position to the opposite crane rail, is shown in figure 5. On the opposite crane rail, the appropriate vertical wheel load, $Q_{r,(min)}$, is determined [4].

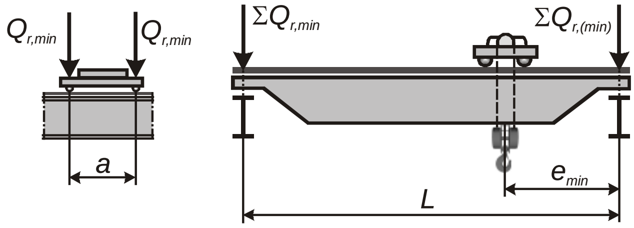

Figure 5: Load arrangement of the unloaded crane to obtain the minimum loading

The maximum vertical wheel load $Q_{r,max}$ at maximum hoist load $Q_{h,nom}$ in the nearest possible position on the observed crane rail, e_{min}, is shown on figure 6. On the opposite side, the appropriate vertical wheel load, $Q_{r,(max)}$, is determined [4].

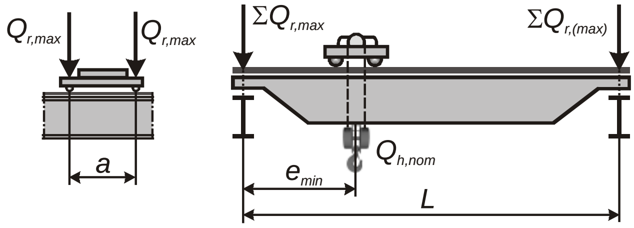

Figure 6: Load arrangement of the unloaded crane to obtain the maximum loading

The relevant vertical wheel loads from a crane on a runway beam, should be determined by considering the load arrangements illustrated on figures 5 and 6, where:
$Q_{h,nom}$ – is the nominal hoist load,
$Q_{r,max}$ – is the maximum load per wheel of the loaded crane,
$Q_{r,(max)}$ – is the accompanying load per wheel of the loaded crane,
$\Sigma Q_{r,max}$ – is the sum of the maximum loads $Q_{r,max}$ per runway of the loaded crane,
$\Sigma Q_{r,(max)}$ – is the sum of the accompanying maximum loads $Q_{r,(max)}$ per runway of the loaded crane,
$Q_{r,min}$ – is the minimum load per wheel of the unloaded crane,
$Q_{r,(min)}$ – is the accompanying load per wheel of the unloaded crane,
$\Sigma Q_{r,min}$ – is the sum of the minimum loads Qr,min per runway of the unloaded crane,
$\Sigma Q_{r,(min)}$ – is the sum of the accompanying minimum loads $Q_{r,(min)}$ per runway of the unloaded crane.

Determination of minimum actions due to vertical loads is carried out as follows:

a) <u>Load groups 1, 2</u>

$$\varphi_1 = 1,1: \ \Rightarrow Q_{c1,k} = 1,1 \cdot 60 = 66 \text{ kN} \\ \Rightarrow Q_{c2,k} = 1,1 \cdot 10 = 11 \text{ kN} \tag{7}$$

$$\sum Q_{r,(\min)} = \frac{1}{2} \cdot 66 + 11 = 44 \text{ kN} \ \Rightarrow \ Q_{r,(\min)} = 22 \text{ kN} \\ \sum Q_{r,\min} = \frac{1}{2} \cdot 66 = 33 \text{ kN} \ \Rightarrow \ Q_{r,\min} = 16,5 \text{ kN} \tag{8}$$

b) <u>Load groups 3, 4, 5, 6</u>

$$\varphi_4 = 1,0: \Rightarrow Q_{c1,k} = 1,0 \cdot 60 = 60 \text{ kN}$$
$$\Rightarrow Q_{c2,k} = 1,0 \cdot 10 = 10 \text{ kN} \quad (9)$$

$$\sum Q_{r,(\min)} = \frac{1}{2} \cdot 60 + 10 = 40 \text{ kN} \Rightarrow Q_{r,(\min)} = 20 \text{ kN}$$
$$\sum Q_{r,\min} = \frac{1}{2} \cdot 60 = 30 \text{ kN} \Rightarrow Q_{r,\min} = 15,0 \text{ kN} \quad (10)$$

Determination of maximum actions due to vertical loads is carried out as follows:

a) Load group 1

$$\varphi_1 = 1,1: \Rightarrow Q_{c1,k} = 1,1 \cdot 60 = 66 \text{ kN}$$
$$\Rightarrow Q_{c2,k} = 1,1 \cdot 10 = 11 \text{ kN} \quad (11)$$
$$\varphi_2 = 1,2: \Rightarrow Q_{h,k} = 1,2 \cdot 100 = 120 \text{ kN}$$

$$\sum Q_{r,(\max)} = \frac{1}{2} \cdot 66 = 33 \text{ kN} \Rightarrow Q_{r,(\max)} = 16,5 \text{ kN}$$
$$\sum Q_{r,\max} = \frac{1}{2} \cdot 66 + 11 + 120 = 164 \text{ kN} \Rightarrow Q_{r,\max} = 82 \text{ kN} \quad (12)$$

b) Load group 2

$$\varphi_1 = 1,1: \Rightarrow Q_{c1,k} = 1,1 \cdot 60 = 66 \text{ kN}$$
$$\Rightarrow Q_{c2,k} = 1,1 \cdot 10 = 11 \text{ kN} \quad (13)$$
$$\varphi_3 = 1,0: \Rightarrow Q_{h,k} = 1,0 \cdot 100 = 100 \text{ kN}$$

$$\sum Q_{r,(\max)} = \frac{1}{2} \cdot 66 = 33 \text{ kN} \Rightarrow Q_{r,(\max)} = 16,5 \text{ kN}$$
$$\sum Q_{r,\max} = \frac{1}{2} \cdot 66 + 11 + 100 = 144 \text{ kN} \Rightarrow Q_{r,\max} = 72 \text{ kN} \quad (14)$$

c) Load groups 4, 5, 6

$$\varphi_4 = 1,1: \Rightarrow Q_{c1,k} = 1,0 \cdot 60 = 60 \text{ kN}$$
$$\Rightarrow Q_{c2,k} = 1,0 \cdot 10 = 10 \text{ kN} \quad (15)$$
$$\varphi_4 = 1,0: \Rightarrow Q_{h,k} = 1,0 \cdot 100 = 100 \text{ kN}$$

$$\sum Q_{r,(\max)} = \frac{1}{2} \cdot 60 = 30 \text{ kN} \Rightarrow Q_{r,(\max)} = 15 \text{ kN}$$
$$\sum Q_{r,\max} = \frac{1}{2} \cdot 60 + 10 + 100 = 140 \text{ kN} \Rightarrow Q_{r,\max} = 70 \text{ kN} \quad (16)$$

3.4. Determination of the horizontal loads

The following types of horizontal forces from overhead travelling cranes should be taken into account:

- horizontal forces caused by acceleration or deceleration of the crane bridge,
- horizontal forces caused by acceleration or deceleration of the crab or underslung trolley,
- horizontal forces caused by skewing of the crane,
- buffer forces related to crane movement,
- buffer forces related to movement of the crab or underslung trolley.

a) Longitudinal horizontal forces caused by acceleration or deceleration of the crane bridge

The longitudinal forces $H_{L,i}$ caused by acceleration and deceleration of crane structures result from the drive force at the contact surface between the rail and the driven wheel, figure 7.

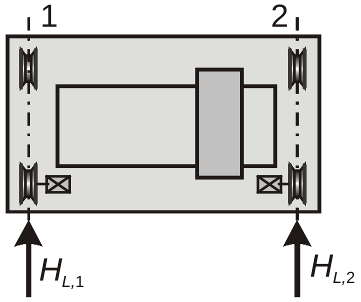

Figure 7: Longitudinal horizontal forces $H_{L,i}$

The longitudinal forces $H_{L,i}$ applied to a runway beam may be calculated as follows:

$$H_{L,i} = H_{L,1} = H_{L,2} = \varphi_5 \cdot K \cdot \frac{1}{n_r} = 1,5 \cdot 6 \cdot \frac{1}{2} = 4,5 \text{ kN} \quad (17)$$

where:
φ_5 – is the dynamic factor,
K – is the drive force,
n_r – is the number of runway beams, $n_r=2$,
i – is the integer to identify the runway beam, $i=1,2$

The drive force K may be calculated as follows:

$$K = K_1 + K_2 = \mu \cdot \sum Q^*_{r,\min} = 0,2 \cdot 30 = 6 \text{ kN} \quad (18)$$

where:
μ=0,2 – is the recommended value for the friction factor for the contact steel-steel. The value of the friction factor may be given in the National Annex.

For a single wheel drive:

$$\sum Q^*_{r,\min} = m_w \cdot Q_{r,\min} = 2 \cdot 15 = 30 \text{ kN} \quad (19)$$

where:
m_w=2 – is the number of single wheel drives.

For a central wheel drive:

$$\sum Q^*_{r,\min} = Q_{r,\min} + Q_{r,(\min)} \quad (20)$$

b) Poprečne horoizontalne sile usled ubrzanja i kočenja krana

The moment M resulting from the drive forces which should be applied at the centre of mass is equilibrated by transverse horizontal forces $H_{T,1}$ and $H_{T,2}$, see figure 8.

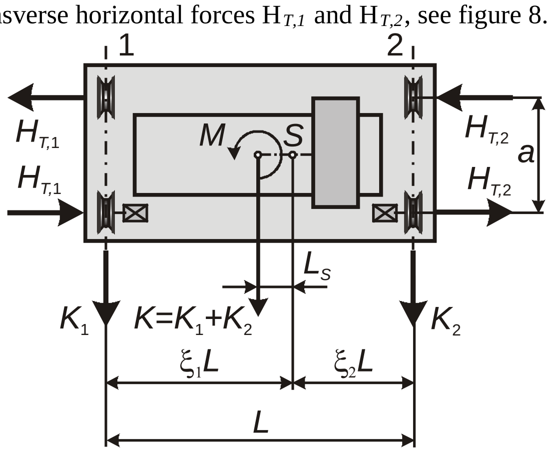

Figure 8: Definition of the transverse forces $H_{T,i}$

The transverse horizontal forces may be calculated as follows:

$$H_{T1} = \varphi_5 \cdot \xi_2 \cdot \frac{M}{a} = 1,5 \cdot 0,18 \cdot \frac{29,7}{2,5} = 3,2 \text{ kN} \quad (21)$$

$$H_{T2} = \varphi_5 \cdot \xi_1 \cdot \frac{M}{a} = 1,5 \cdot 0,82 \cdot \frac{29,7}{2,5} = 14,6 \text{ kN} \quad (22)$$

where:

$$\xi_1 = \frac{\sum Q_{r,\max}}{\sum Q_r} = \frac{140}{170} = 0,82$$

$$\sum Q_r = \sum Q_{r,\max} + \sum Q_{r,(\max)} = 140 + 30 = 170 \text{ kN}$$

$$\xi_2 = 1 - \xi_1 = 1 - 0,82 = 0,18 \quad (23)$$

$$M = K \cdot l_S = 6 \cdot 4,95 = 29,7 \text{ kN}$$

$$l_S = (\xi_1 - 0,5) \cdot l = (0,83 - 0,5) \cdot 15 = 4,95 \text{ m}$$

c) Horizontal forces and the guide force caused by skewing of the crane

The guide force S and the transverse forces $H_{S,i,j,k}$ caused by skewing may be obtained from:

$$S = f \cdot \lambda_{S,j} \cdot \sum Q_r = 0,248 \cdot 0,5 \cdot 170 = 21,1 \text{ kN} \quad (24)$$

$$H_{S,1,j,L} = f \cdot \lambda_{S,1,j,L} \cdot \sum Q_r \quad (25)$$

$$H_{S,2,j,L} = f \cdot \lambda_{S,2,j,L} \cdot \sum Q_r \quad (26)$$

$$H_{S,1,j,T} = f \cdot \lambda_{S,1,j,T} \cdot \sum Q_r \quad (27)$$

$$H_{S,2,j,T} = f \cdot \lambda_{S,2,j,T} \cdot \sum Q_r \quad (28)$$

where:
j - index that indicates the driven wheel pair,
f - the "non-positive" factor may be determined from:

$$f = 0,3 \cdot \left(1 - \exp\left(-250 \cdot \alpha\right)\right) = 0,3 \cdot \left(1 - \exp\left(-250 \cdot 0,007\right)\right) \quad (29)$$
$$f = 0,2484 \leq 0,3$$

The skewing angle α, figure 9, may be determined as follows:

$$\alpha = \alpha_F + \alpha_V + \alpha_0 = 0,004 + 0,002 + 0,001 = 0,007 \leq 0,015 \text{ rad} \quad (30)$$

where α_F, α_V, α_0 are as defined in table 2.7 [1]:

$$\alpha_F = \frac{0,75x}{a_{ext}} = \frac{10}{2500} = 0,004 \text{ rad} \quad (31)$$

$$\alpha_V = \frac{y}{a_{ext}} = \frac{0,10b}{a_{ext}} = \frac{0,1 \cdot 50}{2500} = 0,002 \text{ rad} \quad (32)$$

$$\alpha_0 = 0,001 \text{ rad} \quad (33)$$

The force factor, $\lambda_{S,i,j,k}$, depends on the combination of the wheel pairs and the distance h between the instantaneous centre of rotation and the relevant guidance means, figure 9, where:

i – number of rail,
j – wheel pair,
k – direction of the force (L – longitudinal, T – transversal).

The value of the distance h may be taken from table 2.8 [1]. The force factor, $\lambda_{S,i,j,k}$, may be determined from the expressions given in table 2.9 [1].

$$h = \frac{m \cdot \xi_1 \cdot \xi_2 \cdot l^2 + \sum e_j^2}{\sum e_j} = \frac{0 + 2,50^2}{2,5} = 2,5 \text{ m} \quad (34)$$

where:

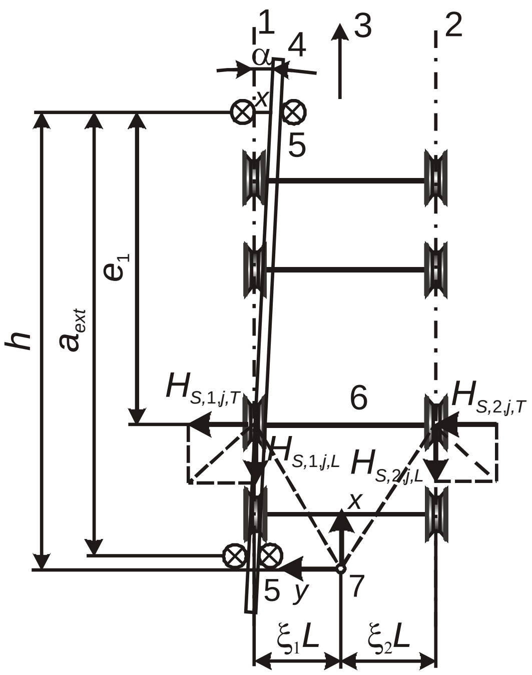

Figure 9: Definition of angle α and the distance h

m – is the number of pairs of coupled wheels (m = 0 for independent wheel pairs IFF),
$\xi_1 l$ – is the distance of the instantaneous centre of rotation from rail 1,
$\xi_2 l$ – is the distance of the instantaneous centre of rotation from rail 2,
L – is the span of the crane,
e_j – is the distance of the wheel pair j from the relevant guidance means.
$e_1=0$
$e_2=a=2,5$ m

$$\lambda_{S,j} = 1 - \frac{\sum e_j}{n \cdot h} = 1 - \frac{2,5}{2 \cdot 2,5} = 0,5 \quad (35)$$

$$\lambda_{S,1,L} = \lambda_{S,2,L} = 0 \quad (36)$$

<u>For wheel pair 1</u>:

$$\lambda_{S,1,1,T} = \frac{\xi_2}{n}\left(1 - \frac{e_1}{h}\right) = \frac{0,18}{2}\left(1 - 0\right) = 0,09 \quad (37)$$

$$\lambda_{S,2,1,T} = \frac{\xi_1}{n}\left(1 - \frac{e_1}{h}\right) = \frac{0,82}{2}\left(1 - 0\right) = 0,41 \quad (38)$$

<u>For wheel pair 2:</u>

$$\lambda_{S,1,2,T} = \frac{\xi_2}{n}\left(1 - \frac{e_2}{h}\right) = \frac{0,18}{2}\left(1 - \frac{2,5}{2,5}\right) = 0 \quad (39)$$

$$\lambda_{S,2,2,T} = \frac{\xi_1}{n}\left(1 - \frac{e_2}{h}\right) = \frac{0,82}{2}\left(1 - \frac{2,5}{2,5}\right) = 0 \quad (40)$$

Longitudinal forces are:

$$H_{S,1,L} = f \cdot \lambda_{S,1,L} \cdot \sum Q_r = 0 \quad (41)$$

$$H_{S,2,L} = f \cdot \lambda_{S,2,L} \cdot \sum Q_r = 0 \quad (42)$$

Guides force is:

$$S = f \cdot \lambda_S \cdot \sum Q_r = 0,248 \cdot 0,5 \cdot 170 = 21,1 \text{ kN} \quad (43)$$

Transverse forces for the wheel pair 1 are:

$$H_{S,1,1,T} = f \cdot \lambda_{S,1,1,T} \cdot \sum Q_r = 0,248 \cdot 0,09 \cdot 170 = 3,8 \text{ kN} \quad (44)$$

$$H_{S,2,1,T} = f \cdot \lambda_{S,2,1,T} \cdot \sum Q_r = \\ = 0,248 \cdot 0,41 \cdot 170 = 17,3 \text{ kN} \quad (45)$$

$$\Rightarrow H_{S,1,T} = S - H_{S,1,1,T} = 17,3 \text{ kN} \\ \Rightarrow H_{S,2,T} = H_{S,2,1,T} = 17,3 \text{ kN} \quad (46)$$

Transverse forces for the wheel pair 2 are:

$$H_{S,1,2,T} = f \cdot \lambda_{S,1,2,T} \cdot \sum Q_r = 0,248 \cdot 0 \cdot 170 = 0 \text{ kN} \quad (47)$$

$$H_{S,2,2,T} = f \cdot \lambda_{S,2,2,T} \cdot \sum Q_r = 0,248 \cdot 0 \cdot 170 = 0 \text{ kN} \quad (48)$$

Horizontal force caused by acceleration or deceleration of the crab is:

$$H_{T,3} = 0,1 \cdot (10 + 100) = 11 \text{ kN} \quad (49)$$

3.5. Eccentricity of vertical wheel loads

The eccentricity of application e of a wheel load Q_r to a rail should be taken as a portion of the width of the rail head b_r, figure 10, and recommendation according to the National Annex (7) where:

$$e = 0,25 \cdot b_r = 0,25 \cdot 55 = 13,75 \text{ mm} \quad (50)$$

3.6. Fatigue loads

The fatigue load may be specified as:

$$Q_{e,i} = \varphi_{fat} \cdot \lambda_i \cdot Q_{\max,i} \quad (51)$$

where:

φ_{fat} – is the damage equivalent dynamic impact factor:

$$\varphi_{fat,1} = \frac{1+\varphi_1}{2} = \frac{1+1,1}{2} = 1,05 \quad (52)$$

$$\varphi_{fat,2} = \frac{1+\varphi_2}{2} = \frac{1+1,2}{2} = 1,1 \quad (53)$$

λ_I – is the damage equivalent factor to make allowance for the relevant standardized fatigue load spectrum and absolute number of load cycles in relation to $N = 2,0 \times 10^6$ cycles. λ -values may be taken from table 2.12 [1] according to the crane classification.

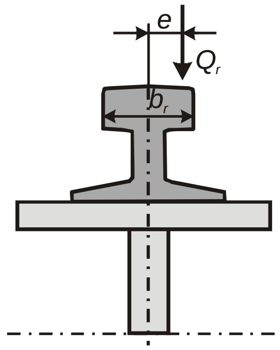

Figure 10: Eccentricity of application of wheel load

Assuming that the crane is classified in class S_6 according to the EN 13001-1 [5] the following is adopted:

$$\lambda_i = 0,794 \text{ for normal stress} \\ \lambda_i = 0,871 \text{ for shear stress} \quad (54)$$

$Q_{max,i}$ – is the maximum value of the characteristic vertical wheel load i.

For normal stress:

$$Q_{e,i} = \varphi_{fat} \cdot \lambda_i \cdot Q_{\max,i} = 1,1 \cdot 0,794 \cdot 70 = 61,1 \text{ kN} \quad (55)$$

For shear stress:

$$Q_{e,i} = \varphi_{fat} \cdot \lambda_i \cdot Q_{\max,i} = 1,1 \cdot 0,871 \cdot 70 = 67,1 \text{ kN} \quad (56)$$

Vertical and horizontal crane actions determined according to the above described procedure are shown in table 3. Table 4 shows the partial factors, while table 5 shows the values of factors ψ factors for combinations of actions according to EN 1991-3.

Table 3: Groups of loads and dynamic factors for numerical example

Groups of loads			1	2	3	4	5	6
Magnification factor which is considered for the group of the load			$\varphi_1=1,1$ $\varphi_2=1,2$ $\varphi_5=1,5$	$\varphi_1=1,1$ $\varphi_3=1,0$ $\varphi_5=1,5$	$\varphi_1=1,1$ $\varphi_5=1,5$	$\varphi_4=1,1$ $\varphi_5=1,5$	$\varphi_4=1,1$	$\varphi_4=1,1$
Vertical loads	Self-weight of the crane	$Q_{r,(min)}$	22	22	20	20	20	20
		$Q_{r,min}$	16,5	16,5	15	15	15	15
	Self-weight of the crane and hoist load	$Q_{r,(max)}$	16,5	16,5	-	15	15	15
		$Q_{r,max}$	82	72	-	70	70	70
Horizontal loads	Acceleration of the crane	$H_{L,1}$	4,5	4,5	4,5	4,5	-	-
		$H_{L,2}$	4,5	4,5	4,5	4,5	-	-
		$H_{T,1}$	3,2	3,2	3,2	3,2	-	-
		$H_{T,2}$	14,6	14,6	14,6	14,6	-	-
	Skewing of the crane	$H_{S1,L}$	-	-	-	-	0	-
		$H_{S2,L}$	-	-	-	-	0	-
		$H_{S1,T}$	-	-	-	-	17,3	-
		$H_{S2,T}$	-	-	-	-	17,3	-
	Acceleration of the crab	$H_{T,3}$	-	-	-	-	-	11

Table 4: Recommended values of γ partial factors for combinations of actions

Action	Symbol	Situation	
		Persistent/Transient	Accidental
Permanent crane action - unfavourable - favourable	 γ_{Gsup} γ_{Ginf}	 1,35 1,00	 1,00 1,00
Variable crane action - unfavourable - favourable Crane present Crane non-present	 γ_{Qsup} γ_{Qinf}	 1,35 1,00 0,00	 1,00 1,00 0,00
Other variable action - unfavourable - favourable	γ_Q	 1,50 0,00	 1,00 0,00
Accidental actions	γ_A		1,00

Table 5: ψ - factors for crane loads

Action	Symbol	ψ_0	ψ_1	ψ_2
Single crane or groups of loads induced by cranes	Q_r	1,0	0,9	ratio between the permanent crane action and the total crane action

For each critical load case, the design values of the effects of actions should be determined by combining the values of actions which occur simultaneously in accordance with Eurocode standard.

For verification of ultimate limit states the following combinations should be taken:

- For persistent and transient situations:

$$\sum_{j\geq 1}\gamma_{G,j}\cdot G_{k,j}+\gamma_P\cdot P+\gamma_{Q,1}\cdot Q_{k,1}+\sum_{i>1}\gamma_{Q,i}\cdot\psi_{0,i}\cdot Q_{k,i} \quad (57)$$

- For accidental situations:

$$\sum_{j\geq 1}G_{k,j}+P+A_d+\left(\psi_{1,1}\text{ ili }\psi_{2,1}\right)Q_{k,i}+\sum_{i>1}\psi_{2,i}\cdot Q_{k,i} \quad (58)$$

4. CONCLUSION

This paper describes the new method of modelling of actions due to the operation of cranes according to Eurocode standards. The developed procedure is more complex and more precise in relation to the already known and used procedures for calculations of the crane actions. The procedure of calculation of the action by crane is illustrated on the concrete numerical example of double girder crane with a hook. Loads that act during crane operation are defined and appropriate dynamic factors were adopted based on their character. The simultaneity of the crane load components may be taken into account by considering groups of loads as identified in tables 2 and table 3 for numerical example. Each of these groups of loads should be considered as defining the one characteristic crane action for the combination with non-crane loads. Due to the size of the complete procedure of calculation, this paper deals only with actions induced by crane which should be taken into account for further proof of the ultimate limit state, serviceability limit state and fatigue verification.

ACKNOWLEDGEMENTS

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