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Formation of problems of elastoplastic deformation of three-dimensional bodies

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Abstract: Formulation of three-dimensional elastoplastic problems, finite elements in the calculation of bodies with elastoplastic three-dimensional complex shape (with voids, inclusions and cavities), algorithms for using Vlasov-Kantorovich, finite difference methods, calculation of coefficients of the system of solving equations solution algorithms are presented. By employing a combination of theoretical analysis and numerical simulations, we explore the interplay between elastic and plastic behaviors under various loading conditions. The research highlights the significance of material properties, geometric configurations, and boundary conditions in influencing deformation patterns.

Keywords: three-dimensional bodies, elastoplastic process, finite elements, finite difference, Vlasov-Kantorovich methods

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Uch o‘lchovli xajmli jismlarning elastoplastik deformatsiyasi masalalarini shakllantirish

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Annotatsiya: Uch o‘lchovli elastoplastik masalalarni shakllantirish, elastoplastik uch o‘lchovli murakkab shaklga (bo‘shliqlar, qo‘shimchalar va chuqurchalar bilan) ega jismlarni hisoblashda chekli elementlar, Vlasov-Kantorovich, chekli ayirmalar usullarini qo‘llash algoritmlari, tenglamalarni yechish tizimining koeffitsiyentlarini hisoblashning yechish algoritmlari keltiriladi. Nazariy tahlil va raqamli simulyatsiyalar kombinatsiyasidan foydalanib, biz turli xil yuklash sharoitida elastik va plastik xatti-harakatlar o'rtasidagi o'zaro bog'liqlikni o'rganamiz. Tadqiqot materialning xususiyatlari, geometrik konfiguratsiyasi va chegara sharoitlarining deformatsiya shakllariga ta'sir qilishdagi ahamiyatini ta'kidlaydi.

Kalit so‘zlar: uch o‘lchovli jismlar, elastikoplastik jarayon, chekli elementlar, chekli ayirma, Vlasov-Kantorovich usullar

1. Kirish

Ortogonal $OX_1X_2X_3$ egri chiziqli koordinatalar tizimida V hajmli ixtiyoriy shakldagi qattiq jismni ko‘rib chiqamiz, unga S_p sirt qismlariga statik va dinamik yuklar $P(P_x,P_y,P_z)$ ta’sir qiladi va S_u qismida $U_{(u,v,w)}$ ko‘chishlarni berilishini hisobga olamiz. Bundan tashqari - $R(R_x,R_y,R_z)$, xajmli kuchlarni berilishi mumkin.

Jismning kuchlanish-deformatsiya holati {KDH} kuchlanish $\{\sigma_{ij}\}$ va deformatsiyasi $\{\varepsilon_{ij}\}$ tenzori bilan tavsiflanadi , ular fazoviy koordinatalar va vaqtni ko‘chish komponentlarining funksiyalari bo‘lib hisoblanadi.

2. Tadqiqot metodikasi

Kichik elastoplastik deformatsiyalar nazariyasiga ko‘ra, kuchlanish va deformatsiya tenzorining tarkibiy qismlari quyidagi munosabat bilan bog‘langan [1]:

$$\sigma_{ij}-\sigma\delta_{ij}=\frac{2\sigma_i}{3\varepsilon_i}(\varepsilon_{ij}-\varepsilon\delta_{ij}) \quad (1.1.1)$$

Bu yerda

$$\sigma=\frac{\sigma_{11}+\sigma_{22}+\sigma_{33}}{3} \quad (1.1.2)$$

Gidrostatik bosim;

$\varepsilon = \varepsilon_{11}+\varepsilon_{22}+\varepsilon_{33}$, δ_{ij}- Kroneker simvoli ($\delta_{ij}=1$ agarda i=j, $\delta_{ij}=0$ agarda i#j).

Tenglamaga kiritilgan kuchlanish intensivligi (σ_i) va deformatsiya intensivligi (ε_i) mos ravishda quyidagi formulalar bilan aniqlanadi:

$$\sigma_i=\frac{\sqrt{2}}{2}\sqrt{(\sigma_{11}-\sigma_{22})^2+(\sigma_{22}-\sigma_{33})^2+(\sigma_{33}-\sigma_{11})^2+6(\sigma_{12}^2+\sigma_{23}^2+\sigma_{13}^2)}$$

$$\varepsilon_i=\frac{\sqrt{2}}{3}\sqrt{(\varepsilon_{11}-\varepsilon_{22})^2+(\varepsilon_{22}-\varepsilon_{33})^2+(\varepsilon_{33}-\varepsilon_{11})^2+\frac{3}{2}(\varepsilon_{12}^2+\varepsilon_{23}^2+\varepsilon_{13}^2)}$$

Bu holda deformatsiya tenzorining elementlari quyidagicha ifodalanadi:

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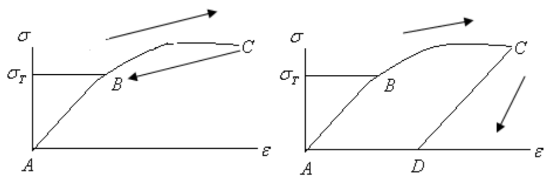
$$\varepsilon_{ij}\begin{cases} \alpha_{ii}\frac{\partial u_i}{\partial x_i}+\sum_{\substack{j=1\\ i\neq j}}^{3}\alpha_{ij}u_j & i=j,\\ & (i,j=1,2,3)\\ \left(\alpha_{ii}\frac{\partial u_j}{\partial x_i}+\alpha_{jj}\frac{\partial u_i}{\partial x_i}\right)-(\alpha_{ij}u_i+\alpha_{ji}u_j) & i\neq j,\end{cases}$$
(1.1.3)

bu yerda

$$\alpha_{ij}=\begin{cases}\frac{1}{H_1} & i=j\\ & (i,j=1,2,3)\\ \frac{1}{H_iH_j}\frac{\partial H_i}{\partial x_j} & i\neq j\end{cases}$$

H_i - Lame koeffitsiyentlari.

Elastiklikning chiziqli nazariyasida jismning deformatsiyasi paytida kuchlanish va deformatsiyalar o‘rtasida chiziqli bog‘liqlik kuzatiladi, deb taxmin qilinadi. Biroq, standart namunalarning diagrammasi cho‘zilishga sinalganda bizni ko‘pchilik materiallar uchun Guk qonuni faqat kichik deformatsiyalar hududida amal qilishiga ishontiradi. Namunalar uchun cho‘zilish sinovi diagrammasi rasmda ko‘rsatilganidek (1-rasm a,b). Shundan ma’lum bir *V* nuqtasidan boshlab σ va εorasidagi chiziqli bog‘liqlik buziladi [2].



1-rasm. Cho‘zilish sinovi diagrammalari:
a) nochiziq elastiklik, b) elastoplastiklik.

Faraz qilaylik, namunani yuklashda kuchlanishlar C nuqtasiga mos keladigan qiymatga yetdi. Namunani keyingi yuklanishdan tushirish vaqtida ikkita imkoniyat paydo bo‘lishi mumkin. Bir holatda, tushirish diagrammasi SVA yuklash sxemasiga to‘g‘ri keladi va keyin yukni olib tashlangandan so‘ng, namuna asl holatiga qaytadi (1-rasm, a). Bunday materiallar nochiziqli elastik deb ataladi. Boshqa holatda, yuklanishdan tushirish diagrammasi *AV* diagrammasining dastlabki qismiga deyarli parallel bo‘lgan *CD* to‘g‘ri chiziq bilan mos keladi (1-rasm, b). Yukni olib tashlaganingizdan so‘ng, *AD* qismida namunaning qoldiq deformatsiyalar paydo bo‘ladi. Bunday materiallar elastoplastik deb ataladi.

Nochiziq elastik va elastikoplastik masalani yechish tenglamalarini qurish.

Nochiziqli elastik va elastoplastik materiallar o‘rtasida tubdan farq bor. Agar birinchi materiallar uchun berilgan deformatsiyalardan jismga ta’sir etuvchi kuchlanishlarni aniqlash imkonini beruvchi kuchlanishlar va deformatsiyalar o‘rtasida aniq bog‘liqlik mavjud bo‘lsa, u holda elastoplastik materiallar uchunσ ~εorasida aniq munosabat bo‘lmaydi, Berilgan deformatsiyaga asoslanib kuchlanishni faqat va faqat aniqlash mumkin, jismning oldingi qadamdagi kuchlanish-deformatsiyalanish holatini aniq bo‘lsa [3].

Shuning uchun plastiklik shartining holatini qandaydir kuchlaniish tenzori komponentlarining ma’lum bir funksiyasi sifatida yozish mumkin. Shubhasiz, izotropik material uchun plastik deformatsiyalarning paydo bo‘lishi sharti koordinatalar tizimini tanlashga bog‘liq bo‘lmasligi kerak. Unda ko‘rsatilgan funksiya kuchlanish tenzorining uchta invariantining funksiyasi bo‘lishi kerak, masalan, uchta bosh kuchlanishlarni olishimiz mumkin:

$$f(\sigma_1,\sigma_2,\sigma_3)=0 \qquad (1.1.4)$$

Elastik jism uchun uning yuklanish ketma-ketligi hech qanday rol o‘ynamaydi, chunki kuchlanish va deformatsiyalangan holatlar o‘rtasida bir qiymatli moslik mavjud, ularning qanday yaralishiga bog‘liq emas. Elastoplastik jismlarda vaziyat tubdan boshqacha bo‘lib chiqadi. Elastoplastik jism uchun nafaqat uning nuqtalaridagi kuchlanish holatining tabiati, balki u yaratilgan yo‘l ham muhimdir. Bunga bog‘liq ravishda, jismning bir xil nuqtalarida deformatsiyalangan holati sezilarli darajada o‘zgarishi mumkin [4].

Kuchlanish va deformatsiyalar, deformatsiyalar va ko‘chishlar o‘rtasidagi munosabatlardan foydalanib, berilgan jismning holati tenglamalarini quyidagicha ifodalash mumkin:

$$\rho\ddot{u}_i=\sum_{j=1}^{3}\frac{\partial}{\partial x_j}(\alpha_{jj}H\sigma_{ij})+\sum_{\substack{j=1\\ i\neq j}}^{3}H(\alpha_{ij}\sigma_{ij}-\alpha_{ji}\sigma_{jj})+P_iH \quad (i=1,2,3) \qquad (1.1.5)$$

S_p va S_u sirtdagi chegaraviy shartlarga mos ravishda

$$(\sigma_{ij}-\sigma_{ij}^{*})\delta u_j\big|_{x_i=const}=0 \quad (i,j=1,2,3) \qquad (1.1.6)$$

va boshlangich shartlar bilan

$$u_i|_{t=t_0}=\phi_i, \dot{u}i|_{t=t_0}=\psi_i \quad (i=1,2,3) \qquad (1.1.7)$$

Deformatsiyalanuvchi jism mexanikasining ko‘rib chiqilgan tenglamalari sirtdagi shartlari va boshlang‘ich shartlari bilan birgalikda differensial shaklda elastiklik va plastiklik nazariyasi masalasining yakunlangan formulasini tashkil qiladi. Biroq, bu jismning kuchlanish-deformatsiyalanish holatini topish muammosining yagona mumkin bo‘lgan formulasi emas. Bunda $\vec{\sigma},\vec{\varepsilon},\vec{u}$ ni aniqlash masalasining holatni tavsiflashda, uni u yoki bu funksiyani aniq intergalini hisoblovchi funksional ko‘rinishga keltirish mamkin, funksiyaning o‘zi jismning haqiqiy holatini akslantiradi, shartdan bu funksionalni ekstremumini topish mumkin. Ushbu yondashuvning matematik apparati matematikaning variatsion hisobi deb ataladigan bo‘limida o‘rganiladi. Shuning uchun elastiklik va plastistiklik nazariyasidagi bunday funksionallarning xususiyatlarini shakllantiradigan qoidalar variatsion prinsip deb ataladi [5].

Muammoni bunday shakllantirishda ularning integrallash juda qiyin ko‘rinadi. Shuning uchun, differensial formulada masala mos ekvivalent variatsion formula bilan almashtiriladi:

$$\delta\int_{t_1}^{t_2}(T-\Pi+A)dt=0 \qquad (1.1.8)$$

Bu yerda

$$\delta T=-\int_v[\rho\sum_{i=1}^{3}\frac{\partial^2 u_i}{\partial t^2}\delta u_i]dV \qquad (1.1.9)$$

$$\delta\Pi=\int_v[\sum_{i=1}^{3}\sum_{j\neq i}^{3}\sigma_{ij}\delta\varepsilon_{ij}]dV \qquad (1.1.10)$$

$$\delta A=\int_v\sum_{i=1}^{3}P_i\delta u_i dV+\int_s\sum_{i=1}^{3}q_i\delta u_i dS, \qquad (1.1.11)$$

ρ -material zichligi.

Aniq chegaraviy shartlarni va jismning geometriyasini, $\sigma-\varepsilon$bog‘lanishini, tashqi yuklarni berib va (Vlasov-Kantorovich, chekli ayirma va chekli elementlar) usullardan birini tanlash orqali qattiq jismni deformatsiyalash mexanikasining turli masalalarini yechishimiz mumkin.

Elastiklik va plastiklik nazariyasi muammosining variatsion shakllantirish

Elastiklik va plastiklik nazariyasi muammosining variatsion shakllantirish asosan ikkita holatda qo‘llaniladi. Birinchisida $\delta\int_{t_1}^{t_2}(T-\Pi+A)dt=0$ tenglama asosida masalani yechishning sonli usullari (Vlasov-Kantorovich, chekli ayirma va chekli elementlar usullari) quriladi [6]. Bu usullarning barchasi elastiklik va plastiklik nazariyasidagi masalalarni yechishning to‘g‘ridan to‘g‘ri usullari sinfiga kiradi, ular aniq differensial tenglamalardan foydalanishni talab qilmaydi. Variatsion yondashuvni qo‘llashning ikkinchi holati ko‘rib chiqilayotgan masalaning differensial tenglamalari va chegara shartlarini mos funksional tenglamalar (1.1.8) sifatida olishdir. Bu yo‘l murakkab shakl va tuzilishga ega bo‘lgan jismlar uchun (masalan, ko‘p qatlamli qobiqlar va boshqalar), shuningdek, bir koordinata tizimidan ikkinchisiga (dekart tizimidan qutbli, egri chiziqli va boshqa tizimlarga) o‘tishda oqlanadi.

Vlasov-Kantorovich metodi jism ichidagi ko‘chishlarning taqsimlanishining taxminiy tabiati bilan berilgan. Kiritilgan yaqinlashuvchi funksiyalar noma’lum funksiyalar bo‘lib, ular ikkita koordinataga bog‘liqdir. Ushbu funksiyalarga nisbatan jami energiyani minimallashtirish oddiy differensial tenglamalar tizimiga olib keladi, keyingi integrallash bizga taxminiy ko‘chish maydonini olish imkonini beradi [7].

Hozirgi vaqtda elastoplastik uch o‘lchovli masalalar tenglamalarini taxminiy yechishda keng qo‘llaniladigan eng universal va samarali usullardan biri chekli ayirmalar usulidir. Usulning mohiyati quyidagicha. argumentlarning uzluksiz o‘zgarishi maydoni to‘r deb ataladigan diskret nuqtalar to‘plami (tugunlari) bilan almashtiriladi. Uzluksiz argument funksiyalari o‘rniga diskret argumentning funksiyalari ko‘rib chiqiladi, ular panjara tugunlarida aniqlanadi va to‘r funksiyalari deb ataladi. Differensial tenglama va chegara shartlariga kiritilgan hosilalar ayirma hosilalari bilan almashtiriladi; bu holda, differensial tenglama uchun chegaraviy masala chiziqli yoki chiziqli bo‘lmagan algebraik tenglamalar tizimi bilan almashtiriladi, ya’ni ayirma sxemalari.

Tenglamalarni yechish uslublari

Chekli elementlar usulida har bir chekli elementga tegishli tugunlarning ko‘chishlarini bilgan holda uning ichidagi ko‘chishlarni (shuning uchun deformatsiya va kuchlanishlarni) qanday topish mumkinligi haqida savol tug‘iladi. Uch o‘lchovli jism uchun muammoni taxminan hal qilish mumkin, agar elementdagi ko‘chish maydonining tabiati haqida ma’lum bir taxminlar amalga oshirilsa. Aniqrog‘i, ma’lum tugunli ko‘chishlar yordamida chekli element ichidagi ko‘chish maydonini yaqinlashtirish imkonini beruvchi ma’lum funksiyalar to‘plamini tanlash kerak. Uch o‘lchovli jismda elementlar orasidagi bog‘lanish nuqtalarining soni cheksiz bo‘lib, har bir element ichidagi ko‘chishlarning taqsimlanishi bilan beriladi va shu bilan uning barcha nuqtalarida, shu jumladan chegaralarda kuchlanishlarning taqsimlanishini o‘rganiladi. Binobarin, muvozanat shartlari butun sirt bo‘ylab bajarilishini ta’minlash mumkin emas [8]. Ushbu qiyinchilikni yengib o‘tish uchun har bir elementning chegarasi bo‘ylab ta’sir qiluvchi kuchlanishlar shartli ravishda ekvivalent xajmli tugun kuchlari bilan almashtirilishi mumkin; keyin tugunlarning ko‘chishlari yo‘nalishi bo‘yicha tugunlarning muvozanat tenglamalarini odatdagi usulda tuzish mumkin, shuningdek, sirt va hajm kuchlarini ularni energetik ma’noda ekvivalent bo‘lgan tashqi tugun kuchlari bilan almashtirish orqali hisobga olish mumkin. Ushbu soddalashtirishlarni kiritgandan so‘ng, jismni diskret tizim deb hisoblash mumkin, ya’ni. tugun nuqtalarida bir-biriga bog‘langan elementlar to‘plami sifatida.

Kutiladigan natija

Konstruksiyani sohalarga bo‘lish va ularning har biri uchun yaqinlashuvchi funksiyalarni tanlash turli usullar bilan amalga oshirilishi mumkin. Shu bilan birga jismning geometriyasining xususiyatlarini hisobga olish kerak va umuman butun jism uchun ko‘chishlar, deformatsiyalar va kuchlanishlarning yaxshi yaqinlashishini ta’minlash kerak. Bunday holda, chekli elementlar usuli yordamida olingan yechim chegarada elementlarning o‘lchamlari kamayishi bilan aniq bo‘lishga intiladi.

3. Xulosa

Ushbu maqola uch o'lchamli jismlardagi elastoplastik deformatsiyalar bilan bog'liq murakkab hodisalarni har tomonlama o'rganib chiqdi. Qattiq nazariy tahlil va raqamli simulyatsiyalar orqali biz moddiy xususiyatlar, yuklash shartlari va deformatsiya naqshlarining shakllanishi va evolyutsiyasini boshqaradigan geometrik konfiguratsiyalar o'rtasidagi murakkab o'zaro bog'liqlik aniqlandi.

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