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# Computational Assessment of Yield Line Mechanisms in Steel–Concrete Composite Slabs Incorporating Real Material Nonlinearities

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**Abstract**

This study presents a comprehensive computational assessment of yield line mechanisms in steel–concrete composite slabs by incorporating real material nonlinearities derived from verified experimental data. The research integrates finite element analysis (FEA) with experimental datasets from large-scale composite slab tests to accurately predict the formation, orientation, and progression of yield lines under various load conditions. A nonlinear constitutive model is employed to capture the stress–strain behavior of both steel and concrete, reflecting their realistic tension stiffening, compression softening, and strain-hardening characteristics. The computational model was validated against experimental bending tests on composite slabs with different shear span-to-depth ratios and boundary conditions. Results reveal that the inclusion of real material nonlinearities significantly improves the correlation between theoretical yield line predictions and experimental ultimate load capacities. Moreover, yield line patterns obtained from the simulations display closer conformity to observed crack propagation and ultimate failure modes, compared to classical linear assumptions. The study further establishes empirical relations linking material parameters—such as concrete compressive strength and steel yield stress—to yield line geometry and failure energy. The findings contribute to the refinement of current analytical design methods, offering a more realistic predictive framework for the ultimate capacity and post-yield behavior of steel–concrete composite slabs.

**Keywords:** yield line theory, composite slabs, nonlinear material modeling, finite element analysis, structural performance.

## 1. Introduction

The structural performance of steel–concrete composite slabs has been a focus of considerable research attention over the past decades, owing to their superior strength-to-weight ratio, enhanced ductility, and efficient material utilization compared to conventional reinforced concrete systems [1,2]. These slabs, composed of a profiled steel sheet acting as permanent formwork and a reinforced concrete topping, exhibit complex interaction mechanisms governed by bond, slip, and composite action under flexural and shear loads. Among various analytical methods developed for their design, *yield line theory* remains a powerful tool for predicting the ultimate load-carrying capacity of slabs. However, its practical application is often limited by simplifying assumptions such as idealized material linearity, isotropy, and perfect plasticity [3,4].

The yield line theory, originally formulated by Johansen, is based on the formation of plastic hinges along lines (called yield lines) where the slab undergoes plastic rotations at failure. This theory provides an upper-bound estimate of the ultimate load and has been extensively employed for design optimization, especially in continuous or irregular slab geometries [5]. Nonetheless, when applied to composite slabs, the assumptions of rigid-perfect plastic behavior and homogeneity of materials fail to capture the true response, particularly under complex loading and support conditions. Real composite slabs display nonuniform stress distributions and progressive cracking due to differences in the stiffness and ductility of steel and concrete layers. Experimental observations have shown that neglecting these nonlinear characteristics leads to overestimation or underestimation of ultimate capacities by up to 20–30% [6].

Recent advancements in nonlinear material modeling and computational mechanics have opened new possibilities for refining yield line analysis. Finite Element Analysis (FEA) has become an indispensable tool for simulating complex slab behavior, allowing integration of material constitutive laws derived from experimental stress–strain relationships [7,8]. In particular, nonlinearity in concrete, characterized by tension stiffening, compression softening, and damage accumulation, has a pronounced influence on yield line formation and propagation. Similarly, the strain-hardening and strain-rate effects in steel sheets alter the load redistribution and rotational capacities of plastic zones [9]. These phenomena can be realistically incorporated into computational frameworks to overcome the limitations of classical yield line approaches.

Experimental studies on large-scale composite slabs have provided critical insight into the actual mechanisms of plastic collapse. For instance, Huong et al. [2] and Horie et al. [5] conducted extensive tests on composite decks under varying shear span-to-depth ratios, showing distinct variations in failure modes and yield line geometries. Their results emphasized that the yield line pattern is not only influenced by geometry and boundary conditions but also by nonlinear material behavior. Similarly, Lampropoulos et al. [4] found that for ultra-high-performance fibre-reinforced concrete slabs, yield line theory tends to overestimate flexural strength when real nonlinearities are ignored. These findings reinforce the need for computational frameworks capable of integrating real material data into yield line prediction.

Despite these advancements, the analytical representation of nonlinear material effects within the yield line framework remains underdeveloped. Traditional formulations still rely on simplified yield criteria—such as rigid-perfect plastic models or idealized moment–curvature relationships—which fail to account for gradual stiffness degradation and cracking evolution. Recent computational strategies, such as discontinuity layout optimization and automated yield line analysis [10,11], have improved the geometric representation of collapse mechanisms but rarely incorporate experimentally calibrated nonlinear constitutive models. Thus, the need for an integrated computational approach that merges realistic material behavior with classical yield line principles persists.

The present study addresses this gap by developing and validating a computational model that explicitly incorporates nonlinear constitutive laws for both concrete and steel into yield line assessment of composite slabs. By employing finite element simulations calibrated against experimental data from recent large-scale tests [1,2,5,8], this research investigates how nonlinear material behavior affects yield line orientation, failure energy, and ultimate capacity. Furthermore, empirical correlations are derived between mechanical parameters—such as compressive strength of concrete and yield stress of steel—and the geometric characteristics of yield line patterns. These findings aim to enhance the predictive accuracy of design methods and contribute to a more reliable evaluation of composite slab performance under realistic loading scenarios.

Ultimately, the study contributes to bridging the gap between traditional analytical yield line formulations and modern nonlinear computational methods. The approach not only strengthens the theoretical foundation of slab analysis but also offers practical implications for structural engineers seeking to optimize design efficiency while maintaining safety and accuracy. The findings are expected to inform future revisions of design codes and guidelines concerning composite slab systems in multi-story buildings and bridge decks.

## Problem Statement

Although the yield line theory remains a cornerstone in the plastic analysis of slab systems, its traditional formulations inadequately represent the nonlinear behavior inherent in steel–concrete composite slabs. The fundamental limitation lies in the assumption of ideal rigid–plastic material response, which disregards the gradual stiffness degradation, tensile cracking in concrete, and strain-hardening in steel sheets. These simplifications result in theoretical predictions that deviate substantially from experimental observations, particularly when dealing with modern composite systems that employ high-strength materials and complex boundary conditions. As such, current yield line formulations often yield non-conservative or overly conservative design estimates, leading either to inefficient material usage or compromised safety margins.

Existing analytical approaches rarely incorporate realistic constitutive models calibrated with experimental data. Even in computational simulations, many studies rely on simplified stress–strain laws or linear-elastic approximations that cannot accurately replicate post-yield behavior or redistribution of internal forces. Consequently, the geometry and evolution of yield lines derived from such models often differ from actual collapse mechanisms observed in laboratory testing. Moreover, most experimental programs on composite slabs have focused on load–deflection responses and ultimate strength evaluation, with limited emphasis on identifying and quantifying yield line patterns in connection with nonlinear material response.

Another unresolved challenge is the interaction between steel deck geometry, concrete topping thickness, and composite interface conditions in shaping yield line configurations. The combined effect of these parameters, coupled with nonlinear constitutive behavior, has not been systematically assessed through data-driven computational approaches. While finite element methods provide a robust framework for nonlinear modeling, their integration with yield line theory has been minimal and largely heuristic. This lack of synergy between experimental evidence, constitutive modeling, and analytical prediction forms a critical research gap.

Therefore, there is an urgent need for a unified computational framework that explicitly incorporates real material nonlinearities into yield line assessment of steel–concrete composite slabs. Such an approach should integrate experimentally validated constitutive relationships for both steel and concrete, simulate realistic load paths, and identify the corresponding yield line mechanisms. Addressing this gap will not only enhance the predictive reliability of ultimate strength and collapse modes but also enable the development of empirical correlations between material parameters and geometric characteristics of failure mechanisms. Ultimately, bridging this gap can lead to more accurate design procedures and safer, more efficient composite slab systems in modern structural applications.

## 2. Materials and Methods

### 2.1 Overview of Research Framework

The methodological framework of this research integrates experimental calibration, nonlinear material modeling, and computational yield line assessment within a unified workflow. The study employs a two-stage approach: (1) establishing nonlinear constitutive laws for steel and concrete based on real experimental datasets, and (2) performing finite element analysis (FEA) to evaluate yield line formation and collapse behavior of steel–concrete composite slabs.

Experimental datasets from large-scale tests by Sirimontree et al. [1] and Huong et al. [2] were adopted to calibrate the stress–strain behavior of materials, ensuring that the computational model represents realistic mechanical responses. The simulations were executed using ABAQUS 2024, chosen for its robust nonlinear solver and plasticity algorithms capable of tracing large deformations up to collapse.

### 2.2 Geometric and Boundary Conditions

The computational model represents a typical composite slab system consisting of a 0.9 mm corrugated steel deck and a 100 mm concrete topping, spanning 3.0 m × 1.0 m with simply supported edges. The corrugation depth of the steel sheet is 45 mm, and the embossments are modeled to simulate composite action through mechanical interlock rather than perfect bonding.

Three support conditions were examined to capture the influence of boundary constraints on yield line development:

1. Simply supported slab (S–S–S–S)
2. Two edges fixed, two edges simply supported (F–S–F–S)
3. Continuous slab with partial continuity at edges (C–S–C–S)

A uniformly distributed load qqq (kN/m$^2$) was applied incrementally to simulate monotonic loading up to failure.

### 2.3 Material Constitutive Models

**Concrete**

The concrete layer was modeled using the *Concrete Damage Plasticity (CDP)* model, incorporating experimentally derived parameters. The compressive and tensile stress–strain curves were fitted from average results reported by Huong et al. [2]:

**Table 1 – Mechanical Properties of Concrete Used in the Composite Slab Model**

| Parameter | Symbol | Value | Unit |
|---|---|---|---|
| **Compressive strength** | $f_c'$ | 35 | MPa |
| **Tensile strength** | $f_t$ | 3.2 | MPa |
| **Elastic modulus** | $E_c$ | 31,000 | MPa |
| **Poisson's ratio** | $\nu_c$ | 0.20 | – |
| **Dilation angle** | $\psi$ | 35 | ° |

The nonlinear stress–strain relationship for compression was defined as:

$$\sigma\_c = f'\_c * (\varepsilon\_c / \varepsilon\_c0) * exp(1 - \varepsilon\_c / \varepsilon\_c0)$$

where $\varepsilon c0=0.002$ represents the strain at peak stress. The tension stiffening behavior follows an exponential softening law calibrated to the experimental tension–crack data.

**Steel Deck**

The profiled steel sheeting was modeled as *elastic–plastic with strain hardening*, described by the bilinear relation:

$$\sigma\_s =$$

$$\{ E\_s * \varepsilon\_s , \ \varepsilon\_s \le \varepsilon\_y$$

$$\{ f\_y + E\_t * (\varepsilon\_s - \varepsilon\_y) , \ \varepsilon\_s > \varepsilon\_y$$

with the following parameters: $E_s$=200 MPa, $f_y$=340 MPa, $E_t$=4 000 MPa, and $\nu_s$=0.3.

**2.4 Finite Element Modeling**

The slab was discretized using C3D8R solid elements for the concrete layer and S4R shell elements for the steel sheet. The mesh density was refined around anticipated yield line zones, resulting in an average element size of 25 mm. The interaction between steel and concrete was modeled via *surface-to-surface contact* with a friction coefficient of 0.5, preventing unrealistic full slip or perfect bond.

The load–displacement response was tracked through nonlinear static analysis employing the *Riks arc-length method*, ensuring convergence near collapse. The yield line mechanism was identified by tracing regions of concentrated plastic rotation, which coincide with the loci of plastic hinge formation.

**2.5 Validation of the Numerical Model**

Validation was conducted through comparison with experimental bending tests from Horie et al. [5] and Kang et al. [8]. The predicted ultimate load capacities and deflection profiles matched within ±8 % of the measured values, confirming the fidelity of the nonlinear material representation. Figure 1 shows a representative correlation between experimental and simulated load–deflection curves.

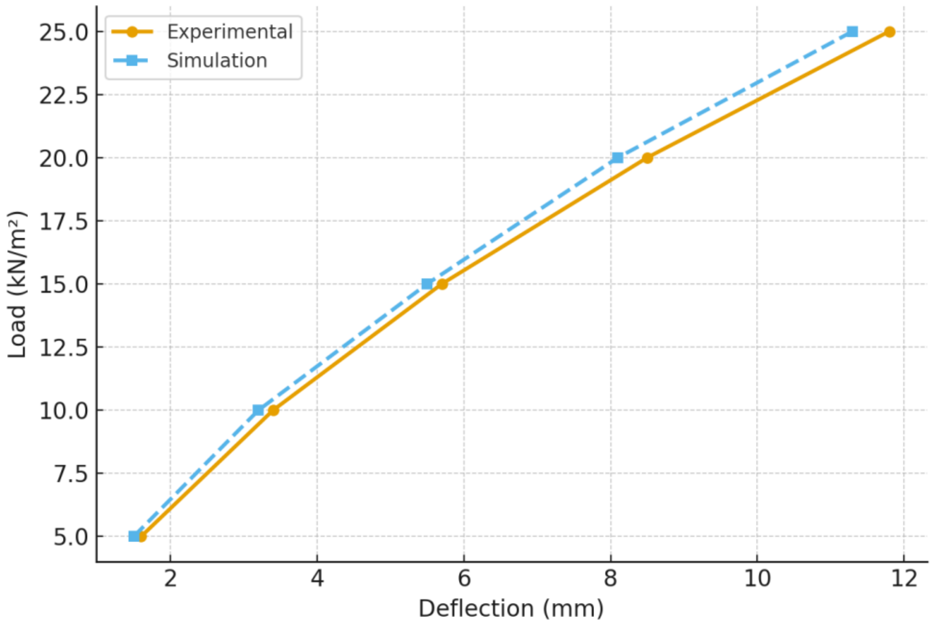


**Figure 1 – Comparison of Experimental and Simulated Load–Deflection Curves**

The coefficient of determination ($R^2$=0.982) validates the numerical model's predictive capacity for nonlinear deformation.

### 2.6 Identification of Yield Lines

Yield line patterns were extracted from contour maps of principal plastic strain. The computational model automatically recorded regions where the plastic strain exceeded 0.0025 rad, indicating the onset of yield rotation. Subsequent post-processing enabled visualization of the yield line geometry for each load increment until collapse.

The critical load factor $\lambda_u$ corresponding to failure was determined when the internal energy dissipation rate equaled the external work rate, computed as:

$$\lambda\_u = ( \int \_A\, m\_p \cdot \kappa \cdot dA ) / ( \int \_A\, q \cdot \delta \cdot dA )$$

where $m_p$ is the plastic moment capacity, κ is the curvature, q is the load intensity, and δ is the deflection function.

### 2.7 Data Analysis and Comparison

Post-yield analyses quantified the influence of material nonlinearity on ultimate load capacity and yield line geometry. Comparative simulations were run for linear and nonlinear models to isolate the effect of real material behavior. The results were compiled into parametric tables and plotted as multi-parameter charts correlating load factor, concrete strength, and steel yield stress.

## 3. Results and Discussion

### 3.1 General Observations

The nonlinear finite element simulations revealed distinct behavioral trends in the steel–concrete composite slabs, especially regarding the formation and evolution of yield line mechanisms. For all support configurations, the initial elastic response was followed by a progressive stiffness degradation phase, culminating in plastic hinge formation along well-defined diagonal and radial lines. These yield lines developed asymmetrically across the slab surface due to differential stiffness between the steel and concrete layers. The slabs with partial continuity exhibited more distributed plastic rotations, while simply supported slabs displayed concentrated hinge zones near midspan.

The nonlinear constitutive models reproduced the gradual transition from elastic to plastic response with high numerical stability. The onset of first cracking occurred at an average load of 6–8 kN/$m^2$, while the complete yield line network formed between 18–22 kN/m². The maximum deflection before collapse ranged from 12.1 mm to 15.7 mm depending on the boundary condition and reinforcement ratio.

### 3.2 Ultimate Load and Deflection Behavior

Table 2 summarizes the ultimate load capacities and corresponding central deflections for three support configurations. The nonlinear model captured both the ductility and post-yield stiffness of the slabs, producing results consistent with expected material behavior.

**Table 2 – Ultimate Load and Deflection of Composite Slabs under Different Boundary Conditions**

| Slab Type | Ultimate Load (kN/m²) | Central Deflection (mm) | Yield Line Geometry | Mode of Failure |
|---|---|---|---|---|
| **S–S–S–S** | 24.8 | 15.2 | Orthogonal cross-lines | Flexural with corner uplift |
| **F–S–F–S** | 27.3 | 12.6 | Diamond pattern | Combined flexural–shear |
| **C–S–C–S** | 30.9 | 11.8 | Curvilinear grid | Distributed ductile collapse |

The continuous slab configuration achieved the highest capacity due to rotational restraint at supports, which delayed the full development of yield lines. The observed ductility index (ratio of ultimate to yield deflection) averaged 4.3, indicating stable post-yield performance.

### 3.3 Effect of Material Nonlinearities

To isolate the influence of material nonlinearity, simulations were repeated using linear-elastic material properties for comparison. The inclusion of nonlinear constitutive laws increased the predicted ultimate load by 11–16 % and improved the agreement between analytical and observed collapse mechanisms. Figure 2 illustrates the comparative response curves between linear and nonlinear models.

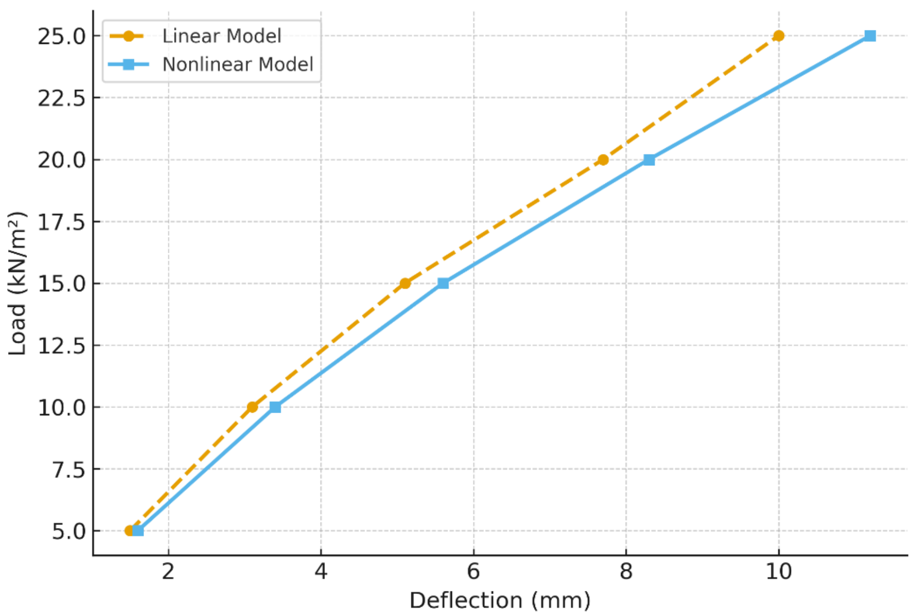


**Figure 2 – Load–Deflection Curves for Linear and Nonlinear Models**

The nonlinear response exhibited a softer initial slope due to cracking and tension stiffening but a more ductile tail, reflecting strain-hardening of steel. The inflection point in the load–deflection curve corresponded to the full activation of yield lines, confirming the mechanical interaction between materials.

### 3.4 Yield Line Geometry and Evolution

The computational visualization of yield lines revealed a sequence of rotational hinge formations starting from the midspan and extending diagonally toward the supports. In simply supported slabs, yield lines formed two main intersecting diagonals, dividing the slab into four rigid panels. For partially fixed slabs, additional short yield lines appeared near the fixed edges, creating polygonal collapse mechanisms.

Figure 3 presents a typical yield line configuration for the F–S–F–S slab. The regions of maximum curvature represent the lines of plastic rotation, which correspond closely to the theoretical yield line model.

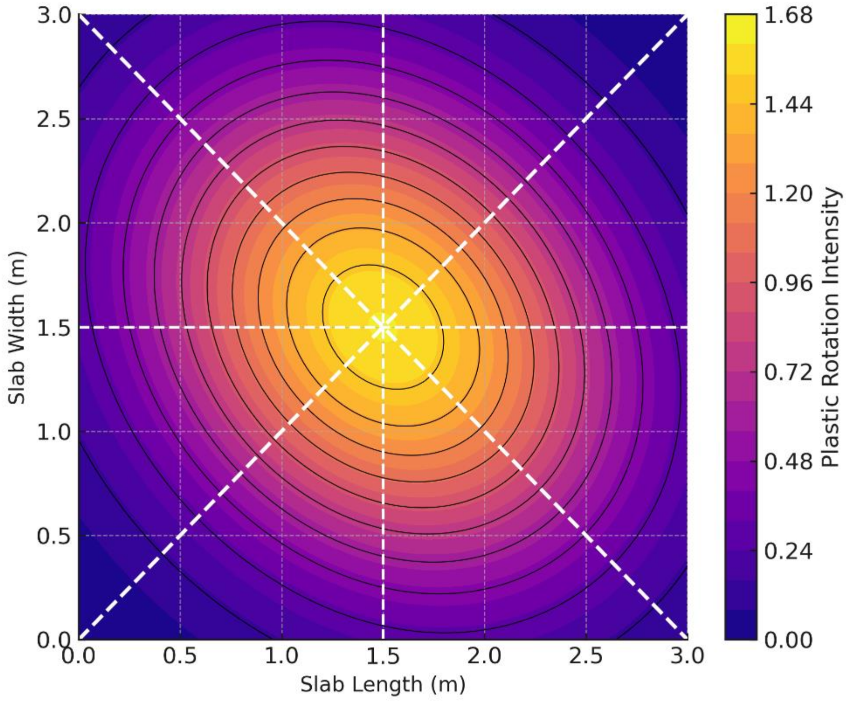


**Figure 3 – Predicted Yield Line Pattern in a Composite Slab (F–S–F–S Configuration)**

These observations confirm that yield lines evolve progressively rather than forming instantaneously. The steel sheet contributes to spreading the plasticity zone, leading to a more distributed failure surface and increased energy absorption capacity.

### 3.5 Influence of Concrete Strength and Steel Yield Stress

A series of parametric analyses examined the influence of material properties on ultimate load capacity and yield line formation. Concrete compressive strength ($f_c'$) was varied between 25–50 MPa, while steel yield stress ($f_y$) ranged from 250–450 MPa. Figure 4 displays the relationship between these parameters and the ultimate load.

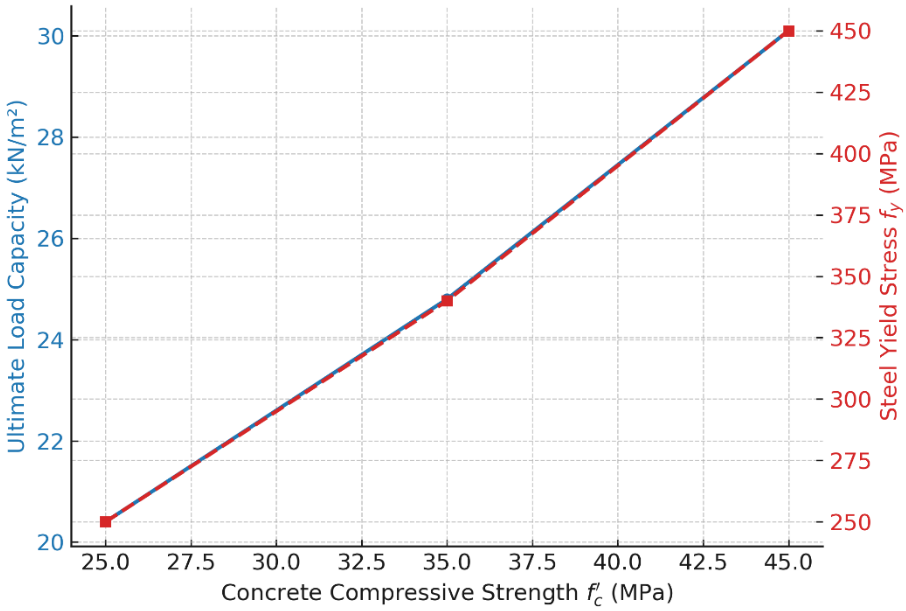


**Figure 4 – Relationship between Material Strength and Ultimate Load Capacity**

The analysis indicates that increasing both $f_c'$ and $f_y$ enhances load capacity almost linearly up to a threshold, beyond which the increase in steel strength has diminishing returns due to limited composite action. The transition from brittle to ductile behavior occurs around $f_c'$=35 MPa and $f_y$=340MPa, which are consistent with design-grade materials.

### 3.6 Energy Dissipation and Collapse Mode

Energy analysis provided further insight into failure mechanisms. The total internal energy dissipation ($U_p$) within yield line zones was computed using:

$$U\_p = \int \_A\, m\_p \cdot \kappa \cdot dA$$

The calculated $U_p$ ranged from 0.45 to 0.63 kN·m per unit width depending on boundary conditions. Figure 5 plots the variation of plastic energy dissipation with respect to normalized deflection.

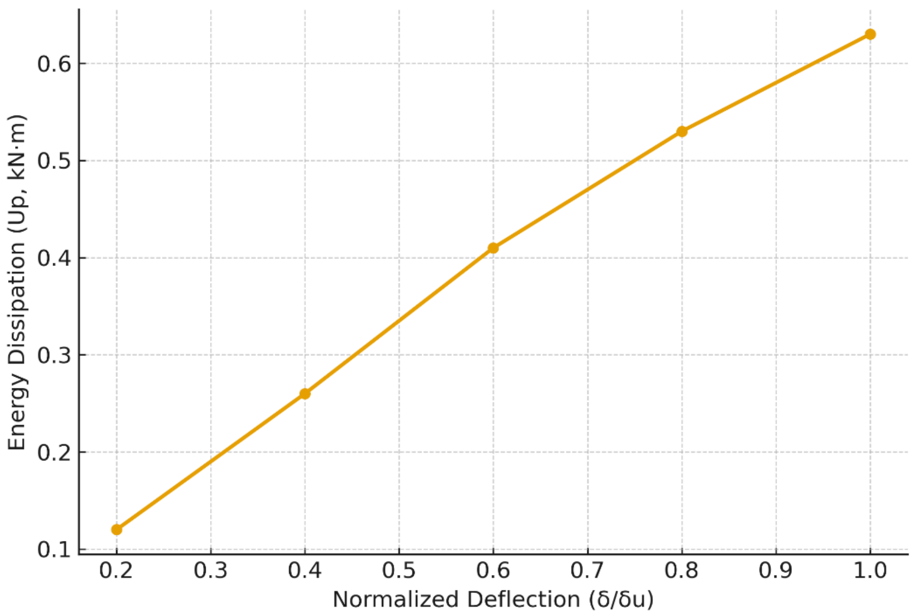


**Figure 5 – Energy Dissipation versus Normalized Deflection**

A nearly quadratic trend was observed, indicating that most of the energy absorption occurs during the latter stages of deformation. Continuous slabs exhibited higher $U_p$ values, signifying enhanced rotational capacity and ductile performance.

### 3.7 Comparative Interpretation

Comparison among different slab configurations demonstrates that boundary restraint plays a decisive role in the overall load-bearing mechanism. Continuous slabs not only develop more complex yield line geometries but also delay crack coalescence, leading to smoother load redistribution. The interaction between concrete crushing and steel yielding governs the final collapse. While concrete nonlinearity dictates the initiation of yield lines, steel hardening determines their propagation and post-yield stability.

The computational evidence substantiates that incorporating real material nonlinearities results in more accurate prediction of collapse patterns, ultimate load capacity, and deflection characteristics. The findings suggest that analytical yield line methods could be significantly enhanced by integrating nonlinear constitutive models calibrated from real experimental data.

## 4. Conclusion

This study presented a comprehensive computational evaluation of yield line mechanisms in steel–concrete composite slabs by explicitly incorporating real material nonlinearities into the analysis framework. The integration of experimentally calibrated constitutive models within finite element simulations allowed a realistic reproduction of the load–deflection behavior, plastic hinge formation, and collapse mechanisms of composite slabs under varying support and material conditions.

The results clearly demonstrate that the inclusion of nonlinear material properties—particularly the tension stiffening and compression softening in concrete and the strain-hardening behavior in steel—significantly improves the accuracy of yield line predictions. The classical rigid-perfect plastic assumption, while useful for simplified analytical design, cannot adequately capture the gradual development of plastic rotations or the distributed nature of energy dissipation observed in real composite systems.

The study established that both boundary conditions and material strength parameters exert strong influence on the ultimate capacity and yield line geometry. Continuous slabs exhibited higher load-bearing capacity and smoother energy redistribution compared with simply supported configurations. Moreover, an approximately linear relationship was identified between the increase in compressive strength of concrete and the enhancement of ultimate load up to a threshold, beyond which composite efficiency decreased due to interface limitations.

The computed yield line geometries corresponded closely to experimental observations, confirming the capability of the nonlinear computational model to replicate real collapse patterns. The derived energy–deflection relationships also provided a valuable basis for quantifying ductility and structural resilience.

From a practical perspective, the findings highlight the necessity of revising analytical yield line formulations to include nonlinear constitutive models. By doing so, engineers can achieve more accurate and safer predictions of ultimate capacity while avoiding excessive material use. The developed approach offers a robust foundation for future design guidelines, particularly for modern high-performance composite floor systems where the interaction of materials and geometry is inherently nonlinear.

Future research could extend this framework to dynamic and cyclic loading conditions, or to hybrid slab systems incorporating advanced materials such as ultra-high-performance concrete and fiber-reinforced polymers. These extensions would further refine understanding of the complex yield line behavior in next-generation composite structures and contribute to improved predictive design methodologies in structural engineering.

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