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Effect of Confinement on Curvature Ductility of Reinforced Concrete Beams

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ABSTRACT

This study explores the enhancement of curvature ductility in reinforced concrete (RC) beams through transverse confinement. Both analytical modeling and experimental testing were conducted to evaluate the performance of RC beams under varying confinement levels provided by stirrups. Analytical modeling employed the OPENSEES platform using stress-strain relations defined by Hong K N and Han S H (2005) and Saatcioglu and Razvi (1992). Six beams with different stirrup configurations were analyzed and cast. Experimental observations showed that reduced stirrup spacing and increased number of stirrup legs significantly improved the curvature ductility of beams. Among the two models, the Saatcioglu and Razvi model yielded results more consistent with experimental findings.

INTRODUCTION

Modern seismic codes emphasize ductility design over strength-based design alone. Ductile members ensure a structure can undergo significant deformations without catastrophic failure. This necessitates the incorporation of confinement reinforcement, especially in regions of potential plastic hinge formation. Failure to detail sufficient confinement has been cited as a major cause of structural collapses during past earthquakes, notably in structures built prior to the adoption of modern ductility design guidelines. Therefore, the focus of this research is to quantify the influence of lateral confinement in enhancing curvature ductility and to evaluate models that can effectively predict this behavior.

Reinforced concrete structures in seismic zones must be designed not just for strength, but also for ductility — the capacity to deform without significant strength loss. Ductility ensures that a structure can absorb and dissipate energy during seismic events. The role of confinement, provided by transverse reinforcement (stirrups), becomes crucial in enhancing ductility, particularly in plastic hinge regions.

However, existing design codes often address strength and ductility separately, resulting in inadequately detailed reinforcement for post-yield behavior. This research addresses this gap by analytically and experimentally investigating how varying stirrup spacing and configuration influence the curvature ductility of RC beams. A total of six beams were tested and modeled to establish the effects of lateral confinement.

LITERATURE REVIEW

In their seminal work, Saatcioglu and Razvi emphasized the role of transverse reinforcement not only in enhancing strength but in stabilizing the core concrete during inelastic excursions. Their model has been widely adopted due to its simplicity and accuracy. Conversely, Hong and Han introduced a confinement model that separately addresses the ascending and descending branches, thereby capturing the post-peak behavior in greater detail. These models serve as the foundation for the analytical component of this study. Moreover, recent studies have introduced machine learning methods to predict confinement effects, but they lack interpretability, making mechanistic models still valuable.

Numerous studies have explored the effects of confinement on concrete behavior. Mander et al. (1988) proposed stress-strain models for confined concrete that showed improvements in both strength and ductility. Saatcioglu and Razvi (1992) extended these models by incorporating reinforcement ratios and stirrup configurations into confinement effectiveness.

Hong and Han (2005) provided separate expressions for the ascending and descending branches of stress-strain behavior, accounting for lateral reinforcement parameters such as yield strength, spacing, and diameter. Their model showed the effectiveness of tighter stirrup spacing and multi-leg stirrups.

Despite these advancements, there is still limited data on the curvature ductility of confined beams — particularly post-peak deformation capacity — which is critical under seismic loads. This study adds to that knowledge base by comparing analytical models with experimental data.

Analytical Modeling

The OpenSees framework provides flexibility for defining non-linear material behavior and section discretization. Fiber-section modeling in particular allows for accurate moment-curvature response by integrating over individual fibers with distinct material properties. Confinement models were incorporated by assigning different stress-strain relations to confined and unconfined regions of the section. Moment-curvature analysis was performed under a gradually increasing curvature-controlled loading until failure, with curvature ductility calculated at the ultimate limit state.

The analytical modeling was carried out using OPENSEES software. The modeling utilized fiber-section analysis based on the confined concrete stress-strain relationships defined by Hong & Han (2005) and Saatcioglu & Razvi (1992). The parameters required include compressive strength (f'c), strain at peak stress (εcc), crushing strain, and ultimate strain (εcu).

Six RC beams (230 mm × 300 mm) were modeled with varying stirrup configurations:
- 2-legged stirrups at 250 mm, 150 mm, and 100 mm spacing
- 3-legged stirrups at 250 mm, 150 mm, and 100 mm spacing

The curvature ductility was computed using:

$$\mu\phi = \phi u / \phi y$$

where ϕu is curvature at ultimate strain and ϕy is curvature at yield of reinforcement.

Experimental Investigation

The beams were cast in steel molds and cured for 28 days under moist conditions to ensure consistent hydration. Prior to testing, each specimen was white-washed to aid crack visibility. Load was applied at the mid-span using a hydraulic jack, and load increments were controlled manually. Three dial gauges were placed to record mid-span deflection and rotation. Mechanical strain gauges recorded strain at tension and compression faces. This allowed direct calculation of curvature at each load step. Observations included first crack, yielding, and ultimate failure modes. Data was recorded until complete crushing or rupture of steel.

Concrete of grade M20 was used, with mix proportion 1:1.7:3.8 and water-cement ratio of 0.6. All beams used Fe415 grade steel. Each beam was reinforced with two 12 mm bars on the tension side and two 10 mm bars on the compression side. Stirrups of 8 mm diameter were used with 2-leg and 3-leg configurations.

Each beam was tested under single-point loading until failure. Strain measurements were recorded at both compression and tension zones using a mechanical strain gauge. The curvature at each loading increment was calculated as the slope of the strain profile across the depth of the beam.

Cracks were monitored visually and failure patterns were documented. Beams with denser stirrup spacing showed delayed crack propagation and higher curvature values before failure.

RESULTS AND DISCUSSION

The experimental results confirmed that beams with closer stirrup spacing exhibited higher curvature ductility, confirming theoretical expectations. For instance, the curvature ductility increased nearly five-fold when stirrup spacing was reduced from 250 mm to 100 mm.

While the Hong and Han model overestimated ductility values, it captured the general trend. The Saatcioglu and Razvi model provided better alignment with actual results. Furthermore, load-deflection behavior also improved with increased confinement, indicating enhanced energy absorption capacity. Cracking patterns showed more distributed cracks in tightly confined beams. Analytical results showed an increase in curvature ductility with decreased stirrup spacing and increased number of stirrup legs. Hong and Han model consistently predicted higher ductility values, while the Saatcioglu and Razvi model showed better agreement with experimental values.

Sample Values:

- 2-legged @ 250 mm: 33.69 (H&H), 32.27 (S&R)
- 2-legged @ 100 mm: 144.82 (H&H), 50.00 (S&R)
- 3-legged @ 100 mm: 166.67 (H&H), 61.12 (S&R)

Experimental findings confirmed the trends. The maximum curvature ductility was observed for beams with 3-legged stirrups at 100 mm spacing. Moment-curvature plots showed a more ductile post-yield behavior for confined specimens.

Saatcioglu and Razvi model proved more reliable in predicting actual field behavior, though Hong & Han model showed potential for theoretical analysis.

CONCLUSIONS AND FUTURE SCOPE

Future studies can consider the impact of concrete grades beyond M20, as high-strength concrete tends to be more brittle. Additionally, dynamic and cyclic loading tests will be valuable in replicating real earthquake conditions. The effect of stirrup shape (rectangular vs circular) and high-strength stirrup steel can also be explored. Computational models using AI and hybrid analytical-numerical methods may offer enhanced predictive power, especially in complex geometries or boundary conditions.

- Curvature ductility increases with decreasing stirrup spacing.
- Adding more legs to stirrups improves confinement, but the effect is less pronounced than spacing.
- Saatcioglu and Razvi model better matches real-world data.
- Hong and Han model predicts higher ductility but overestimates for practical use.
- Future studies can focus on using higher grades of concrete and performance under cyclic loading.

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