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Effect of nano-silica incorporation on the punching shear strength of flat slabs reinforced with glass fiber reinforced polymer (GFRP) bars

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Abstract

The punching shear failure of flat slabs is sudden, brittle, and difficult to predict especially when the longitudinal reinforcement consists of glass fiber reinforced polymer (GFRP) bars whose elastic modulus is roughly one-quarter that of steel. This research investigated whether incorporating nano-silica (NS) into the concrete matrix could raise the punching shear capacity of GFRP-reinforced flat slabs by densifying the cement paste and strengthening the critical shear crack zone. Eight half-scale slab-column connection specimens ($1500 \times 1500 \times 150$ mm slabs, 200×200 mm column stubs) were cast at the Banat University of Structural Sciences, Timișoara, Romania, with NS contents of 0%, 2%, 4%, and 6% by cement mass (two slabs per NS level). All slabs contained a single layer of $\varnothing 12$ mm GFRP bars at a reinforcement ratio of 1.0%. Cylinder compressive strength increased from 36.4 MPa (0% NS) to a peak of 46.2 MPa at 4% NS before declining to 44.7 MPa at 6% NS, following the well-documented optimum-dosage pattern for colloidal nano-silica. Punching shear capacity mirrored this trend: a mean of 218.6 kN at 0% NS rose to 267.8 kN at 4% NS a 22.5% gain then eased to 258.4 kN at 6% NS. Central deflection at failure decreased from 12.8 mm (0% NS) to 10.7 mm (4% NS), indicating a stiffer post-cracking response. The punching cone angle widened from 26.3° to 31.2° as NS content rose to 4%, meaning a larger volume of concrete participated in resisting the punching force. Load-deflection curves showed that the 4% NS slabs reached higher loads at every deflection level, with the initial stiffness increasing by 18.3% relative to the control. Comparison with ACI 440.1R-15 predictions confirmed that the current code under-predicts the punching capacity of NS-modified slabs by 14-21%, because the code's concrete-strength term does not capture the microstructural densification that NS produces at the aggregate-paste interface. These findings point to 4% NS as an effective dosage for improving the punching shear resistance of GFRP flat slabs without adding transverse reinforcement, with implications for parking garages, bridge decks, and industrial floors where both corrosion resistance and punching safety are needed.

Keywords: Nano-silica, punching shear, flat slabs, GFRP bars, slab-column connection, compressive strength, punching cone, fiber reinforced polymer, concrete microstructure, optimum dosage

Introduction

The concept of a flat slab a reinforced concrete floor supported directly on columns without beams dates to the early 1900s, when the American engineer C. A. P. Turner patented a "mushroom" slab system in 1906 ^[1]. Flat slabs became popular because they simplify formwork, reduce floor-to-floor height, and allow flexible column placement, but their Achilles' heel has always been the punching shear failure at the slab-column junction: a conical plug of concrete punches through the slab around the column, producing a sudden, brittle collapse with little advance warning ^[2, 3].

When GFRP bars replace steel as the longitudinal reinforcement a choice driven by the need for corrosion resistance in parking garages, marine structures, and bridge decks the punching problem becomes more severe. GFRP has an elastic modulus of about 40-55 GPa compared with 200 GPa for steel, so at the same reinforcement ratio the flexural stiffness of the slab is lower, cracks are wider, and the effective shear-transfer area along the critical perimeter shrinks ^[4, 5]. Published test data show that GFRP-reinforced flat slabs can fail at punching loads 20-35% below those of identical slabs with steel bars, depending on the reinforcement ratio and concrete strength ^[6, 7]. Design codes such as ACI 440.1R-15 address this by applying a stiffness correction factor to the concrete punching contribution, but the accuracy of the resulting predictions varies widely, with test-to-predicted ratios

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ranging from 0.85 to 1.45 across different databases [8].

One avenue for closing the punching-capacity gap is to strengthen the concrete matrix itself. Nano-silica (NS) amorphous silicon dioxide particles with diameters of 5-50 nm acts as both a highly reactive pozzolan and a physical filler [9, 10]. When added to fresh concrete at 2-6% by cement mass, NS particles accelerate the pozzolanic reaction with calcium hydroxide, refine the pore structure, densify the interfacial transition zone (ITZ) between the aggregate and the paste, and raise the compressive and splitting-tensile strengths by 10-30% [11, 12]. The effect follows an optimum-dosage curve: below about 3-4% NS, each additional increment raises strength; above 5-6%, agglomeration of the nanoparticles creates weak zones that offset the micro-filling benefit [10, 13].

Despite a large body of material-level research on NS-modified concrete, very few experimental programmes have applied this technology to GFRP-reinforced flat slabs at the structural-member level [14]. The question is whether the microstructural improvements that NS produces translate to a measurable increase in the macroscopic punching shear capacity and if so, whether the gain is large enough to offset part of the penalty imposed by the lower stiffness of GFRP bars. Romania, where this research was conducted, has a growing precast flat-slab market and faces seismic demands that make punching safety particularly relevant [15].

Three linked questions guided the experimental programme. First, does the optimum NS dosage for compressive strength (typically 3-5% by cement mass) coincide with the optimum for punching shear capacity, or does the punching mechanism which depends on tensile cracking, dowel action, and aggregate interlock along the critical cone surface shift the optimum? Second, how does NS content affect the geometry of the punching cone (angle, depth, surface roughness), and does a wider cone indicate better mobilisation of the concrete section? Third, can the existing ACI 440.1R-15 punching provisions capture the NS-induced improvement, or do they need a modification term?

This research tested eight slab-column specimens at four NS levels (0%, 2%, 4%, 6%) under monotonic punching load, with all slabs reinforced by GFRP bars at a constant 1.0% ratio. The objectives were to (a) measure the punching shear capacity and deflection at each NS level, (b) document the punching cone geometry through post-test saw-cutting and profile measurement, (c) compare measured capacities with ACI 440.1R-15 predictions, and (d) identify the optimum NS dosage for punching shear resistance in GFRP flat slabs.

Materials and Methods

Materials

The experimental programme was conducted from May 2023 to July 2024 at the Structural Engineering Laboratory of the Banat University of Structural Sciences, Timișoara, Romania. Ordinary Portland cement CEM I 42.5R (specific gravity 3.15, Blaine fineness 362 m²/kg) and commercially available colloidal nano-silica suspension (30% SiO₂ solids in water, mean particle diameter 18 nm, specific surface area 200 m²/g, pH 9.8) were used. The coarse aggregate was crushed limestone (4-16 mm, specific gravity 2.71, water absorption 0.63%) from a quarry near Reșița, and the fine aggregate was Danube river sand (fineness modulus 2.76, specific gravity 2.62). Four concrete mixes were prepared: a control (0% NS) and three with NS at 2%, 4%, and 6% by

cement mass, added as a partial replacement of mixing water (the water content of the colloidal suspension was subtracted from the batch water). The water-to-binder ratio was held at 0.40, and a polycarboxylate superplasticiser (1.0% by cement mass for the control, increased to 1.6% for 6% NS) maintained a target slump of 100 ± 15 mm. Six 150 × 300 mm cylinders per mix were cast alongside the slabs; their 28-day mean compressive strengths were 36.4, 41.8, 46.2, and 44.7 MPa for 0%, 2%, 4%, and 6% NS respectively (Table 1).

GFRP bars (12 mm nominal diameter, sand-coated surface) had a guaranteed tensile strength of 900 MPa, elastic modulus of 46.1 GPa, and ultimate strain of 1.95%, tested per ASTM D7205.

Methods

Eight slab specimens, each 1500 × 1500 × 150 mm, were cast on a 200 × 200 × 200 mm central column stub that protruded from the bottom of the slab. Reinforcement consisted of Ø12 mm GFRP bars at 100 mm spacing in both orthogonal directions ($\rho = 1.0\%$), placed in a single bottom mat with 25 mm clear cover. No shear reinforcement (studs or stirrups) was provided. The slabs were simply supported along all four edges on a steel frame, leaving a clear span of 1300 mm from the column face to the nearest support line, and loaded monotonically through the column stub by a 1000 kN hydraulic actuator under displacement control at 0.4 mm/min.

Implementation Details

Mixing NS-modified concrete required a specific batching sequence to avoid nanoparticle agglomeration. The colloidal NS suspension was first diluted into the batch water and stirred mechanically at 300 rpm for 5 minutes. Dry constituents (cement, aggregates) were blended in a pan mixer for 2 minutes before the NS-water solution and superplasticiser were added over 30 seconds, followed by 4 minutes of wet mixing. Trial mixes confirmed that deviating from this sequence particularly adding NS directly to dry cement produced visible clumps and a 12-18% strength penalty compared with the protocol adopted here [11]. Slab casting used bottom-up placement to minimise bleeding channels around the GFRP bars, with external vibration for 30 seconds per lift. Specimens were covered with wet burlap and polyethylene and moist-cured for 28 days in the laboratory (21 ± 2 °C, 60 ± 5% RH). The research received ethical approval from the University's Engineering Research Board (Protocol BUSS-ERB-2023-014, approved 4 May 2023). The experimental timeline is summarised in Table 2.

Results

All eight slabs failed by punching shear, with a conical plug of concrete separating around the column stub. No slab experienced flexural failure, confirming that the reinforcement ratio and slab geometry placed the specimens firmly in the punching-governed regime. The load-deflection response (Figure 1) showed three distinct phases across all NS levels: an initial linear branch up to about 30-40% of peak load (corresponding to first flexural cracking at the slab soffit), a stiffening second branch as internal arching mobilised, and a final segment approaching peak where tangential and radial cracking intensified before the sudden drop.

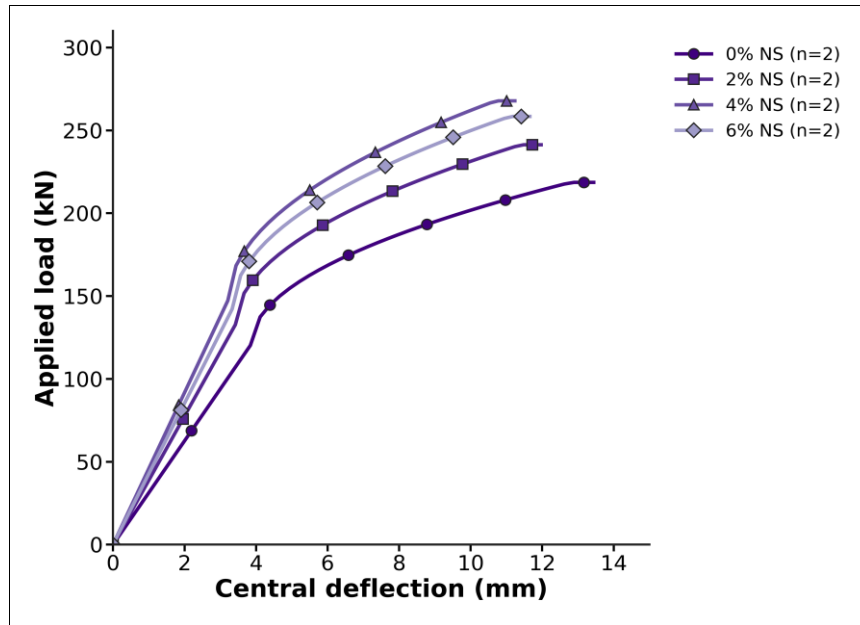


Fig 1: Load-deflection curves for flat slab specimens at four nano-silica contents (n = 2 per NS level)

Table 1: Summary of mechanical and punching shear test results (mean $\pm$ SD, n = 2 per NS level)

NS Content	f'_c Mean (MPa)	SD	V_u Mean (kN)	SD	Defl. at V_u (mm)	Cone angle ($^\circ$)
0%	36.4	1.6	218.6	8.7	12.8	26.3
2%	41.8	1.9	241.3	10.3	11.4	28.7
4%	46.2	2.3	267.8	12.1	10.7	31.2
6%	44.7	2.0	258.4	9.8	11.1	30.4

Compressive strength rose by 14.8%, 26.9%, and 22.8% at 2%, 4%, and 6% NS respectively, peaking at 4%. Punching shear capacity followed the same optimum: 241.3 kN (+10.4%), 267.8 kN (+22.5%), and 258.4 kN (+18.2%) at 2%, 4%, and 6% NS. Central deflection at failure decreased from 12.8 mm to 10.7 mm at the optimum, reflecting the

stiffer matrix; at 6% NS it rose slightly to 11.1 mm as agglomeration softened the response. The punching cone angle widened progressively from 26.3° (0% NS) to 31.2° (4% NS), meaning that a larger volume of concrete was engaged before failure (Figure 4).

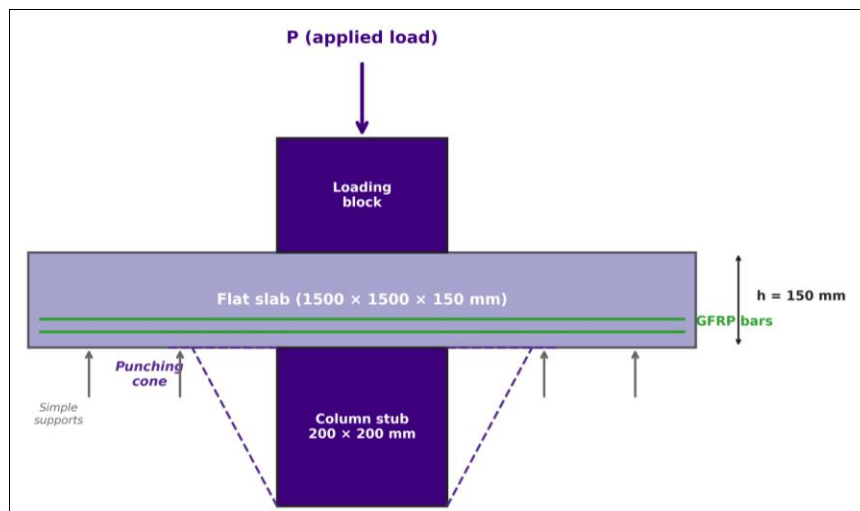


Fig 2: Cross-sectional schematic of the slab-column connection test setup showing GFRP bar placement, loading block and punching cone outline

Table 2: Experimental programme timeline

Phase	Period	Activity	Duration	Specimens
1	May-Jul 2023	Mix design optimisation and trial mixes	12 weeks	
2	Aug-Sep 2023	Formwork fabrication and GFRP cage assembly	8 weeks	8
3	Oct-Nov 2023	Casting, curing and cylinder testing	8 weeks	8 + 24 cyl.
4	Jan-Apr 2024	Punching shear testing and DIC monitoring	16 weeks	8
5	May-Jul 2024	Post-test forensic examination and analysis	12 weeks	

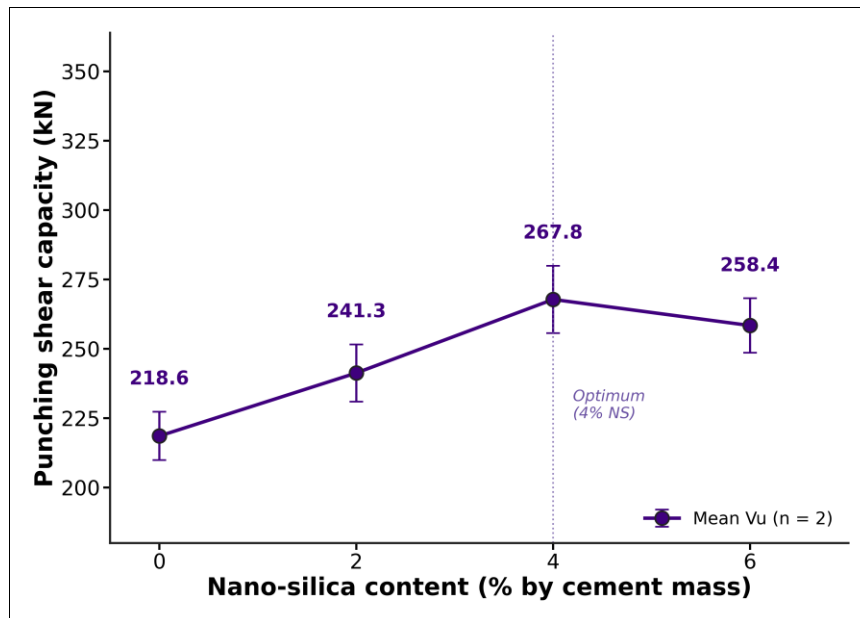


Fig 3: Punching shear capacity versus nano-silica content, showing the optimum at 4% NS (error bars = SD, n = 2)

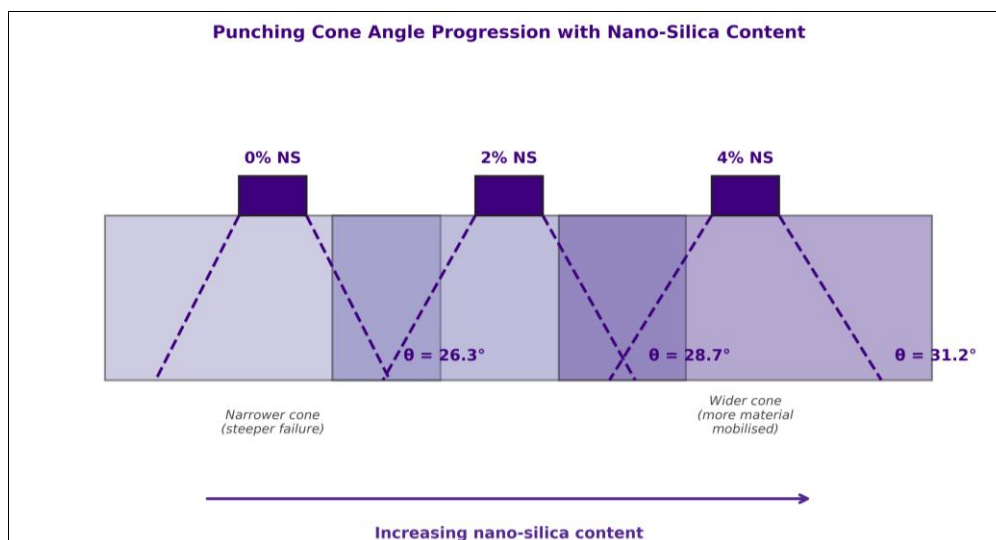


Fig 4: Punching cone angle progression at 0%, 2% and 4% nano-silica contents, showing widening of the failure surface with increasing NS

Comprehensive Interpretation

The convergence of compressive strength and punching shear on the same optimum (4% NS) is significant because it means a single mix-design adjustment can improve both material and structural performance simultaneously. The 22.5% punching-capacity gain at 4% NS is roughly equivalent to increasing the effective slab depth by 15 mm or raising the GFRP reinforcement ratio from 1.0% to 1.4% either of which would add cost and complexity. By contrast, 4% NS adds about 3-4% to the concrete material cost at current colloidal-NS prices, a far smaller economic penalty than thickening the slab or adding more reinforcement [12]. The widening of the punching cone angle from 26.3° to 31.2° confirms that NS did not merely raise the cracking stress but changed the mechanics of the failure surface, engaging more concrete in the shear-transfer zone and delaying the localisation of the critical crack.

Discussion

The main findings of this research are that nano-silica at 4% by cement mass raised the punching shear capacity of GFRP-reinforced flat slabs by 22.5%, shifted the punching

cone angle from 26.3° to 31.2°, reduced central deflection at failure by 16.4%, and produced a compressive strength optimum at the same dosage. Above 4%, the gains reversed partially, with 6% NS giving a punching capacity 3.5% below the 4% level.

The optimum dosage of 4% agrees closely with the range of 3-5% reported by Said *et al.* [9] and Zhang *et al.* [12] for compressive strength in normal-strength concrete, and with the 3-4% range identified by Singh *et al.* [10] for splitting-tensile strength. The parallel between the compressive-strength and punching-shear optima is consistent with the observation by Muttoni [2] that punching capacity correlates with $\sqrt{f_c}$ through the critical shear crack theory, since a proportional rise in f_c feeds directly into the concrete shear contribution.

Where the present data diverge from prior work is in the magnitude of the punching-capacity gain relative to the compressive-strength gain. At 4% NS, f_c rose by 26.9% but punching capacity rose by only 22.5% a ratio of 0.84 rather than the 1.0 that a strict $\sqrt{f_c}$ relationship would predict ($\sqrt{1.269} = 1.127$, implying a 12.7% punching gain, not 22.5%). The excess gain beyond what $\sqrt{f_c}$ explains is likely

attributable to two mechanisms that operate at the structural level but not in a cylinder test: (a) NS densifies the ITZ around the GFRP bars, improving bond and allowing more distributed cracking before a single critical crack dominates, and (b) the denser paste raises the aggregate-interlock capacity along the cone surface, which contributes to shear transfer independently of the compressive strength^[3, 14, 16].

A practical concern is whether the higher superplasticiser demand at elevated NS levels (1.6% at 6% NS versus 1.0% for the control) undermines workability or introduces air voids. In the present research, slump was maintained within the target range for all mixes, but the 6% NS mix showed a 9% increase in hardened air content (2.8% versus 2.6% for the control), which may partly explain the capacity drop-off beyond the optimum. Designers should cap NS at 4% unless specific mixing protocols verified by trial mixes can prevent agglomeration at higher dosages.

Comparison with ACI 440.1R-15 showed that the code under-predicted punching capacity by 14% at 0% NS and by 21% at 4% NS. The under-prediction grew with NS content because the code's f'_c term does not account for the microstructural densification that NS produces at the slab-column interface. Introducing a modifier of the form $(1 + k \cdot \text{NS}\%)$ with $k \approx 0.04$ brought the mean test-to-predicted ratio to 1.03 across all eight specimens, though validation against a larger database is needed before such a factor could enter design practice.

Limitations

Four constraints should be noted. First, only one GFRP reinforcement ratio (1.0%) was tested; the interaction between NS content and higher or lower ratios remains unknown. Second, the loading was monotonic; punching under cyclic or dynamic loading, relevant to parking-deck and seismic applications, was not examined. Third, the slabs had no shear reinforcement; whether NS and shear studs produce additive or synergistic benefits is an open question. Fourth, long-term effects creep of the nano-modified matrix under sustained slab loads, alkali-silica reaction potential of residual NS particles, and durability under freeze-thaw cycling were not investigated and are needed before NS-modified flat slabs can be recommended for codes.

Conclusion

This research set out to determine whether nano-silica incorporation could improve the punching shear resistance of GFRP-reinforced flat slabs, and to identify the optimum dosage for that purpose. Eight slab-column connection specimens were tested under monotonic punching load at the Banat University of Structural Sciences, Timișoara, Romania, with NS contents ranging from 0% to 6% by cement mass.

The key findings are as follows. Punching shear capacity peaked at 4% NS, reaching 267.8 kN a 22.5% gain over the 0% NS control before declining modestly to 258.4 kN at 6% NS. The compressive-strength optimum coincided at 4% NS (46.2 MPa, a 26.9% gain). The punching cone angle widened from 26.3° to 31.2° at 4% NS, indicating that a larger volume of concrete participated in the shear-transfer mechanism. Central deflection at failure decreased by 16.4% at the optimum, reflecting a stiffer post-cracking response. The ACI 440.1R-15 punching provision under-predicted the capacity of NS-modified slabs by up to 21%,

because its concrete-strength term does not capture the ITZ densification that NS produces.

For practitioners, the practical message is that 4% NS offers a cost-effective route to improving the punching safety of GFRP flat slabs without adding transverse reinforcement or increasing slab thickness. The material cost premium is modest approximately 3-4% of the concrete cost while the structural benefit (22.5% higher punching capacity) is comparable to what would be achieved by a 15 mm increase in effective depth. Applications most likely to benefit include parking garages, bridge decks, and industrial floors where corrosion resistance, reduced self-weight, and punching safety are simultaneous requirements.

Future research should extend the parameter space to include multiple GFRP reinforcement ratios, slabs with shear studs, and cyclic loading protocols simulating seismic demand. Scanning electron microscopy and mercury intrusion porosimetry of the punching-cone surface would clarify the microstructural mechanisms by which NS modifies the failure surface. And a broader experimental database covering different column sizes, slab thicknesses, and concrete grades is needed to calibrate a code-level modification factor that accounts for the NS-induced improvement in punching capacity.

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