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Numerical calculation of the bending of an elastic beam using the finite difference method

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Abstract: The problem of solving plane bending issues by the finite difference method was examined. The values of the bending function at the beam's node points were studied using a system of linear algebraic equations. The deflection and bending moment of the beam were determined. The bending moment depends on the stiffness of the beam, its width, and the properties of the support. The article examines two loading cases (combined loading and edge loading), as well as two types of support conditions (cantilever supports at the edges and hinged supports).

Keywords: flexible beam, bending, flexible foundation, finite difference method, mesh method

Elastik to'sinni egilishga chekli ayirmalar usuli bilan sonli hisoblash

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Annotatsiya: Tekis egilish masalalarini chekli ayirmalar usuli bilan yechish masalasi ko'rildi. To'sin tugun nuqtalaridagi egilish funksiyasi qiymatlari chiziqli algebraik tenglamalar tizimi yordamida o'rganildi. To'sinning salqiligi va eguvchi momenti aniqlandi. Eguvchi moment to'sinning egilishdagi bikrligi, uning (eni) kengligi va asosning xususiyatiga bog'liq. Maqolada yuklanishning ikki holati (umumiy yuklanish va chetlardan yuklanish), shuningdek, ikki xil mahkamlanish holati (chekkalarda biki tayanchlar va sharnirli tayanchlar) ko'rib chiqildi.

Kalit so'zlar: egiluvchan to'sin, egilish, egiluvchan asos, chekli ayirma usuli, to'rlar usuli.

1. Kirish


Egiluvchan asosda yotgan konstruksiyalarni hisoblashga bag'ishlangan ko'plab ilmiy ishlar mavjud [1–4]. Zamonaviy tadqiqot usullari fundament plitalari va yo'l qoplamalarini loyihalashda ham sonli, ham analitik hisoblash usullariga asoslangan. Chekli ayirmalar usulini balkalar, plastinalar va qobiqlarni hisoblashga qo'llash masalalariga A. V. Aleksandrov, N. P. Abrovskiy, M. A. Koltunov, S. P. Timoshenko, P. M. Varvak kabi ko'plab olimlar o'z ishlarini

bag'ishlaganlar [1–8]. Chekli ayirmalar usulining katta afzalligi shundaki, u chegaraviy shartlarga va boshlang'ich kuchlanish holatiga kam bog'liq bo'ladi. Kamchiliklaridan biri – algebraik tenglamalar tizimining yuqori tartibda bo'lishi, lekin zamonaviy dasturiy komplekslar bu muammoni bartaraf etadi. Bunday masalalar plitali fundamentlar, inshoot pollari, aerodrom va yo'l qoplamalarini loyihalashda uchraydi. Egiluvchan asosda yotgan to'sin-tasma, balka egilishi masalalari inshootlar konstruksiyasini loyihalashda katta amaliy ahamiyatga ega.


2. Tadqiqot metodologiyasi

Tekis egilishga uchragan, chekkalari biki yoki sharnirli maxkamlangan, butun eni bo'ylab elastik asosga tayangan tekis yuklangan to'sin-tasmaning holatini ko'rib chiqamiz. Plastinadan to'sin-tasmani kesib olib, uni elastik asosdagi balka sifatida qaraymiz. Bunda to'sin-tasma elastik muhitli "to'shak" ustiga yotqizilgan, muhit pastga hamda yuqoriga qarab ta'sir etuvchi kuchlarga qarshilik ko'rsata oladi deb hisoblanadi. Ushbu holatda, tekis yuklangan, butun eni bo'ylab elastik asosga tayangan va chetlari biki yoki sharnirli maxkamlangan uzun to'g'ri to'rtburchak plastinaning egilishini tahlil qilamiz (rasm 1).

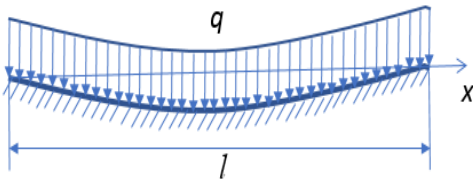
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1-rasm. Elastik asosdagi, butun uzunligi bo'ylab teng yuklangan va chetlari bikr yoki sharnirli maxkamlangan to'g'ri to'rtburchak to'sin-tasma

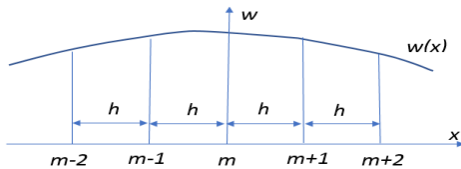
Differensial tenglama quyidagi ko'rinishda bo'ladi [1,2]:

$$D \frac{d^4 w}{dx^4} = q - kw. \quad (1)$$

Bu yerda

D — to'sin-tasmaning silindrik bikrligi, k — elastik asos ko'effitsiyenti, q — tekis tarqalgan yukning intensivligi.

Avvalo funksiyaning hosilasini chekli miqdorlar nisbati orqali ifodalash imkonini beruvchi formulalarni olamiz. Bunda Teylor formulasidan foydalanib, to'sin-tasmaning ixtiyoriy m nuqtasida funksiyaning hosilalarini taxminan hisoblaymiz (rasm 2).



2-rasm. To'sin-tasmaning egilish funksiyasini bo'lish sxemasi

Bunda m nuqtani markaziy nuqta deb ataymiz, unga yaqin nuqtalar esa teng masofada joylashgan deb hisoblanadi. Teylor formulasidan foydalanib, birinchi uch hadni olamiz:

$$\begin{cases} w_{i+1} \approx w_i + h * w'_i + \frac{h^2}{2} * w''_i; \\ w_{i-1} \approx w_i - h * w'_i + \frac{h^2}{2} * w''_i; \end{cases} \quad (2)$$

Ayirish va qo'shish orqali quyidagini hosil qilamiz:

$$\begin{cases} w_{i+1} - w_{i-1} = 2h * w'_i; \\ w_{i+1} + w_{i-1} = 2w_i + h^2 * w''_i; \end{cases} \quad (3)$$

Bundan:

$$w'_i = \frac{w_{i+1} - w_{i-1}}{2h} \quad (4)$$

$$w''_i = \frac{w_{i+1} - 2w_i + w_{i-1}}{h^2} \quad (5)$$

Ikkinchi hosilaning (5) ifodasidan birinchi hosilaning (4) formulasi bo'yicha hosila olamiz:

$$w'''_i = \frac{w_{i+2} - 2w_{i+1} + 2w_{i-1} - w_{i-2}}{2h^3} \quad (6)$$

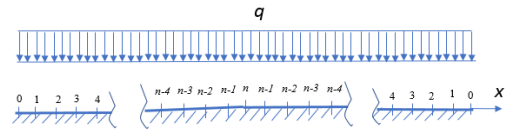
Xuddi shunday to'rtinchi tartibli hosilani olamiz:

$$w^{iv}_i = \frac{w_{i+2} - 4w_{i+1} + 6w_i - 4w_{i-1} + w_{i-2}}{h^4} \quad (7)$$

To'sin-tasmaning elementar qismini ajratib, uni teng uzunlikdagi chekli bo'laklarga bo'lamiz:

$$h = \Delta_x = \frac{l}{2} * \frac{1}{n} = \frac{l}{2n} \quad (8)$$

Bu yerda L — to'sin-tasmaning uzunligi; n — yarim uzunlik bo'yicha bo'lishlar soni. Bo'laklarning raqamlanishi simmetriyani hisobga olgan holda 3-rasmda ko'rsatilgan.



3-rasm. Elastik asosdagi, tekis yuklangan va chetlari bikr yoki sharnirli maxkamlangan to'sin-tasmaning bo'laklarini simmetriyali raqamlash

To'rtinchi hosilaning chekli ayirmalar usuli orqali i nuqtadagi ko'rinishi:

$$\frac{d^4 w}{dx^4} = \frac{w_{i+2} - 4w_{i+1} + 6w_i - 4w_{i-1} + w_{i-2}}{\Delta_x^4} \quad (9)$$

Buni (1) tenglamaga qo'ysak, m nuqta uchun quyidagi tenglamani olamiz:

$$\frac{w_{i+2} - 4w_{i+1} + 6w_i - 4w_{i-1} + w_{i-2}}{\Delta_x^4} + \frac{k}{D} w_i = \frac{q_i}{D} \quad (10)$$

Yoki:

$$w_{i+2} - 4w_{i+1} + 6w_i - 4w_{i-1} + w_{i-2} + \frac{k \Delta_x^4}{D} w_i = \frac{q_i \Delta_x^4}{D} \quad (11)$$

bu yerda i=1,2,...,n.

Belgilashlar kiritamiz:

$$\alpha = \frac{k \Delta_x^4}{D}, \quad \delta_i = \frac{q_i \Delta_x^4}{D} \quad (12)$$

U holda (11) quyidagi ko'rinishni oladi:

$$w_{i+2} - 4w_{i+1} + 6w_i - 4w_{i-1} + w_{i-2} + \alpha w_i = \delta_i \quad (13)$$

To'sin-tasmaning ikki chekkasi sharnir bilan biriktirilgan bo'lsa, chegara shartlari:

$$x = \pm \frac{a}{2}; w=0; M_x=0.$$

Bu $M_x=0$ shartdan, $\frac{d^2 w}{dx^2} = 0$ kelib chiqadi.

Chekli ayirmalar usulida bu shart $w_{-1} = w_1$ quyidagicha ifodalanaadi. (13) tenglamalarni ichki nuqtalar uchun va chegara shartlarini hisobga olgan holda tuzsak, w_i salqiliklarni aniqlash uchun n*n tartibli algebraik tenglamalar tizimi ko'effitsiyentlari dasturda quyidagi ko'rinishni hosil qiladi:

$$\begin{aligned} A_i &= (i == 0 || i == 1 || i == n) ? 0 : 1; \\ B_i &= (i == 0 || i == n) ? 0 : 4; \\ C_i &= (i == 0 || i == 1 || i == n) ? 1 : - \\ &(i == 1 || i == n - 1) ? 7.0 + K : 6.0 + K; \\ D_i &= (i == 0 || i == n) ? 0 : 4; \\ E_i &= (i == 0 || i == n - 1 || i == n) ? 0 : 1; \\ f_i &= (i == 1 || i == n) ? 0 : q_x * \left(\frac{l x}{n}\right)^4 - \\ &(b * h b * h b * h b / 12 * E); \end{aligned} \quad (14)$$

Yuqoridagi (14) tenglama matritsalar ko'rinishida quyidagicha yoziladi:

$$\mathbf{A} \mathbf{W} = \mathbf{B},$$

bunda \mathbf{A} — ko'effitsiyentlar matritsasi; \mathbf{W} — salqiliklar ustun- vektori; \mathbf{B} — erkin hadlar ustuni.

Matritsa A quyidagi ko'rinishni oladi:



$$A = \begin{bmatrix} a_{11} & \dots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \dots & a_{nn} \end{bmatrix} \quad (15)$$

W va B ustun-vektorlari:

$$\left. \begin{aligned} W^T &= [W_1 \quad W_2 \quad \dots \quad W_{n-1} \quad W_n] \\ B^T &= \frac{1}{D} [\delta_1 \quad \delta_2 \quad \dots \quad \delta_{n-1} \quad \delta_n] \end{aligned} \right\} \quad (16)$$

Ushbu tenglamalar tizimini yechish orqali to'sin-tasmaning belgilangan nuqtalaridagi salqilik qiymatlarini $w = \frac{1}{D} A^{-1} B$ aniqlaymiz.

Silindrik egilish uchun eguvchi moment quyidagicha aniqlanadi:

$$M_x = -D \frac{d^2 w}{dx^2}.$$

Ikkinchi hosilaning chekli ayirmalar ko'rinishida yozamiz:

$$\left(\frac{d^2 w}{dx^2}\right)_m = \frac{w_{m+1} - 2w_m + w_{m-1}}{\Delta^2}. \quad (17)$$

m nuqta uchun eguvchi momentning aniqlanishi:

$$M_{x(m)} = -D \cdot \frac{w_{m+1} - 2w_m + w_{m-1}}{\Delta^2}. \quad (18)$$

To'sin-tasma salqiligini quyidagi son qiymatlarda hisoblaymiz:

$E=2,1 \cdot 10^8 \text{ kN/m}^2$, $\nu=0,3$, $k_r=3,75 \cdot 10^4 \text{ kN/m}^3$, $l=10 \text{ m}$, $h_b=0,3 \text{ m}$, $q=1 \text{ kN/m}$.

$$D = \frac{Eh^3}{12(1-\nu^2)}, \quad J = \frac{h^3}{12}.$$

1-jadvalda chekli ayirma usulining oraliqda tugun nuqtalar soni n=20, 40, 80, 160, 320 bo'lganda 2 ustunda sonli usulning natijasida hosil bo'lgan ko'chishning x=0.5L da W(0.5L) qiymati va 3 ustunda ko'chishning analitik yechimi keltirilgan. Ularni solishtirganda tugun nuqtalar soni n ortishi bilan analitik yechim bilan sonli usul yechimining ishonchli qiymatlar soni to'rtga teng bo'lishi ko'rsatilgan.

1-jadval

Chekli ayirma usuli bo'yicha n ortishi bilan x=0.5L dagi sonli va analitik ko'chish qiymatlari taqqoslangan va moslik yaxshilangani ko'rsatilgan

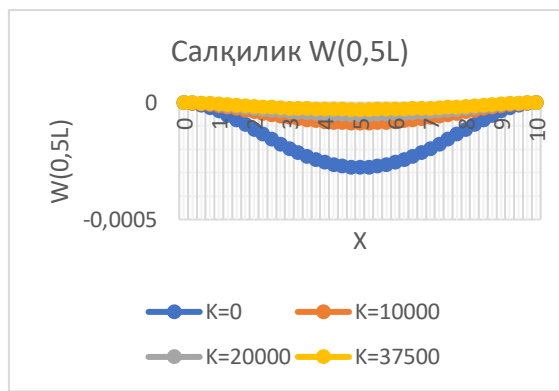
Tugun nuqtalar soni n	Sonli usul yechimi-W(0.5L)	Analitik yechim-W(0.5L)
20	-0,000281085	-0,0002756
40	-0,000276951	-0,0002756
80	-0,000275918	-0,0002756
160	-0,000275659	-0,0002756
320	-0,000275595	-0,0002756

2-jadvalda chekli ayirma usulining oraliqda tugun nuqtalar soni n=20, 40, 80, 160, 320 bo'lganda, hamda to'sin-tasmaning elastik asos koeffitsiyenti $k_r=3,75 \cdot 10^4$ qiymatni olganda, 2 ustunda sonli usulning natijasida hosil bo'lgan W(0.5L) qiymatini yaqinlashishi ko'rsatilgan. Ularni solishtirganda tugun nuqtalar soni n ortishi ishonchli qiymatlar soni to'rtga teng bo'lishi ko'rinib turibdi.

2-jadval

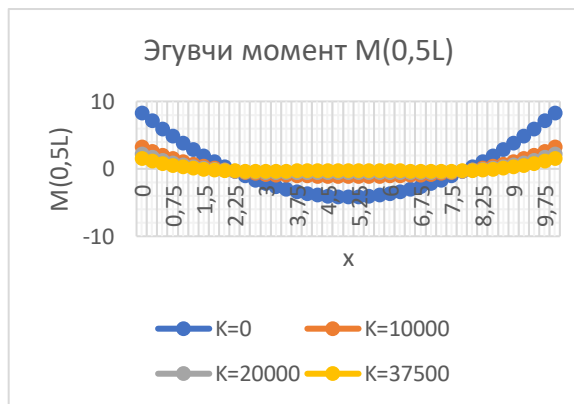
$k_r = 3,75 \cdot 10^4$ uchun n ortishi bilan W(0.5L) qiymatining yaqinlashuvi va aniqligi oshishi

Tugun nuqtalar soni n	Sonli usul yechimi-W(0.5L)
20	-0,000028574434
40	-0,000028625753
80	-0,000028638811
160	-0,000028642090
320	-0,000028642911



4-rasm. Tasmaning to'shak ta'siri va ta'sirisiz holda ko'chishning grafigi

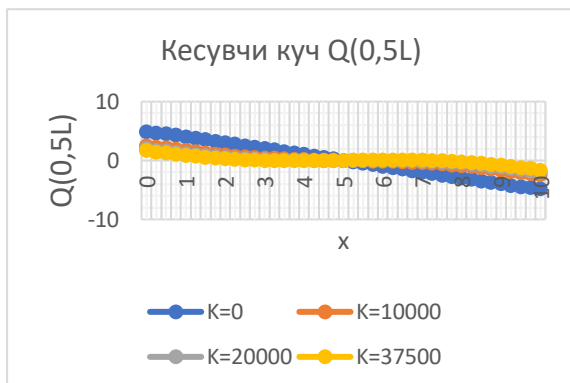
4- rasmda x=0; 0,25m; 0,5m;...9,25m; 9,5m; 9,75m; 10,0m dagi qiymatlarda W(x) ko'chishning qiymatlari grafigi keltirilgan. Ko'rsatilgan chizmadan W(x) markazda ya'ni x=0.5Lda maksimal qiymatga erishadi, hamda yechimning grafigi parabolik ko'rinishi oladi va x=0 va x=L tugun nuqtalarda W(x) nol qiymatga teng bo'ladi. Tasma to'shagi ta'siri K ning qiymati kattalashgan sari W(x) ning maksimal qiymati kamayib boradi.



5-rasm. Tasmaning to'shak ta'siri va ta'sirisiz holda eguvchi momentning grafigi



5- rasmda $x=0; 0,25m; 0,5m; \dots 9,25m; 9,5m; 9,75m; 10,0m$ dagi qiymatlarda $M(x)$ momentning qiymatlari grafigi keltirilgan. Ko'rsatilgan chizmadan $M(x)$ markazda ya'ni $x=0,5L$ da ekstremal qiymatga erishadi, hamda yechimning grafigi parabolik ko'rinishi oladi va $x=0$ va $x=L$ tugun nuqtalarda $M(x)$ eng katta qiymatga teng bo'ladi. Tasma to'shagi ta'sirining qiymati kattalashgan sari $M(x)$ ning maksimal qiymati kamayib boradi.



6-rasm. Tasmaning to'shak ta'siri va ta'sirisiz holda kesuvchi kuchning grafigi

6- rasmda $x=0; 0,25m; 0,5m; \dots 9,25m; 9,5m; 9,75m; 10,0m$ dagi qiymatlarda $Q(x)$ kesuvchi kuchning qiymatlari grafigi keltirilgan. Ko'rsatilgan chizmadan $Q(x)$ markazda ya'ni $x=0,5L$ da nol qiymatga erishadi, hamda yechimning to'g'ri chiziqli ko'rinishi oladi va $x=0$ da $Q(x)$ musbat maksimal qiymatga, hamda $x=L$ tugun nuqtalarda $Q(x)$ manfiy maksimal qiymatga teng bo'ladi. Tasma to'shagi ta'sirining qiymati kattalashgan sari $Q(x)$ ning maksimal qiymati kamayib boradi.

3. Xulosa

Elastik to'sinni egilishini chekli ayirmalar usuli orqali sonli hisoblash masalasi tahlil qilinib, ushbu yondashuvning samaradorligi va qo'llash imkoniyatlari ko'rsatib berildi. Tadqiqot natijalari shuni ko'rsatadiki, chekli ayirmalar usuli differensial tenglamalarni yaqinlashtirib yechishda qulay va aniq usullardan biri hisoblanadi. U orqali to'sinning turli yuklanish holatlaridagi egilishini aniqlash, chegaraviy shartlarni hisobga olgan holda ishonchli natijalar olish mumkin.

Shuningdek, sonli usullar an'anaviy analitik yechimlar qiyin yoki mumkin bo'lmagan hollarda muhim ahamiyat kasb etishi ta'kidlandi. Chekli ayirmalar usulining oddiy algoritmgaga egaligi va kompyuterda oson amalga oshirilishi uni muhandislik masalalarida keng qo'llash imkonini beradi. Olingan natijalar ushbu usulning aniqligi yetarli darajada yuqori ekanligini va amaliyotda samarali qo'llanilishi mumkinligini ko'rsatdi.

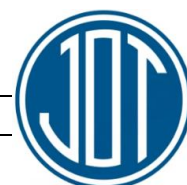
Xulosa qilib aytganda, chekli ayirmalar usuli elastik to'sinlarning egilishini tahlil qilishda ishonchli, samarali va amaliy jihatdan ahamiyatli vosita hisoblanadi.

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