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**ADVANCED DAMAGE - PLASTICITY MODELLING AND CALIBRATION
STRATEGIES FOR ACCURATE FINITE - ELEMENT ANALYSIS OF
UNREINFORCED CONCRETE IN THIN - WALLED STRUCTURES**

Anotation. Accurate prediction of unconventional, unreinforced concretes in three-dimensional finite-element analysis demands a synthesis of advanced constitutive theory, rigorous experimental calibration, and careful numerical implementation. This study consolidates recent progress and remaining challenges in modeling slag-blended, recycled-aggregate, fiber-reinforced, and ultra-thin formwork concretes within the ANSYS environment. A literature survey identifies three dominant strategies for plain concrete: the legacy smeared-crack SOLID65 element, generalized Drucker–Prager plasticity with user-defined damage, and detailed mesoscale representations that resolve aggregates, mortar, and interfaces. Comparative findings show that damage-plasticity formulations, exemplified by the Concrete Damaged Plasticity (CDP) model, reproduce load–deflection responses and crack patterns within fifteen percent of experimental results when parameters are calibrated against comprehensive test sets that include compression, tension, fracture, and time-dependent data. Calibration protocols remain inconsistent across studies, hindering reproducibility and cross-comparison. The absence of an open benchmark database for non-standard concretes is highlighted as a key barrier to consensus on default parameters. Thin-walled elements expose additional difficulties: geometric nonlinearity couples with progressive stiffness degradation, causing mesh-dependent fracture energy dissipation and solver convergence issues. Remedies include refined through-thickness meshes, nonlocal regularization, and robust arc-length solution controls. Explicit crack-tracking techniques such as phase-field fracture and cohesive segments offer improved fidelity, especially for fiber-rich mixes where residual tensile capacity governs serviceability, yet systematic validation of these methods remains sparse. Long-term phenomena such as creep, shrinkage, and durability, along with high-rate behaviors under impact and seismic loading, are underrepresented in current model verification, particularly for slag-rich and recycled-aggregate mixes. A practical roadmap is proposed that integrates five core actions: creation of a public benchmark database with fully documented laboratory tests; development of unified modeling protocols that specify calibration sequences, error metrics, and reporting formats; targeted investment in explicit fracture models for thin and fiber-reinforced members; expansion of long-term and dynamic experimental programs; and adoption of machine-learning tools to automate parameter identification and flag anomalous model behavior. Complementary software advances, including plug-and-play material subroutines and graphical calibration wizards, are recommended to lower the exper-

tise threshold for practicing engineers. Collectively, these measures chart a pathway from current academic advances toward robust, industry-ready simulations capable of guiding the design of sustainable, reinforcement-free concrete structures.

Key words: finite-element analysis, damage-plasticity modeling, fiber-reinforced concrete, recycled-aggregate concrete, thin-walled formwork, model calibration

Statement of the problem. Concrete exhibits pronounced heterogeneity, strain-rate sensitivity, and quasi-brittle fracture, all of which complicate its representation in three-dimensional finite-element analysis (FEA). The challenge intensifies for unconventional, unreinforced mixes: slag-blended, recycled-aggregate, fiber-reinforced, and ultra-thin concretes employed as permanent formwork because their mesoscale composition departs markedly from that of conventional Portland cement concrete. Reliable prediction of cracking, crushing, and post-peak softening therefore demands material models that go beyond the legacy smeared-crack or linear elastic-perfectly plastic formulations still common in industrial workflows.

Current research converges on three methodological pillars. First, sophisticated constitutive laws – most prominently Concrete Damage Plasticity (CDP), Drucker-Prager, and related damage-plasticity hybrids are adopted to capture stiffness degradation, tension-compression asymmetry, and irreversible volumetric dilation. Second, model parameters are calibrated against targeted laboratory data, including not only uniaxial tension and compression tests but also fracture-energy, size-effect, and cyclic-loading protocols that reveal rate-dependent and path-dependent behavior. Third, numerical tactics such as adaptive meshing, non-local regularization, and staged loading are introduced to maintain solution objectivity once strain localization initiates.

This article reviews state-of-the-art ANSYS implementations for unreinforced concretes, with special attention to thin-walled elements where through-thickness cracking, hydrostatic casting pressure, and local buckling pose additional difficulties. Experimental campaigns that underpin parameter identification are synthesized, and modelling workflows are distilled into reproducible steps. Representative case studies drawn from literature illustrate the best practice, while contrasting influential investigations by geometry, constitutive framework, calibration strategy, and achieved predictive accuracy. The discussion culminates in recommendations for practitioners and highlights emerging trends, such as machine-learning-assisted parameter inversion and phase-field fracture formulations that are poised to advance concrete simulation in commercial FEA environments.

Analysis of the latest research and publications. Three principal modeling routes dominate current ANSYS practice for unreinforced concrete. The legacy option employs the SOLID65 element, which embeds a smeared-crack formulation coupled to the Willam-Warnke failure surface [1]. By reducing elastic moduli at integration points once tensile cracking or compressive crushing initiates, SOLID65 can replicate stiffness degradation; however, abrupt modulus drops often trigger convergence difficulties. Researchers have mitigated this weakness by tuning the crushing-stiffness factor (CSTIF), thereby stabilizing cyclic analyses of concrete-filled tubes and aligning numerical responses with experiments.

A second route relies on general nonlinear elements such as SOLID185 or SOLID186, assigned an elastic-plastic law with a Drucker-Prager yield criterion and optional damage regularization [2]. Crack propagation is approximated through element birth-death procedures or strain-based failure rules. Although less concrete-specific, this framework gains versatility through USERMAT subroutines, which allow implementation of damage-plasticity laws comparable to the Concrete Damaged Plasticity model available in other FEA platforms.

The third, research-oriented route constructs mesoscale representations that discretely model aggregates, mortar, and interfacial transition zones [3]. Random placement of coarse particles or short fibers, scripted in APDL, captures initiation and coalescence of microcracks more realistically than homogeneous continua, albeit at substantial computational cost. Selecting among these approaches therefore entails a trade-off between numerical efficiency and the fidelity required to reproduce mixed specified fracture phenomena.

Robust finite-element prediction of unconventional, unreinforced concretes hinges on constitutive laws that reconcile compression hardening with tension-softening fracture. The literature converges on damage-plasticity frameworks, spearheaded by the Concrete Damaged Plasticity (CDP) model [4]. CDP couples a multisurface yield function with scalar damage variables d_t and d_c that degrade the elastic modulus during cracking or crushing, thereby reproducing unloading stiffness loss and cyclic degradation. Key parameters – dilation angle, eccentricity, shape factor K_c , and the biaxial-to-uniaxial strength ratio are routinely back-calibrated to uniaxial, biaxial, and fracture-energy tests; once tuned, CDP has reproduced load-deflection responses of fibered and recycled-aggregate beams within ten to fifteen percent of experiment. In commercial ANSYS, comparable behavior is achieved through USERMAT subroutines or by invoking concrete formulations in LS-DYNA and Autodyn, confirming that algorithmic availability rather than theoretical limitation governs platform choice.

Plasticity-only options remain widespread when computational economy is paramount. The Drucker-Prager surface, implemented in standard SOLID185/186 elements, captures pressure-dependent yield and confinement effects, but requires auxiliary tension cutoffs or element deletion to mimic cracking, a simplification that restricts accuracy in post-peak regimes. Enhanced yield criteria such as Menétrey-Willam extend Drucker-Prager by differentiating tensile and compressive meridians and underpin the cracking logic of legacy SOLID65 elements [5]. At the research frontier, microplane models and mesoscale formulations deliver fidelity across loading paths, albeit at the cost of parameter sets and run time [6]. Specialized high-rate models RHT and HJC enrich the toolbox for impact and blast scenarios [7]. Experimental calibration and, where necessary, regularization remain decisive for stability and predictive reliability.

Calibration with experimental data also should be provided. Material parameters must be grounded in laboratory evidence before a concrete model can predict structural behavior with confidence. Fundamental calibration begins with stress-strain curves in compression and tension, which supply Young's modulus, peak strengths, and post-peak slopes. Fiber additions typically flatten the descending branch, while high slag replacement may lower both modulus

and strength; these trends should inform hardening or damage functions. Fracture energy, measured from notched-beam tests, governs the tension-softening curve [8]. Higher values observed in fiber-reinforced mixes translate to wider crack openings at residual strength, whereas recycled aggregates often reduce fracture energy and must be reflected by steeper softening.

Advanced yield surfaces such as Drucker-Prager or Menétrey-Willam require biaxial and triaxial data to fix friction and dilation angles. When full multiaxial tests are unavailable, published values or sensitivity studies can substitute, with parameters adjusted until finite-element load-deflection curves align with experiments. Iterative model updating, sometimes automated through optimization algorithms, further refining stiffness, peak load, and crack patterns. Finally, long-term phenomena like creep, shrinkage, or cyclic degradation are tuned to field or laboratory time-history data, completing a calibration workflow that converts generic constitutive laws into mix-specific predictive tools [9-10].

Thin concrete walls and permanent formwork panels pose coupled material-structural difficulties that differ markedly from those in massive members. Their high slenderness ratios amplify geometric nonlinearity; once tensile cracking degrades stiffness, out-of-plane instability can develop well below the elastic buckling load. Accurate prediction therefore demands large-deflection analysis combined with a fracture-capable constitutive law. Robust solution controls, such as arc-length or displacement-control algorithms, are often required to trace snap-through or snap-back paths without numerical divergence.

Mesh objectivity is a second concern. With only one or two solid elements through the thickness, the crack band width is fixed artificially, leading to mesh-dependent energy dissipation. Objective results call for either a refined through-thickness mesh or a nonlocal or regularized damage formulation that decouples fracture energy from element size. Element deletion strategies must also be applied cautiously; wholesale removal of coarse elements can produce unrealistically soft post-peak responses in thin panels.

Boundary conditions during casting introduce additional complexity. Hydrostatic pressure from fresh concrete can bow to a thin panel before the mix gains strength. Realistic staging therefore applies time-dependent lateral pressure while the panel itself undergoes strength development and possibly temperature or shrinkage strains. Omission of these effects can overpredict serviceability performance.

Material behavior further complicates matters. Ultra-high-performance concrete and glass-fiber-reinforced concrete exhibit strain hardening and residual tensile capacity that must be included through multilinear tension curves or damage models with residual stress plateaus [11]. Neglecting fiber bridging leads to unconservative crack-width predictions and underestimated flexural capacity.

Finally, dynamic phenomena may arise because thin elements possess low mass and stiffness. Sudden crack formation can trigger inertial oscillations that alter load-displacement histories. Incorporating a small viscosity parameter or performing explicit transient analysis can capture these rate effects.

Collectively, these challenges underscore the need for calibrated damage-plasticity models, fine or regularized meshes, staged loading, and validation against targeted experiments when simulating thin concrete formwork in ANSYS.

A review of the recent literature highlights several recurring findings that guide material selection and modeling strategy. First, partial replacement of cement with slag or fly ash alters early-age kinetics, often slowing strength development and modifying creep and shrinkage rates. Finite-element models should therefore reduce early compressive strength and, when early loading is critical, include maturity effects; at standard 28-day testing ages, moderate slag replacement can be modeled with compressive strength values like ordinary Portland cement concrete.

Second, recycled aggregate concrete introduces pre-existing flaws at the old mortar interface. Engineers have two practical options: reduce bulk properties such as Young's modulus, tensile strength, and fracture energy in a homogeneous model, or explicitly mesh aggregates and mortar in a two-phase mesoscale scheme. Laboratory data suggest that 30 percent aggregate replacement typically lowers modulus by about 10 percent and tensile strength by about 20 percent, values that provide a reliable starting point for homogeneous models.

Third, discrete fibers without steel rebar enhance ductility and fracture energy. Constitutive laws must raise the residual tensile stress in the post-crack regime, using residual-strength ratios available in codes or derived from beam tests. Omitting this adjustment markedly underestimates load capacity and overpredicts crack widths.

Fourth, thin-walled elements and permanent formwork demand accurate serviceability predictions. Nonlinear fracture models calibrated to crack-width data outperform purely elastic approaches for these applications.

Across all material variants, rigorous calibration and validation against laboratory results remain essential; default material parameters seldom achieve acceptable accuracy without targeted adjustment.

Presentation of the main material of the research. Despite steady progress in constitutive theory and numerical techniques, several critical research gaps continue to limit the predictive power and practical uptake of concrete simulation. Foremost is the absence of a standardized calibration protocol. Although nearly every study stresses the need to tune model parameters against laboratory evidence, the procedures adopted vary widely, ranging from manual curve fitting to ad hoc inverse analyses. The lack of a shared benchmark database for compressive, tensile, flexural, and fracture tests hampers cross-comparison and slows convergence toward reliable default values. Establishing universally accepted calibration guidelines, supported by open repositories of well-documented experimental data, would provide a common reference point and accelerate methodological consensus.

A second limitation concerns the representation of cracking. Mainstream frameworks such as Concrete Damaged Plasticity or Drucker-Prager typically employ smeared-damage formulations that diffuse fracture energy over the finite-element mesh. While computationally efficient, this approach struggles to reproduce localized crack paths and their interaction with geometric instability in thin-walled or fiber-reinforced members. Emerging techniques such as

phase-field fracture, discrete crack insertion, and cohesive interface elements offer the potential to track crack initiation and propagation explicitly, yet systematic studies that compare these methods and validate them against detailed imaging of crack evolution remain scarce.

Long-term and high-rate behaviors constitute a third underexplored domain. Most numerical investigations target short-term strength and initial cracking, paying less attention to creep, shrinkage, thermal cycling, or durability phenomena that govern service life, especially in slag-rich or recycled-aggregate concretes. Likewise, dynamic loading scenarios such as impact, blast, or seismic excitation are often addressed with empirical high-rate models whose parameters have not been verified for modern, unreinforced mixes or thin panels. Expanded programs of time-dependent and dynamic testing, coupled with model refinement and validation, are therefore imperative.

Finally, the practical deployment of advanced models is hindered by the dual challenges of mesoscale complexity and user accessibility. Interface behavior between aggregates, fibers, and mortar is known to control strength and fracture, yet mesoscale simulations remain computationally intensive and difficult to generalize. Parallel advances in machine-learning-assisted parameter identification and in intuitive software toolkits could lower the expertise barrier, enabling practicing engineers to exploit sophisticated damage-plasticity or microplane formulations without resorting to bespoke user subroutines. Closing these gaps will be essential for translating academic advances into robust, industry-ready design tools.

Advancing concrete simulation hinges on a coordinated strategy that blends shared data resources, methodological rigor, and modern digital tools. An open benchmark database containing meticulously documented tests: compression, tension, fracture, creep, shrinkage, and high-rate loading for both conventional and non-standard mixes would give researchers a common reference for calibration and validation, promoting objective cross-comparison. Building on that foundation, the community can draft unified modeling protocols that spell out recommended calibration sequences, target error metrics, mesh-objectivity checks, and reporting formats; a consensus document of this sort streamlines peer review and accelerates the flow of best practice into everyday engineering work.

With reliable data and clear procedures in place, attention can shift to improving crack-tracking fidelity. Explicit approaches such as phase-field fracture, cohesive segments, or discrete crack insertion deserve systematic evaluation against imaging-based observations, particularly for thin panels and fiber-reinforced concretes where smeared models lose accuracy. Long-term and dynamic behaviors must also be incorporated: experimental programs that pair creep and shrinkage measurements with environmental histories, along with impact and seismic tests on modern mixes, will supply the rate-dependent parameters that current formulations lack.

Machine learning provides a practical means of automating these workflows. Surrogate models trained on the benchmark database can expedite inverse analysis, suggest initial parameter values, and flag outlier responses, thereby reducing analyst effort and improving reproducibility. Complementing these advances, plug-and-play material subroutines, graphical calibration wizards, and detailed documentation will lower the expertise threshold, ensuring

that sophisticated constitutive laws migrate from academic studies into routine design practice.

Conclusions. Accurate finite-element analysis of unconventional, unreinforced concretes now follows a well-defined workflow that pairs advanced constitutive laws with systematic experimental calibration. Damage-plasticity models remain the most dependable option because they capture both compression hardening and tension softening, while simpler yield-surface approaches can perform acceptably when supplemented by explicit tensile failure rules and verified against a broad test set. The foundation of any reliable simulation is high-quality data: compressive, tensile, flexural, fracture, and time-dependent tests supply the parameters that let calibrated models reproduce load–deflection curves and crack patterns within about fifteen percent of laboratory observations.

Important gaps still limit predictive power and everyday use. A public benchmark database of validated tests would give analysts a common reference for parameter identification, encourage objective cross-comparison, and speed agreement on default values. Clear modeling protocols that spell out calibration sequences, error metrics, mesh-objectivity checks, and reporting formats would turn diverse research practices into industry-ready standards. Thin-walled and fiber-reinforced elements continue to expose weaknesses in smeared-damage formulations; focused studies that compare phase-field, cohesive, and discrete-crack methods against detailed imaging are needed to track localized fracture and its interaction with geometric instability. Long-term effects such as creep, shrinkage, and durability, along with dynamic loading scenarios like impact and seismic excitation, are still underrepresented in validation programs, especially for slag-rich and recycled-aggregate mixes.

Machine learning can bridge complexity and usability. Surrogate models trained on benchmark data can automate inverse analysis, suggest starting parameter sets, and flag outliers, reducing analyst effort and improving reproducibility. User-friendly software additions plug-and-play material subroutines, graphical calibration tools, and thorough documentation will further lower the expertise threshold. By combining these practical recommendations with proven damage-plasticity modeling and rigorous calibration, engineers can extend finite-element simulation confidently to the next generation of sustainable, reinforcement-free concrete structures.

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**Удосконалені моделі пластичності з урахуванням руйнування
та стратегії калібрування для точного скінченно-елементного аналізу
бетону без армування у тонкостінних конструкціях**

Точне прогнозування поведінки нетрадиційних, неармованих бетонів у тривимірному скінченно-елементному аналізі потребує синтезу розвинутої конститутивної теорії, ретельної експериментальної калібровки та уважної числової реалізації. У цій роботі узагальнено останні досягнення й окреслено актуальні виклики моделювання шлакопортландцементних, бетонів на переробленому заповнювачі, волокнистих та ультратонких опалубних бетонів у середовищі ANSYS. Огляд літератури виділяє три провідні підходи для звичайного бетону: класичний елемент SOLID65 із розмазано-тріщинною моделлю, узагальнена пластичність Друкера-Прагера з користувацьким пошкодженням і детальні мезомоделі, що розрізняють заповнювач, розчин і межові зони. Порівняльний аналіз показує, що пошкоджено-пластичні формулювання, зокрема модель Concrete Damaged Plasticity (CDP), відтворюють криві навантаження-прогину

та картини тріщиноутворення з точністю до 15 % за умови калібрування параметрів на повному наборі випробувань на стиск, розтяг, розкол і тривалу поведінку. Проте протоколи калібрування залишаються несистематизованими, що ускладнює відтвореність і порівнянність результатів. Відсутність відкритої еталонної бази даних для нетрадиційних бетонів визнано ключовою перешкодою на шляху до узгоджених початкових параметрів. Тонкостінні елементи створюють додаткові труднощі: геометрична нелінійність поєднується з прогресуючим зниженням жорсткості, спричиняючи залежне від сітки розсіяння енергії руйнування та проблеми збіжності розв'язку. Як заходи пропонуються уточнене сіткування крізь товщину, нелокальна регуляризація та стійкі алгоритми дугової довжини. Явні методи відстеження тріщин, зокрема фазово-польове руйнування та когезійні сегменти, підвищують точність, особливо для сумішей із високим вмістом волокон, де залишкова несуча здатність у розтягу визначає експлуатаційну придатність, однак їх систематична верифікація поки що обмежена. Довготривалі явища, такі як повзучість, усадка, довговічність, а також високошвидкісні навантаження при ударах чи сейсмічних впливах недостатньо представлені у сучасних програмах перевірки моделей, особливо для бетонів зі шлаком і переробленим заповнювачем. Запропоновано практичну «дорожню карту», що об'єднує п'ять ключових дій: створення публічної еталонної бази випробувань; розроблення уніфікованих протоколів моделювання з чіткими метриками похибок; цільові інвестиції в явні моделі тріщиноутворення для тонкостінних та волокнистих елементів; розширення довготривалих і динамічних експериментальних програм; упровадження машинного навчання для автоматизації підбору параметрів і виявлення аномальної поведінки моделей. Супутні програмні вдосконалення підключні підпрограми матеріалів «plug-and-play» та графічні майстри калібрування знижують поріг входу для практикуючих інженерів. Сукупно ці заходи прокладають шлях від академічних напрацювань до надійних, готових до промислового використання симуляцій, здатних підтримати проектування стійких бетонних конструкцій без арматури.

Ключові слова: Скінченно-елементний аналіз, пошкоджено-пластичне моделювання, волокнистий бетон, бетон на переробленому заповнювачі, тонкостінна опалубка, калібрування моделей.

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