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Crack resistance of reinforced concrete beams with hybrid steel–glass composite reinforcement

N.R. Khodjiev[1][a], K.K. Muminov[1]
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Abstract: In this study, the stresses in reinforcement and concrete as well as the crack resistance of six types of reinforced concrete beams with hybrid steel–glass composite reinforcement (GFRP) and three types of conventionally steel-reinforced concrete beams were investigated using the finite element method in the ANSYS Workbench environment. A total of nine beams were analyzed through numerical modeling, in which the hybrid steel–GFRP reinforced beams were compared with conventionally steel-reinforced beams. The obtained results showed that the steel reinforcement in the tension zone maintained ductile behavior after reaching the yield strength. Although cracks developed earlier in the hybrid reinforced beams due to the lower elastic modulus of the GFRP reinforcement, their overall load-carrying capacity did not decrease significantly compared to that of conventionally reinforced concrete beams.
Keywords: steel reinforcement, glass fiber–reinforced polymer (GFRP) reinforcement, hybrid reinforcement, strength, crack resistance, reinforced concrete beam

Gibrid-po‘lat shisha kompozit armaturali temirbeton to‘sinlarning darzbardoshligi

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Annotatsiya: Ushbu maqolada olti xili gibrid po‘lat–shisha kompozit armatura (ShKA)li temirbeton to‘sinlar va uch xil an’anaviy po‘lat armaturalangan temirbeton to‘sinlarda armatura va betondagi kuchlanishlar hamda darzbardoshlik ANSYS Workbench dasturida chekli elementlar usuli orqali tadqiq qilindi. Raqamli modellashtirishda jami to‘qqizta to‘sinlar o‘rganilgan bo‘lib, gibrid po‘lat–ShKA to‘sinlar an’anaviy po‘lat armaturalangan to‘sinlar bilan solishtirildi. Olingan natijalar shuni ko‘rsatdiki, cho‘zilish zonasidagi po‘lat armatura oquvchanlik chegarasidan keyin, egiluvchanlikni saqlab qoldi. Gibrid armaturalangan to‘sinlarda ShKA armatura elastiklik modulining pastligi tufayli darzlar ertaroq yuzaga kelsa ham, ularning umumiy yuk ko‘tarish qobiliyati an’anaviy armaturalangan temirbeton to‘sinlarga nisbatan sezilarli darajada kamaymagan.
Kalit so‘zlar: po‘lat armatura, shisha kompozit armatura, gibrid armaturalash, mustahkamlik, darzbardoshlik, temirbeton to‘sin

1. Kirish

Ko‘p yillar davomida po‘lat temirbeton konstruksiyalarda asosiy material sifatida qo‘llanib, yuqori mustahkamlik va egiluvchanlikni ta’minlab kelmoqda. Biroq, uning kamchiliklari ham e’tibordan chetda qoldirmaslik lozim. Po‘lat armatura korroziyaga moyil bo‘lib, po‘lat armaturali beton konstruksiyalar ko‘pincha qayta ta’mirni talab qiladi, bu esa ularning tannarxi oshishiga sababi bo‘ladi. Shuningdek, qurilish sanoatining ekologik ta’siri po‘lat ishlab chiqarish bilan bog‘liq CO_2 chiqindilari orqali yanada ortmoqda [1-3]. Po‘lat armaturani korroziyadan himoya qilishning an’anaviy usullari murakkab va qimmatga tushadi. Shu sababli, ko‘p davlatlar xar xil turdagi kompozit armaturalarni faol ravishda qo‘llamoqda. Hozirgi iqtisodiy va ekologik sharoitlardan kelib chiqib, zamonaviy kompozit armaturalardan, ayniqsa shisha kompozit armatura (ShKA)lardan foydalanishga alohida e’tibor qaratilmoqda, bu esa mazkur muammolarga muqobil yechim sifatida qaraladi [4-7].

Po‘lat armaturaga nisbatan ShKA armaturalar to‘rt barobar yengil, elektr toki o‘tkazmaydi, magnit maydon hosil qilmaydi, korroziyabardosh va tabiiy, ekologik toza hamda iqtisodiy jihatdan samarali xom ashyodan ishlab chiqariladi. Garchi, ShKAning elastiklik moduli po‘latga nisbatan kichik bo‘lganligi uchun, ular yuk ko‘taruvchi beton konstruksiyalarida po‘lat armaturani to‘liq almashtira olmaydi [8]. Betonning cho‘zilish zonasida po‘lat va ShKAlarni birgalikda qo‘llash orqali samarali natijaga erishish mumkin. Shu bois, gibrid po‘lat-ShKAli temirbeton to‘sinlar mustahkamlikni, darzbardoshlikni, bikrlikni hamda iqtisodiy samaradorlikni ta’minlashda muhim innovatsion yechim bo‘la oladi [9].

Po‘lat armaturaning korroziyasi temirbeton konstruksiyalarda konstruktiv xavfsizlikni sezilarli darajada

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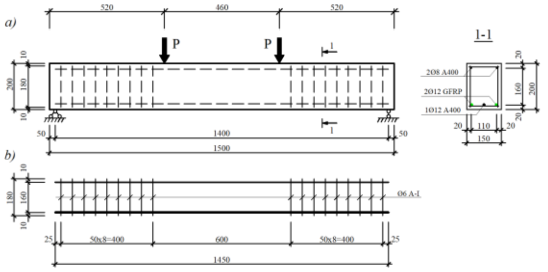
pasaytiradi va uzoq muddatli ekspluatatsiyani cheklaydi. Garchi beton yuqori ishqorli muhitni ta'minlab, armaturaning yuzasida passiv himoya qiluvchi plyonka shakllantirsa-da, bu betonning ishqorligi vaqt o'tishi bilan karbonizatsiya jarayoni tufayli pasayadi. Natijada, kislorod, namlik va turli agressiv kimyoviy moddalar ta'sirida armaturaning korroziyasi boshlanadi [8, 9]. Biroq, korroziya barcha armaturalarda bir vaqtda yuz bermaydi. U odatda tashqi yuzaga yaqin zonada, ayniqsa konstruksiya burchaklarida kuzatiladi, chunki bu joylar eng ko'p zarar ko'radigan zona hisoblanadi. Tashqi yuzaga yaqin beton himoya qatlamida darzlarning hosil bo'lishi armaturaning korroziyasini ham tezlashtiradi [10-12].

2. Tadqiqot metodologiyasi

Raqamli tadqiqot uchun jami to'qqiz turdagi to'sinlar tanlandi. Namunalarning ko'ndalang kesimi to'g'ri to'rtburchakli bo'lib, kengligi 150 mm va balandligi 200 mm ni tashkil etadi. To'sinlar po'lat va ShKA hamda betondagi normal kuchlanishlarni aniqlash uchun normal kesim bo'yicha sinov o'tkazildi. Geometrik parametrlar va armatura karkasining to'sinda joylashtirilishi 1-rasmda keltirilgan [5, 12].



1-rasm. To'sinning hisobiy sxemasi va armatura karkasi (mazkur sxemada B3-1S12-2G12 to'sin ko'rsatilgan): *a*) temirbeton to'sin; *b*) armatura karkasi

1-jadval

To'sin uchun qo'llanilgan beton va armaturalarning xarakteristikalari

Belgilanishi	Cho'ziluvchi po'lat armatura	Cho'ziluvchi ShKA	Po'lat armatura yuzasi A_s, sm²	ShKA yuzasi A_f, sm²	Nisbat A_f/A_s	Po'lat armaturalash foizi μ_s, %	ShKA foizi μ_f, %	Beton mustahkamligi, MPa
B1-3S12	3Ø12 A400	-	3.39	-	-	1,26		31,2
B2-1S12-2G10	1Ø12 A400	2Ø10	1.13	1.57	1.39	0,42	0,58	31,2
B3-1S12-2G12	1Ø12 A400	2Ø12	1.13	2.26	2	0,42	0,84	31,2
B4-4S12	4Ø12 A400	-	4.52	-	-	1,68		30,2
B5-2S12-2G12	2Ø12 A400	2Ø12	2.26	2.26	1	0,84	0,84	30,2
B6-2S10-2G12	2Ø10 A400	2Ø12	1.57	2.26	1.44	0,58	0,84	30,2
B7-5S10	5Ø10 A400	-	3.93	-	-	1,59		30,8
B8-3S10-2G10	3Ø10 A400	2Ø10	2.36	1.57	0.67	0,98	0,58	30,8
B9-2S10-3G10	2Ø10 A400	3Ø10	1.57	2.36	1.5	0,65	0,87	30,8

To'sinlarning cho'ziluvchi zonasida armaturalar joylashishiga ko'ra uch guruhga bo'lindi. 1-guruhda uchta armatura bir qator joylashtirilgan; 2-guruhda to'rtta armatura bir qatorda; 3-guruhda esa beshta armatura ikki qator, ular orasida yetarli masofa qoldirilgan. Barcha armatura diametri, miqdori, ko'ndalang kesim yuzasi, armaturalash foizi va beton mustahkamligi 1-jadvalda ko'rsatilgan..

3. Natija va muhokamalar

2-jadvalda barcha to'sinlar cho'zilish va siqilish zonalaridagi bo'ylama armaturada yuzaga kelgan normal kuchlanishlar, shuningdek, ularning chegaraviy yuk ko'tarish qobiliyatlari va maksimal solqilik qiymatlari keltirilgan. Tahlil ko'rsatdiki, namunaning cho'zilish zonasidagi po'lat armaturadagi o'rtacha normal kuchlanishlar 450 dan 505 MPa gacha bo'lib, armaturalash foiziga qarab oquvchanlik chegarasidan katta qiymatda bo'ldi. Masalan, B2-1S12-2G10 va B4-4S12 to'sinlarida cho'zilish zonasidagi po'lat armaturalarning kuchlanishlari mos ravishda 504,32 MPa va 442,41 MPa ni tashkil etib, po'lat armatura oquvchanlik chegarasiga yetgandan keyin esa qayta mustahkamlanish bosqichiga o'tdi. Bu holat to'sinning mo'rt xarakterdagi buzilishining oldini olishga yordam berdi. Mazkur holatda to'sinlar oquvchanlik chegarasidan keyin ham qo'shimcha yukni ko'tara olishini ko'rsatadi, bu esa xavfsizlikni oshiradi va gibrid hamda an'anaviy po'lat armaturalangan temirbeton to'sinlarda po'lat armaturaning egiluvchanligini namoyon etadi.

2-jadval

Siqiluvchi va cho'ziluvchi zonada joylashgan armaturalardagi normal kuchlanishlar

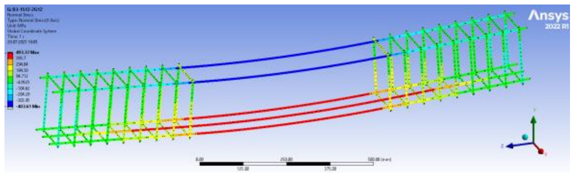
Belgilanishi	Buzuvchi yuk P_u, kN	Chegaraviy moment M_u, kN·m	Eng katta solqilik f, mm	Po'lat armaturadagi normal kuchlanish, Mpa	ShKadagi normal kuchlanish, MPa	Siqiluvchi zonadagi armaturadagi kuchlanish, MPa
B1-3S12	106.6	24.87	15.15	488.98		405.01
B2-1S12-2G10	100.2	23.38	21.36	504.32	623.28	404.23
B3-1S12-2G12	106.5	24.85	17.79	479.49	493.37	403.61
B4-4S12	129.1	30.12	9.01	442.41		418.23
B5-2S12-2G12	120.01	28.00	16.12	460.43	402.17	408.29
B6-	110.	25.83	15.	469.09	440.0	403.54

2S10-2G12	7		9		5	
B7-5S10	107.05	24.98	13.98	475.41		406.03
B8-3S10-2G10	105.7	24.66	18.73	477.31	488.99	409.70
B9-2S10-3G10	102.1	23.82	15.89	448.37	442.28	403.69

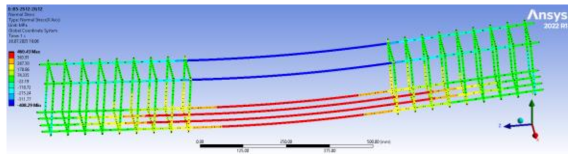
Siqilish zonalarida barcha to‘sinlar uchun armaturada hosil bo‘lgan normal kuchlanishlar ham 400 MPa ga yaqin yoki undan yuqori qiymatlarga yetdi. Siqilishdagi kuchlanishlar taxminan 403 MPa (B3-1S12-2G12) dan 418 MPa (B4-4S12) gacha oraliqda bo‘lib, bu siqiluvchi armaturaning yuk ta’sirida o‘zining chegaraviy mustahkamligiga yetganini ko‘rsatadi. Ushbu holat siqilish zonasidagi armatura qo‘yilgan yuklarni qabul qilishda faol ishtirok etganini hamda cho‘zilish va siqilish zonalari o‘rtasida kuchlanishlarning bir xilda taqsimlanishiga muayyan darajada hissa qo‘shganini ko‘rsatadi. Ayniqsa, armaturalash foizi katta bo‘lgan to‘sinlarda, masalan B4-4S12 ($\mu = 1{,}68$ %), ham yuk ko‘tarish qobiliyati (129,1 kN), ham siqiluvchi zonadagi kuchlanish katta bo‘lib, bu armatura miqdorining to‘sinning umumiy ishlash qobiliyatiga bevosita ta’sirini yaqqol namoyon etadi (2-rasm).

Cho‘zilish zonasidagi ShKAning ishlashi kuchlanishlarning keng diapazonda o‘zgarishi bilan tavsiflanadi, ya’ni 402 MPa dan 620 MPa dan yuqori qiymatlargacha. Eng katta qiymat 623,28 MPa, nisbatan po‘lat armaturalash foizi nisbatan kichik bo‘lgan B2-1S12-2G10 to‘sinda ($\mu = 1{,}0$ %) kuzatildi. Bu holat po‘lat armatura ulushi kam bo‘lganda, ShKAlar cho‘zilish kuchlanishlarini qabul qilishda ancha faol ishtirok etishini ko‘rsatadi. Aksincha, po‘lat va ShKAlarning ko‘ndalang kesim yuzalari teng bo‘lgan to‘sinlarda (masalan, B5-2S12-2G12) ShKAdagi kuchlanishlar nisbatan kichik 402,17 MPa atrofida bo‘ldi. Bu esa cho‘zuvchi kuchlanishlarning ShKA va po‘lat armatura o‘rtasida deyarli teng taqsimlanganini anglatadi (2-rasm).

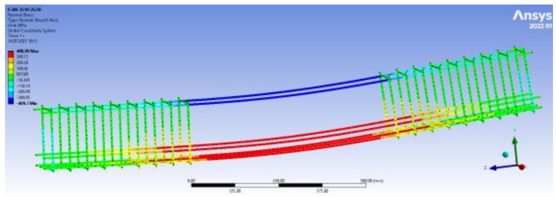
Solqilik qiymatlari ham turli to‘sinlar orasida sezilarli darajada farq qildi, bu esa armaturalash foizi o‘zgarishi bilan to‘sin bikrligining qanday o‘zgarishini ko‘rsatadi. Masalan, B1-3S12 va B2-1S12-2G10 to‘sinlarida solqilik qiymatlari eng katta bo‘lib, mos ravishda 15,15 mm va 21,36 mm ni tashkil etdi. Bu holat, ayniqsa armaturalash foizlari farq qilgan namunalarda, ularning yuk ta’sirida katta deformatsiyaga ega ekanini ko‘rsatdi. Armaturalash foizi bir xil bo‘lgan B1-3S12 va B3-1S12-2G12 to‘sinlarida solqilik qiymatlari mos ravishda 15,15 mm va 17,79 mm ni tashkil qildi. Shu bilan birga, ko‘proq po‘lat armaturaga ega bo‘lgan B4-4S12 to‘sinida (po‘lat kesim yuzasi 4,524 sm²) solqilik 9,01 mm ga teng bo‘ldi. Bu holat po‘lat armatura miqdorining ortishi to‘sin bikrligini oshirishini va solqilikni kamaytirishini yaqqol ko‘rsatadi (1-jadval).



B3-1S12-2G12



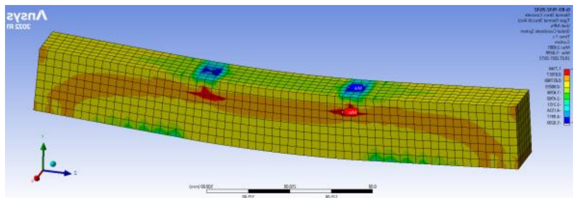
B5-2S12-2G12



B8-3S10-2G10

2-rasm. Armaturalardagi normal kuchlanishlar

3-rasmda keltirilgan modellashtirish natijalariga ko‘ra, betonda hosil bo‘lgan eng katta kuchlanishlar to‘sinning siqilish zonasida kuzatilib, yuk qo‘yilgan nuqtada 5,83 MPa qiymatga yetgani aniqlandi. Ushbu normal kuchlanish yuk to‘sinning o‘rta qismiga yaqin joyda qo‘yilgani natijasida betonni siqilish holatiga o‘tishi bilan izohlanadi. Yuk *l*/3 masofada qo‘llanilgani sababli ichki kuchlar kesimning yuqori tolalari tomon siljib, yuk ortishi bilan ushbu zonada siqilish kuchlanishlarining bosqichma-bosqich o‘sishiga olib keldi.

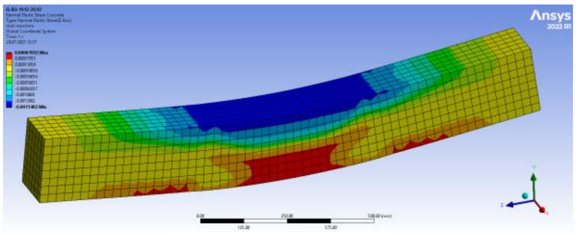


3-rasm. B3-1S12-2G12 to‘sining betonida hosil bo‘lgan normal kuchlanishlar

Beton deformatsiyalari, odatda, temirbeton elementlarning konstruktiv ishlash qobiliyati va deformatsiya xususiyatlarini baholashda eng muhim parametrlardan biri hisoblanadi. 4-rasmda ko‘rsatilganidek, to‘sinning siqilish va cho‘zilish zonalarida hosil bo‘lgan eng katta nisbiy deformatsiya qiymatlari mos ravishda ko‘k va qizil ranglar bilan ifodalangan.

Siqilish zonasida beton o‘zining eng katta siqilish deformatsiyasiga, ya’ni $\varepsilon_{b1,red}$=0,0015 qiymatga yetgan bo‘lib, bu mahalliy yemirilish holati yuzaga kelganini anglatadi. Ushbu holat beton katta siqilish kuchlanishlari ta’sirida deformatsiyalanish qobiliyati juda cheklangan ekanini ko‘rsatadi hamda sonli tahlillarda deformatsiyalar taqsimotini aniq modellash zarurligini ta’kidlaydi [13-15].

Cho‘zilish zonasida esa eng katta nisbiy deformatsiya ε_{bt}=0,00062 qiymatda qayd etildi, bu betonning armatura orqali uzatilayotgan cho‘zilish kuchlanishlariga qarshiligini ifodalaydi. Ushbu deformatsiyalarni kuzatib borish beton va armatura o‘rtasidagi o‘zaro ta’sirni baholashda, ayniqsa to‘sinning elastik bosqichdan keyingi yuklarni qabul qilish qobiliyatini aniqlashda muhim ahamiyatga ega bo‘lib, materialning egiluvchanligi hamda konstruksiyaning umumiy ishlashini kompleks tarzda tahlil qilish imkonini beradi [16-19].



4-rasm 4. B3-1S12-2G12 to‘sindagi nisbiy deformatsiyalar

ANSYS dasturi yordamida to‘sinlarni sonli modellash natijalari an’anaviy po‘lat armaturali temirbeton to‘sinlar va gibrid po‘lat–ShKAli temirbeton to‘sinlarning darzbardoshligida sezilarli farq mavjudligini ko‘rsatdi. An’anaviy po‘lat armaturali temirbeton to‘sinlarda ilk darzlar yuklanishning keyingi bosqichida, aniqroq aytganda, qo‘yilgan yuk chegaraviy yuk ko‘tarish qobiliyatining taxminan 14–15 % iga yetganda kuzatildi. Darzlarning kechroq paydo bo‘lishi po‘lat armatura boshlang‘ich yuklanish bosqichida cho‘zilish kuchlanishlarini samarali qabul qilib, betonda kuzatiladigan darzlarning yuzaga kelishini sekinlashtirgani bilan izohlanadi (3-jadval).

Bundan tashqari, gibrid po‘lat–ShKAli temirbeton to‘sinlarda ilk darzlar chegaraviy yuk ko‘tarish qobiliyatining taxminan 11–13 % iga to‘g‘ri keluvchi yuklamada qayd etildi. Gibrid armaturalangan to‘sinlarda darzlarning ertaroq paydo bo‘lishining asosiy sababi sifatida ShKAning elastiklik moduli po‘latnikiga nisbatan past ekanini ko‘rsatish mumkin. ShKAning elastik moduli cho‘zilish zonasida kuchlanishlarning taqsimlanishiga ma’lum darajada ta’sir ko‘rsatib, betonda cho‘zilish deformatsiyalarining jamlanishiga olib keladi va natijada darz hosil bo‘lish jarayonini ertaroq boshlanishiga sabab bo‘ldi.

3-jadval

To‘sinlar uchun darzbardoshlik momenti qiymatlari

Belgilanishi	M_{crc}^{num}, kN·m	M_{u}^{num}, kN·m	$M_{crc}^{num} / M_{u}^{num}$
B1-3S12	3.73	24.87	0.15
B2-1S12-2G10	3.04	23.38	0.13
B3-1S12-2G12	3.23	24.85	0.13
B4-4S12	4.22	30.12	0.14
B5-2S12-2G12	3.08	28.00	0.11
B6-2S10-2G12	3.10	25.83	0.12
B7-5S10	3.75	24.98	0.15
B8-3S10-2G10	3.21	24.66	0.13
B9-2S10-3G10	3.10	23.82	0.13

3-jadvalda barcha to‘sin namunasi uchun dastlabki darzlar hosil bo‘lgan momentlar keltirilgan bo‘lib, dastlabki darzlar hosil bo‘ladigan yuk qiymatlaridagi farqlar yaqqol ko‘zga tashlanadi. Ushbu kuzatishlar temirbeton to‘sinlarning boshlang‘ich ishlash bosqichida armatura turining juda muhim ahamiyatga ega ekanligini ko‘rsatadi.

Ayniqsa, gibrid armaturalash to‘sinlarda darzlarning ertaroq rivojlanishiga sabab bo‘lishi mumkin, biroq bu holat to‘sinlarning umumiy yuk ko‘tarish qobiliyatining pasayishiga olib kelmaydi. Aksincha, ShKA armatura darzlar paydo bo‘lgandan keyingi ishlash bosqichida samarali ishtirok etib, to‘sinlarning egiluvchanligi va plastik ishlash qobiliyatini ta’minlaydi hamda dastlabki darzlar kuzatilgandan keyin ham qo‘shimcha yuklarni qabul qilish imkoniyatini yaratadi.

Shu bois, gibrid armaturali konstruksiyalarda po‘lat va kompozit armaturalar o‘rtasidagi o‘zaro nisbatni to‘g‘ri aniqlash darzlarning hosil bo‘lishini, uzoq muddat xizmat qilishini va yuk ta’sirida ishlaydigan egiluvchan temirbeton elementlarni loyihalashni ishonchli bashorat qilish uchun muhim ahamiyatga ega.

4. Xulosa

1. Sonli tadqiqot natijalariga ko‘ra, ham po‘lat, ham ShKAlar beton to‘sinlarning ishlashiga ijobiy ta’sir ko‘rsatishi aniqlandi. Cho‘zilish zonasida joylashgan po‘lat armatura o‘zining oquvchanlik chegarasidan oshib, egiluvchan holatda ishlashni ta’minladi va oquvchanlik chegarasidan keyin konstruksiya xavfsizligini oshirdi. Po‘lat armatura bilan birgalikda, ShKAlar ham cho‘zilish kuchlanishlarining katta qismini qabul qildi.

2. Siqilish zonasidagi armatura ham yuklarni qabul qilishda ma’lum darajada ishtirok etib, kesim bo‘ylab kuchlanishlarning taqsimlanishiga hissa qo‘shdi. Gibrid po‘lat–ShKAli temirbeton to‘sinlarda darzbardoshlik va yuk ko‘tarish qobiliyati o‘rtasida muvozanat holat kuzatildi. ShKAning elastiklik modulining pastligi sbabli gibrid armaturalangan to‘sinlarda darzlar ertaroq paydo bo‘lsa-da, ularning umumiy yuk ko‘tarish qobiliyati an’anaviy po‘lat armaturali temirbeton to‘sinlarga nisbatan sezilarli darajada kamaymagan.

3. Gibrid po‘lat–ShKAli temirbeton to‘sinlarda po‘lat armatura egiluvchanlikni ta’minlab, solqiliklarni nazorat qiladi, shu bilan birga ShKAlar cho‘zilish mustahkamligini oshiradi va darzlar paydo bo‘lgandan keyin konstruksiyaning ishlashini yaxshilaydi. Siqilish zonasida betonda hosil bo‘lgan kuchlanishlar o‘zining chegaraviy qiymatlariga yetgan bo‘lib, bu betonning qo‘yilgan yuklarga qarshilik ko‘rsatishda faol ishtirok etganini ko‘rsatadi.

4. Umuman olganda, gibrid po‘lat–ShKA qo‘llanilishi yuk ta’sirida ishlaydigan to‘sinlarni ekspluatatsiya qilishda muhim va amaliy yechim hisoblanadi. Bunday yechim an’anaviy po‘lat armaturali temirbeton to‘sinlarga nisbatan mustahkamlik, xavfsizlik, chidamlilik va iqtisodiy samaradorlikni oshirish imkonini beradi.

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