UDC 616.71-001.5-089.22-76/-77-046.32
DOI: 10.14739/2310-1210.2026.6.370795

Comparison of the static strength of implant–screw junctions in titanium and carbon-composite implants for osteosynthesis

M. L. Golovakha[1,A,F], **V. M. Chornyi**[1,A,E], **D. V. Pavlenko**[2,B,C,D], **V. V. Chornyi**[1,B,C,D]

[1]Zaporizhzhia State Medical and Pharmaceutical University, Ukraine; [2]National University "Zaporizhzhia Polytechnic", Ukraine

A – research concept and design; B – collection and/or assembly of data; C – data analysis and interpretation; D – writing the article; E – critical revision of the article; F – final approval of the article

Keywords: osteosynthesis, implant, titanium alloy Ti-6Al-4V, carbon-composite material, fixation, biomechanics, implant–screw junction, mechanical complications, strength.

Zaporozhye Medical Journal. 2026;28(6):512-518

Stability of plate osteosynthesis depends not only on plate strength but also on the implant–screw junction. Screw loosening, thread stripping, plastic deformation of the shaft or hole failure can result in loss of fixation and revision. Ti-6Al-4V remains the standard alloy for extra-osseous plates, yet its elastic modulus is substantially higher than that of cortical bone and favors stress shielding. Carbon composites offer high specific strength, biocompatibility, radiolucency and a modulus closer to bone; they are already used for osteosynthesis and defect reconstruction. Comparative data on the strength of the implant–screw junction in carbon-composite versus titanium bodies under identical loading remain scarce.

Aim. To compare failure modes of implant–screw junctions in Ti-6Al-4V and carbon-composite implants and to relate screw deflection to static load.

Materials and methods. Junction strength was tested on a modified servohydraulic machine (maximum force 10 kN) in cantilever bending. Screws of different lengths with a conical head thread were inserted into a full-size titanium implant and into a composite-body model of the same wall thickness and hole diameter. The composite body was a Ukraine-manufactured carbon–carbon composite previously used for extra-osseous osteosynthesis. Each material–overhang combination was tested on at least five identical specimens ($n \geq 5$). Load was applied to the free end of the screw at lever arms of 14-, 22- and 24-mm. Force and deflection were recorded; testing stopped after failure of the junction or of the implant body.

Results. Mean relative strength of the composite implant–screw junction was 78 %. Failure modes differed: composite body failed by hole-rim crushing or plate fracture; titanium screws failed by plastic deformation. The conical threaded interface remained intact in every material and overhang tested. Indicative material-level ratio (composite junction capacity vs. published cortical bone strength) was approximately 4.4 versus 5.6 for titanium; this ratio is not a safety factor of a complete bone–implant construct.

Conclusions. Under ultimate load, the composite construct is inferior to the titanium construct but remains substantially stronger than cortical bone. Differences in failure mechanisms may be relevant for planning osteosynthesis and predicting the likely type of complication. A reduction in the construct's load-bearing capacity could potentially be compensated by increasing the number of fixation points or by enlarging the plate's cross-sectional dimensions.

Ключові слова: остеосинтез, імплантат, титановий сплав Ti-6Al-4V, вуглецево-композитний матеріал, фіксація, біомеханіка, вузол «імплантат – гвинт», механічні ускладнення, міцність.

Запорізький медичний журнал. 2026. Т. 28, № 6(159). С. 512-518

Порівняння статичної міцності вузлів «імплантат – гвинт» в імплантатах для остеосинтезу з титану та вуглецевого композиту

М. Л. Головаха, В. М. Чорний, Д. В. Павленко, В. В. Чорний

Надійність накісткового остеосинтезу визначається не лише міцністю пластини, але й поведінкою вузла «імплантат – гвинт». Розхитування гвинта, зрив різі, пластична деформація стрижня або руйнування отвору призводять до втрати стабільності та зумовлюють необхідність ревізій. Ti-6Al-4V залишається базовим сплавом для пластин, але його модуль пружності істотно вищий за модуль пружності кортикальної кістки, що може спричиняти стресове екранування. Вуглецеві композити мають високу питому міцність, біосумісність, рентгенпрозорість і модуль пружності, наближений до кістки; матеріал уже використовують для остеосинтезу та заміщення дефектів. Разом із тим, досі недостатньо порівняльних даних щодо міцності саме вузла «імплантат – гвинт» у композитному та титановому корпусах за однакового навантаження.

Мета роботи – порівняти характер відмови вузлів «імплантат – гвинт» в імплантатах із Ti-6Al-4V та вуглецевого композиту, оцінити залежність прогину гвинта від прикладеного статичного навантаження.

Матеріали і методи. Статичну міцність вузла досліджено на модернізованій сервогідравлічній машині (максимум 10 кН) за консольною схемою. Гвинти різної довжини встановлювали конічною різзю в натурний титановий імплантат і в модель композитного корпусу з тією самою товщиною стінки та діаметром отворів. Корпус моделі виготовлено з вітчизняного вуглець-вуглецевого композиту, який уже застосовували для накісткового остеосинтезу. Кожну комбінацію матеріалу та вильоту випробовували щонайменше на п'яти однакових зразках ($n \geq 5$). Навантаження прикладали до вільного кінця гвинта при плечах 14 мм, 22 мм і 24 мм. Реєстрували зусилля та прогин; випробування припиняли після відмови вузла або корпусу.

Результати. Відносна міцність композитного вузла становила 78 % титанового. Тип відмови був різним: у композиті руйнувався корпус (зминання крайки отвору або злам пластини), у титані – гвинти (внаслідок пластичної деформації). Конічне різьбове спряження не зруйнувалося в жодному варіанті матеріалу та вильоту. Орієнтовне співвідношення несучої здатності вузла до значень міцності кортикальної кістки людини, що наведені у фаховій літературі, збереглося (4,4 проти 5,6 для титану); цей показник не є коефіцієнтом запасу повної системи «кістка – імплантат».

© The Author(s) 2026. This is an open access article under the Creative Commons CC BY 4.0 license

Висновки. За граничним навантаженням композитний вузол поступається титановому, але залишається суттєво міцнішим за кортикальну кістку. Різниця механізмів відмови може мати значення для планування остеосинтезу та прогнозу можливого типу ускладнення. Зниження несучої здатності вузла потенційно може бути компенсоване більшою кількістю точок фіксації або збільшенням перерізу пластини.

Intra-articular and meta-epiphyseal fractures remain a common cause of temporary and permanent disability. Open reduction and internal fixation with angular-stable locking plates is the standard operative treatment for many fractures at these sites. The clinical outcome of osteosynthesis depends on multiple factors. These may be grouped as surgical (approach, intraoperative soft-tissue injury, quality of reduction, iatrogenic damage), patient-related (age, comorbidity, pre-injury function) and implant-related (bioinertness, overall construct stiffness, and, critically, the ability of the screw–plate junctions to remain stable throughout union).

The material used for the plate and its fasteners must meet several requirements at once: biocompatibility, an acceptable toxicological profile of the surface and of any degradation products, antimicrobial properties, and mechanical performance consistent with in vivo loading. High short-term strength is needed, as is a fatigue limit under low- and high-cycle loading, together with an elastic modulus close to that of cortical bone. A separate demand is placed on the implant–screw system: the threaded interface must remain intact under the bending and shear forces generated by walking, upper-limb weight-bearing and rehabilitation.

From the standpoint of structural reliability, the weakest point of this system is usually not the plate body but the screw junction. The strength reserve of the plate material often exceeds that of cortical bone for a given load and geometry. If the threaded interface weakens, the reserve of the whole construct falls and stable fixation may be lost [1,2]. The clinical consequences are secondary displacement, delayed union or nonunion, implant migration and the need for revision osteosynthesis [3,4].

Ti-6Al-4V remains a staple alloy in trauma surgery because of its high strength, corrosion resistance and established biocompatibility. Its elastic modulus, however, is substantially higher than that of cortical bone, which predisposes to stress shielding, local reduction of bone density beneath the plate and redistribution of load onto the screws. Clinical experience with implants and augments, and observation of their behavior during postoperative rehabilitation, indicate that the main mechanical problems arise at the junctions [2,3]. Non-metallic materials respond differently; that response may loosen screw purchase and the rigid plate–bone coupling. Thread failure in the implant hole is occasionally catastrophic and requires reoperation [4,5].

Composites are of interest because they combine the properties of their constituents and are already used in prosthetics and osteosynthesis. Carbon-composite materials offer high specific strength, thermal stability and biocompatibility. Their structure tends to distribute load more evenly in the bone–implant system and to reduce local overload. Additional clinical advantages include radiolucency (which simplifies intraoperative assessment of reduction and postoperative evaluation of union), the absence of marked CT artefact, and the option of radiotherapy in orthopedic oncology without secondary scatter from a metal construct [2,4,6,7]. Ukraine-manufactured carbon–carbon composites have already been used for osteosynthesis of the humeral neck [8] and for reconstruction of long-bone defects [4], which supports the material's basic clinical acceptability.

What remains unresolved is the behavior of the screw junction in such an implant under static and cyclic load. When a new material is proposed as a substitute for an established design, the static reserve is usually taken from tensile tests of standard specimens, and the cyclic reserve from a comparison of geometrically identical laboratory specimens in titanium and in the candidate material. Calculated estimates for the junction itself are unreliable, so full-scale tests on dedicated rigs are required [6].

Few studies have compared the strength of threaded junctions in carbon-composite implants with titanium constructs under identical loading. Without that comparison it is difficult to judge whether a composite plate retains an adequate reserve relative to cortical bone and which mode of mechanical failure should be expected in practice.

Aim

To determine how the implant–screw junctions fail in implants made of titanium alloy and of carbon-composite material, and to relate screw deflection to applied load, with a view to improving the reliability and service life of the constructs.

Materials and methods

Static strength of the implant–screw junction was tested on a modified servohydraulic machine with a maximum force of 10 kN *(Fig. 1a)*. Crosshead displacement, load and temperature were recorded. Before each series the machine was calibrated with a lever dynamometer *(Fig. 1b)*; load measurement error did not exceed ±1.5 % at 20 % of maximum capacity.

A fixture mounted on the fixed lower crosshead *(Fig. 2)* held the implant–screw assembly for both the titanium and the composite variants *(Fig. 3)*.

Screws of different lengths *(Fig. 4b)* were inserted with a conical thread into a full-size titanium implant *(Fig. 4a)* and into the composite-body model *(Fig. 3)*. Body thickness and hole diameters were the same. The composite specimen was a purpose-built model of a Ukraine-manufactured carbon–carbon composite extra-osseous plate of the type previously used for proximal humeral osteosynthesis and reconstruction of long-bone defects [4,8]. Wall thickness and locking-hole diameter matched those of the full-size Ti-6Al-4V plate; identical Ti-6Al-4V locking screws with a conical head thread were used in both materials. The protocol compared the implant–screw junction under identical geometry and loading and did not include a bone bed. Load was applied to the cantilever portion of the screw at different lever arms.

Force and deflection of the free end of the screw were recorded; the latter corresponded to crosshead travel under cantilever loading. Displacement was sampled every 0.01 s with an accuracy of ±1 μm.





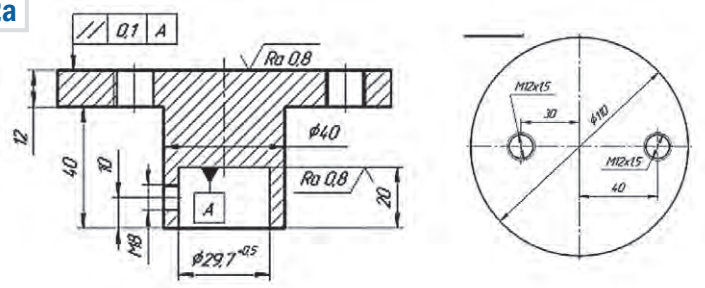
Fig. 1. Test rig for screw–implant junctions (**a**) and the working area with the dynamometer (**b**).

Fig. 2. Fixture for the implant–screw assembly.

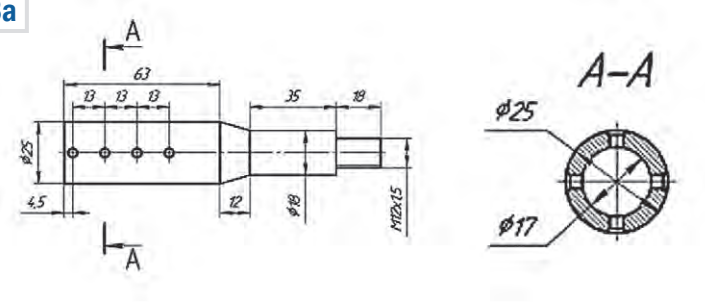
Fig. 3. Fixture representing a composite implant with screw holes.

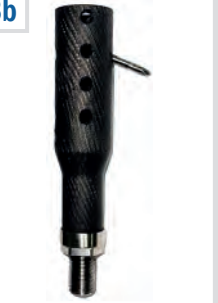
Fig. 4. Titanium implant with locking screws (**a**) and screws of different designs (**b**).

Fig. 5. Working area during cantilever bending: carbon-composite implant (**a**) and titanium alloy implant (**b**).

















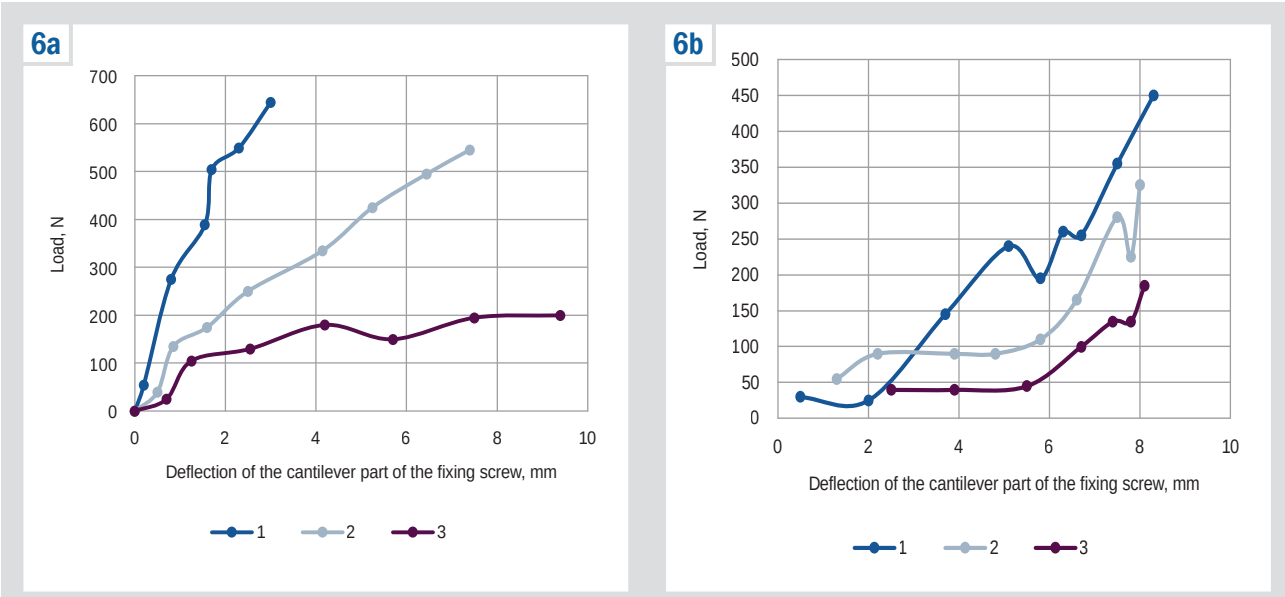


Fig. 6. Screw-tip deflection versus load for a Ti-6Al-4V body (**a**) and a carbon-composite body (**b**). **1:** L = 14 mm; **2:** L = 22 mm; **3:** L = 24 mm.

Table 1. Peak load at failure of the implant–screw junction under cantilever bending (n ≥ 5 per group)

Lever arm, mm	Ti-6Al-4V, N	Carbon composite, N	Relative strength	Predominant failure
14	630–660	440–470	0.72	See notes
22	530–560	340–370	0.65	See notes
24	180–210	170–200	0.95	See notes
Mean	–	–	0.78	–

Failure modes were consistent within each material and are therefore not repeated in every row. Relative strength is the ratio of group-mean peak loads.
Notes: in Ti-6Al-4V the screws failed by plastic deformation; in the composite the body failed by hole-rim crushing or plate fracture.
The conical threaded interface remained intact in all tests.

Six experimental groups were formed (two body materials × three lever arms). Each group comprised at least five identical specimens (n ≥ 5). Peak load was reported as the observed range and as group mean ± SD. The mean relative strength of the composite implant–screw junction was calculated as the ratio of group-mean peak loads to the corresponding titanium values. Descriptive statistics and 95 % confidence intervals were obtained at α = 0.1, accepted for this comparative engineering experiment.

The study was an experimental biomechanical investigation and did not involve patients. Ethics review of a clinical protocol was not required.

Results

The junction was loaded in cantilever bending of a screw inserted into the implant body. The working area with the mounted specimens is shown in *Fig. 5*.

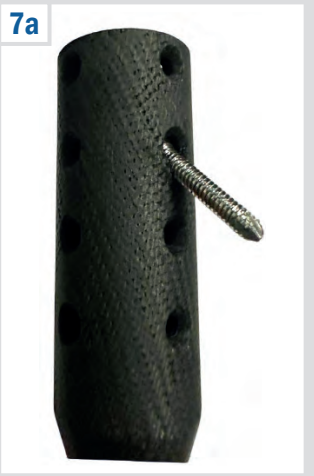
Under load the screw both bent and acquired some play in the junction. Displacement–load curves were constructed for lever arms of 14 mm, 22 mm and 24 mm, and the force on the screw in the titanium and composite bodies was compared at the same overhang. Testing was stopped after complete failure of the threaded junction or of the implant body. The peak load at failure was recorded.

Deflection of the free end of the screw versus force for both materials is shown in *Fig. 6*. The assembly after testing is shown in *Fig. 7*.

The failure mode was determined by the material of the implant body. In composite specimens, failure occurred either through crushing of the lower rim of the hole *(Fig. 8a)* or via fracture of the body itself *(Fig. 8b)*. Titanium specimens maintained the integrity of the threaded junction even at peak load; instead, the screws underwent plastic deformation *(Fig. 8c)*. Consequently, failure in the composite system originated within the body, whereas in the titanium system it occurred in the screws. Owing to the high ductility of the titanium alloy, the screws lost their original shape and were no longer able to fulfill their mechanical function *(Fig. 8c)*.

The curves for the titanium body *(Fig. 6a)* were similar at all lever arms tested: an elastic segment, then plastic deformation of the screw, after which the screw lost its shape and load-bearing capacity [9] *(Fig. 8c)*. Peak force depended on overhang and was 630–660 N, 530–560 N and 180–210 N at 14 mm, 22 mm and 24 mm, respectively. The titanium junction did not fail at any overhang.

The composite curves were different. They showed segments of changing slope and inflection points *(Fig. 6b)*, consistent with sequential deformation and failure of different assembly parts. After testing, the screws showed little plastic deformation *(Fig. 7)*, indicating that the implant itself had failed: crushing of the lower hole rim *(Fig. 8a)* or fracture of the body *(Fig. 8b)*. The threaded interface did not fail at any load or overhang. This suggests that the junction itself is adequately reliable for implant fixation [10]. Peak force



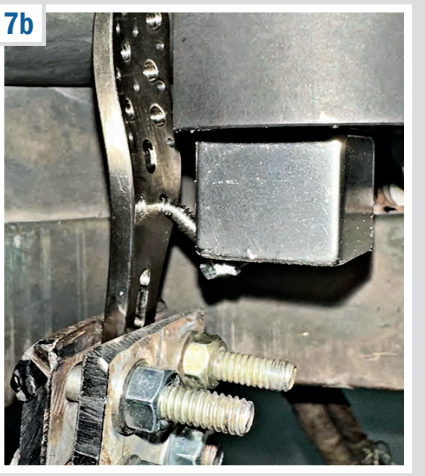


Fig. 7. Implant–screw assembly after testing: screw deformation in the composite implant (**a**) and in the titanium implant (**b**).







Fig. 8. Failure of implant–screw components: carbon composite (**a**, **b**) and titanium alloy (**c**).
a: Crushing of the threaded hole in the composite implant;
b: fracture of the implant body;
c: screw failure in the titanium implant.

was 440–470 N, 340–370 N and 170–200 N at 14 mm, 22 mm and 24 mm *(Table 1)*.

Taking the peak load of the titanium implant–screw junction as the reference, the mean relative strength of the composite implant–screw junction is 0.78. For an indicative comparison only, the ultimate tensile strength of Ti-6Al-4V (about 850 MPa) and published values for human cortical bone (about 150 MPa) give material-level ratios of approximately 5.6 and, after a 22 % reduction in junction capacity, approximately 4.4. These figures are not a safety factor of a complete bone–implant–screw construct, which was not modelled in the present static protocol.

Discussion

The findings address a clinical question: does the screw junction in a carbon-composite implant retain adequate strength reserve for stable osteosynthesis, and how does its failure mode differ from that of a conventional titanium system?

A composite junction at 78 % of titanium strength means a 22 % drop in ultimate load. That drop does not take the construct outside a biomechanically acceptable range relative to bone: an indicative material-level ratio versus published values for human cortical bone remains 4.4, compared with 5.6 for titanium. Even on a conservative reading, the composite implant–screw junction failed at loads several times the reference strength of cortical bone. As a potential practical implication, provided load is shared among several screws, the limiting factor for union may still more often be bone than implant; this inference requires confirmation in a complete bone–implant–screw system.

The mode of failure matters as much as the absolute load. In the titanium system, the implant body and the conical threaded interface remained intact, while the screws underwent marked plastic deformation and lost the geometry needed to hold fragments. Clinically this maps onto the familiar “bent or broken screw with an intact plate”: removal of deformed screws can be technically difficult, and loss of screw axis reduces the stability of angular-stable locking. In the composite system the screws showed little plastic deformation after testing; the hole rim crushed, or the body failed. That pattern is closer to local plate damage with preserved screw geometry. It is easier to anticipate at the design stage (larger plate cross-section, reinforcement of the hole zone, more fixation points) and potentially simpler with respect to revision of the screw component. These observations should be read as potential practical consequences of the bench-test failure modes rather than as established clinical rules.

The conical threaded interface survived in both materials at every overhang and load tested. In locking plates, it is this conical head-to-hole coupling that creates a rigid plate–screw monoblock. Its integrity indicates that the chosen thread geometry is sufficiently robust and is not the weak link even in a composite body, consistent with reports

that catastrophic hole stripping depends largely on junction design rather than plate material alone [4].

The dependence of ultimate load on screw overhang (14 mm, 22 mm and 24 mm) is directly relevant to surgical technique. Increasing the cantilever sharply reduces capacity in both the titanium (down to 180–210 N) and the composite system (down to 170–200 N). At large overhangs the difference between materials narrows: the limiting element is then the screw acting as a cantilever rod, not the implant body. In practice, working length of the screw, unicortical versus bicortical purchase, distance from the plate to the far cortex, and the quality of reduction, which affect junction life, no less than the choice of plate material.

The 22 % reduction in capacity of the composite junction can potentially be offset by increasing plate cross-section or the number of locking screws, thereby sharing load and lowering the demand on each junction. That approach is standard in planning osteosynthesis of osteoporotic bone and comminuted fractures and does not require abandoning the carbon-composite plate as a concept. Given the lower mass of the composite, a larger cross-section need not produce a clinically unacceptable implant bulk.

The data complement existing clinical use of carbon-composite fixators. Radiolucency facilitates intraoperative control and postoperative assessment of regenerate, as already applied in proximal humeral osteosynthesis and femoral defect reconstruction [4]. Biomechanical characterization of the junction closes the gap between those clinical observations and the strength requirements of an extra-osseous construct. The elastic modulus of carbon composites, closer to bone, should in theory reduce stress shielding relative to Ti-6Al-4V, a further argument for the material provided the junction reserve remains adequate [2,6,10,7].

The limitations must be kept in mind when translating the results to the clinic. Testing used a static cantilever protocol; cyclic (fatigue) loading that would mimic walking and repeated rehabilitation cycles was not examined, although junction fatigue is a separate and clinically important failure mechanism. The composite implant was represented by a purpose-built fixture of matching body thickness and hole diameter; this allows a fair material comparison but does not cover the full range of production plate shapes. The bone bed, screw purchase in bone and the effect of osteoporosis were not modelled. Accordingly, the material-level ratio versus cortical bone should not be interpreted as the reserve of a complete biomechanical system with bone tissue. The significance level of 0.1 is acceptable for a comparative engineering experiment but is more liberal than the conventional medical threshold of 0.05. These limitations do not negate the main conclusions, but they define the next steps: low- and high-cycle testing, tests of production plates in a bone–implant–screw system, and correlation with clinical series.

Conclusions

1. Under static loading, the screw junction in a carbon-composite implant sustained on average 78 % of the ultimate load of the corresponding junction in Ti-6Al-4V.

2. The failure modes differ. In the composite system the body fails (crushing of the hole rim or plate fracture). In the titanium system the body and thread remain intact and the screws undergo plastic deformation.

3. The conical threaded interface did not fail in any combination of material, overhang or load examined.

4. Junction strength in this bench test exceeded published reference values for human cortical bone. In ultimate load, carbon-composite implants are inferior to titanium implants, but an indicative material-level ratio (4.4 relative to cortical bone) remains above 4. This comparison does not replace testing of a complete bone–implant–screw system. Use in osteosynthesis may be considered if the reduced capacity of the junction is offset by more fixation points or a larger implant cross-section.

5. The difference in failure mode may be taken into account when planning osteosynthesis and when anticipating the possible type of mechanical complication: plastic deformation of screws is the leading risk with titanium constructs; local damage to the implant body with preserved screw geometry is the leading risk with carbon-composite constructs. These statements are potential implications of the bench-test results and require confirmation in cyclic tests and clinical series.

Ethical approval
The Bioethics Commission of the Zaporizhzhia State Medical and Pharmaceutical University reviewed the materials provided in the article and found no violations of the ethical standards set forth in applicable regulatory documents, including the Declaration of Helsinki and other legal acts (Protocol of 10.09.2026 No. 13).

AI statement
Generative AI tools (Grok, xAI) were used for language editing, paraphrasing of selected passages and translation of the manuscript into English. The study design, experimental work, data, analysis, interpretation and conclusions are solely those of the authors. All AI-assisted text was reviewed, verified and approved by the authors, who take full responsibility for the content of the article.

Funding
The study received no external funding.

Conflicts of interest
Maksym Golovakha is a member of the Editorial Team of Zaporozhye Medical Journal but was not involved in the peer review process or the decision to publish this article and had no access to information about the identities of the reviewers. The manuscript was handled by an independent handling editor. The authors declared no other potential conflicts of interest.

Конфлікт інтересів
Максим Головаха є членом редакційної колегії «Запорізького медичного журналу», але не брав участі в рецензуванні та ухваленні рішення щодо публікації цієї статті й не мав доступу до інформації про особи рецензентів. Редакційний супровід рукопису здійснював незалежний відповідальний редактор. Інших потенційних конфліктів інтересів автори не задекларували.

Надійшла до редакції /Received: 07.08.2026
Після доопрацювання / Revised: 30.09.2026
Схвалено до друку / Accepted: 12.10.2026

Information about the authors:
Golovakha M. L., MD, PhD, DSc, Professor, Head of the Department of Traumatology and Orthopedics, Zaporizhzhia State Medical and Pharmaceutical University, Ukraine.
ORCID ID: 0000-0003-2835-9333

Chornyi V. M., MD, PhD, DSc, Professor of the Department of Traumatology and Orthopedics, Zaporizhzhia State Medical and Pharmaceutical University, Ukraine.
ORCID ID: 0000-0002-8273-9276
Pavlenko D. V., PhD, DSc, Professor, Head of the Department of Aircraft Engine Technology, National University "Zaporizhzhia Polytechnic", Ukraine.
ORCID ID: 0000-0001-6376-2879
Chornyi V. V., MD, PhD, Assistant of the Department of Traumatology and Orthopedics, Zaporizhzhia State Medical and Pharmaceutical University, Ukraine.
ORCID ID: 0000-0003-0902-7616

Відомості про авторів:
Головаха М. Л., д-р мед. наук, професор, зав. каф. травматології та ортопедії, Запорізький державний медико-фармацевтичний університет, Україна.
Чорний В. М., д-р мед. наук, професор каф. травматології та ортопедії, Запорізький державний медико-фармацевтичний університет, Україна.
Павленко Д. В., д-р техн. наук, професор, зав. каф. технології авіаційних двигунів, Національний університет «Запорізька політехніка», Україна.
Чорний В. В., PhD, асистент каф. травматології та ортопедії, Запорізький державний медико-фармацевтичний університет, Україна.

Вадим Чорний (Vadym Chornyi)
chorniy.vadim.doc@gmail.com

References

1. Alimi L, Chaoui K, Boukhezar S, Sassane N, Mohamed H, Guettaf Temam T. Structure and mechanical properties of PMMA/GF/Perlon composite for orthopedic prostheses. Mater Today. 2020;31:S162-7. doi: 10.1016/j.matpr.2020.07.085
2. Tan Z, Zhang X, Ruan J, Liao J, Yu F, Xia L, et al. Synthesis, structure, and properties of carbon/carbon composites artificial rib for chest wall reconstruction. Sci Rep. 2021;11(1):11285. doi: 10.1038/s41598-021-90951-8
3. Shekhawat D, Singh A, Bhardwaj A, Patnaik A. A short review on polymer, metal and ceramic based implant materials. IOP Conf Ser Mater Sci Eng. 2021;1017(1):012038.doi: 10.1088/1757-899x/1017/1/012038
4. Chornyi VM, Pertsov VI. [A clinical example of using a carbon-carbon composite to replace a femur diaphyseal defect]. Zaporozhye Medical Journal. 2024;26(1):84-8. Ukrainian. doi: 10.14739/2310-1210.2024.1.291937
5. Khare JM, Dahiya S, Gangil B, Ranakoti L. Influence of different resins on Physico-Mechanical properties of hybrid fiber reinforced polymer composites used in human prosthetics. Mater Today. 2021;38:345-9. doi: 10.1016/j.matpr.2020.07.420
6. Filip N, Radu I, Veliceasa B, Filip C, Pertea M, Clim A, et al. Biomaterials in orthopedic devices: Current issues and future perspectives. Coatings. 2022;12(10):1544. Available from: http://dx.doi.org/10.3390/coatings12101544
7. Souza J, Pinho SS, Braz MP, Silva FS, Henriques B. Carbon fiber-reinforced PEEK in implant dentistry: A scoping review on the finite element method. Comput Methods Biomech Biomed Engin. 2021;24(12):1355-67. doi: 10.1080/10255842.2021.1888939
8. Golovakha ML, Chornyi VV. [Results of a clinical trial of humeral neck osteosynthesis with carbon–carbon composite material]. Current issues in pharmacy and medicine: science and practice. 2023;16(3):254-9. Ukrainian. doi: 10.14739/2409-2932.2023.3.286567
9. Bandyopadhyay A, Mitra I, Goodman SB, Kumar M, Bose S. Improving biocompatibility for next generation of metallic implants. Prog Mater Sci. 2023;133:101053. doi: 10.1016/j.pmatsci.2022.101053
10. Vázquez-Silva E, Abad-Farfán G, Peña-Tapia PG, Torres-Jara PB, Moncayo-Matute FP, Viloria-Ávila TJ, et al. Composites and hybrid materials used for implants and bone reconstruction: a state of the art. Contemp Eng Sci. 2022;15(1):105-35. doi: 10.12988/ces.2022.91974