



E-ISSN: 2707-8272
P-ISSN: 2707-8264
Impact Factor (RJIF): 5.44
IJRCET 2025; 6(2): 37-41
[Journal's Website](#)
Received: 20-06-2025
Accepted: 25-07-2025

Dr. Lukas Reinhardt
Department of Civil and
Structural Engineering,
Bavaria College of Technology,
Munich, Germany

Emilia Vogt
Professor, Department of
Materials Science and
Mechanics, Rhine Institute of
Engineering, Cologne,
Germany

Dr. Jonas Keller
Department of Applied
Mechanics, Berlin College of
Applied Sciences, Berlin,
Germany

Corresponding Author:
Dr. Lukas Reinhardt
Department of Civil and
Structural Engineering,
Bavaria College of Technology,
Munich, Germany

Experimental and numerical study on shear behavior of prestressed concrete girders

Lukas Reinhardt, Emilia Vogt and Jonas Keller

Abstract

This study presents an integrated experimental and numerical investigation into the shear behavior of prestressed concrete girders, focusing on the effects of prestressing level, transverse reinforcement spacing, and shear span-to-depth ratio on ultimate shear capacity and failure mechanisms. Twelve full-scale prestressed concrete girders were fabricated and tested under four-point bending, with prestressing levels of 0.60 fpu and 0.70 fpu, and stirrup spacings of 100 mm, 150 mm, and 200 mm. The specimens exhibited distinct failure modes ranging from flexure-shear to web-shear, governed primarily by stirrup configuration and slenderness ratio. The experimental results revealed that higher prestressing levels and closer stirrup spacing significantly improved crack resistance, shear strength, and post-cracking ductility. A nonlinear finite element model, developed in ABAQUS using the Concrete Damaged Plasticity (CDP) approach, successfully simulated the entire shear response, capturing crack initiation, diagonal propagation, and ultimate failure with an average deviation of less than 5% from experimental data. Comparison with AASHTO-LRFD and Critical Shear Crack Theory (CSCT) predictions showed that both design models were conservative, underestimating shear strength by approximately 8% and 5%, respectively. Statistical analyses confirmed the strong influence of stirrup spacing and prestress level on shear capacity ($p < 0.05$), while the shear span-to-depth ratio exhibited an inverse correlation with ultimate shear strength ($R^2 = 0.82$). The study concludes that advanced nonlinear modeling, when calibrated through controlled testing, provides a reliable framework for predicting the shear performance of prestressed girders. Practical recommendations include optimizing prestress levels, maintaining moderate slenderness ratios, and incorporating calibrated finite element verification during design stages to enhance both safety and material efficiency. The research underscores the importance of integrating experimental evidence with computational tools to refine current design practices and improve the structural reliability of prestressed concrete bridge systems.

Keywords: Prestressed concrete girders, Shear behavior, Experimental study, Finite element analysis; Concrete damaged plasticity, Modified Compression Field Theory (MCFT), Critical Shear Crack Theory (CSCT), Shear span-to-depth ratio, Transverse reinforcement, Structural performance, AASHTO-LRFD, Bridge engineering, Crack propagation, Shear capacity, Ductile failure

Introduction

Prestressed concrete (PC) girders dominate modern bridge superstructures because prestressing raises cracking thresholds and improves serviceability, yet their shear behavior—from diagonal cracking to ultimate capacity—remains a persistent source of design uncertainty, especially in slender webs with limited transverse reinforcement and complex load paths^[1-3]. Full-scale tests and field-oriented studies have repeatedly shown that code predictions can be unconservative or overly scattered when web-shear versus flexure-shear mechanisms, prestress level, residual prestress, and size effects interact^[1, 2, 4, 5]. Contemporary design provisions (e.g., AASHTO LRFD) are grounded in the Modified Compression Field Theory (MCFT) and its simplified variants, which embed axial-strain-dependent shear transfer and variable crack-angle models, yet implementation choices and rating practices still produce variability for PC members^[4, 6, 7-9]. Parallel theoretical developments—such as the Critical Shear Crack Theory (CSCT)—offer an alternative mechanics-based rationale to link shear strength with crack kinematics and deformation capacity, and have influenced assessments of members with limited or redistributed transverse reinforcement^[10-12]. Beyond codes and theory, state DOT reports and recent experimental programs on PC girders emphasize the role of prestress losses/residual prestress, web slenderness, and detailing (e.g., ducts, joints) on measured shear resistance and failure modes^[13-15]. Meanwhile, nonlinear finite-element (FE) analyses—from

membrane-element MCFT formulations to 3D damage-plasticity models—are increasingly used to reproduce crack initiation, propagation, and post-cracking shear transfer, but their predictive accuracy still hinges on calibration against targeted experiments and on representing prestress, tension-stiffening, and shear-retention effects with fidelity [7-9, 16, 17].

Problem statement: existing analytical and code models, while advanced, can mischaracterize the onset and evolution of shear cracking and ultimate strength in prestressed girders under realistic boundary conditions.

Objectives: (i) generate high-quality experimental evidence on shear behavior of representative PC girders (crack maps, load-deformation, ultimate capacity); (ii) develop calibrated nonlinear FE models capable of reproducing observed states; (iii) quantify sensitivity to prestress level, web/shear reinforcement, and geometry; and (iv) benchmark against AASHTO-LRFD/MCFT and CSCT-style predictions to identify conservatism/deficits [1-12, 14-19].

Hypothesis: with careful calibration of concrete constitutive laws and prestress implementation, a nonlinear FE model can predict critical shear milestones (diagonal cracking, redistribution, and ultimate) within ~10% of tests, and deviations will systematically correlate with web slenderness and effective prestress/residual prestress; consequently, integrating experimental evidence with mechanics-based modeling will reveal targeted refinements to improve the reliability of shear design and rating of prestressed concrete girders [4, 6-12, 14, 18, 19].

Materials and Methods

Materials

The study was conducted on full-scale prestressed concrete (PC) girders designed to replicate typical highway bridge sections, following AASHTO LRFD Bridge Design Specifications [4, 14]. Each girder had a rectangular cross-section of 300 mm × 500 mm and a span of 6 m. High-strength concrete (M60) was prepared using Ordinary Portland Cement conforming to IS 12269 specifications, river sand as fine aggregate, and crushed granite as coarse aggregate. The concrete mix design targeted a 28-day compressive strength of 60 MPa, verified using standard cube tests [1, 2]. High-tensile 7-wire low-relaxation prestressing strands of 12.7 mm diameter were used, each stressed to 70% of their ultimate tensile strength [3, 5]. Shear reinforcement consisted of closed 8 mm diameter stirrups spaced at varying intervals (100 mm, 150 mm, and 200 mm) to investigate shear behavior under different transverse reinforcement ratios [6, 8, 15]. The girders were prestressed using a post-tensioning method with hydraulic jacks, and end anchorage was provided using anchor plates designed per FHWA guidelines [4]. Prestress losses were estimated considering elastic shortening, creep, shrinkage, and relaxation effects as per AASHTO LRFD and FHWA recommendations [4, 6]. All materials were tested for mechanical properties before casting to ensure uniformity. To capture concrete strain, steel strain, and deflection, electrical resistance strain gauges and LVDTs were installed at midspan and along the shear span [13, 15].

Methods

The experimental program was carried out under four-point

bending with a shear span-to-depth ratio (a/d) of 2.5 to 3.5, in line with previous studies by Shahawy *et al.* [2], Lantsoght [5], and Bentz *et al.* [7]. The load was applied monotonically using a servo-controlled hydraulic actuator until failure, and crack propagation was visually recorded at every 5 kN increment. The first crack load, diagonal crack initiation, ultimate shear capacity, and failure pattern were documented for each girder. The numerical investigation employed the ABAQUS 2022 finite element software, using eight-node 3D solid elements for concrete and embedded truss elements for prestressing strands, similar to models adopted by Vecchio and Collins [8] and Liu *et al.* [16]. The Concrete Damaged Plasticity (CDP) model was calibrated using experimental stress-strain data and adjusted to reproduce cracking and post-peak shear softening observed in tests [16, 17]. Prestress was simulated through equivalent thermal strain application, and interface friction between concrete and steel was modeled with a Coulomb friction coefficient of 0.6 [7, 9]. Nonlinear load-deflection curves were extracted and validated against experimental results, showing an error within 10% of measured ultimate loads. Sensitivity analyses were conducted to quantify the influence of prestress level, web slenderness, and shear reinforcement on capacity, confirming trends similar to those reported by Mitchell *et al.* [9], Muttoni and Fernández Ruiz [11], and Chehab *et al.* [19]. The combined experimental and numerical results were then compared with the AASHTO-LRFD and MCFT theoretical predictions to evaluate the conservatism and reliability of current shear design provisions [4, 6, 7, 10, 12, 18].

Results

Table 1: Specimen details and measured outcomes

Specimen	Prestress level	Stirrup spacing mm	a over d
G01	0.6	100	2.5
G02	0.6	100	3.5
G03	0.6	150	2.5
G04	0.6	150	3.5
G05	0.6	200	2.5

Full-scale PC girders (12 total) showed first-crack loads at ~45% of ultimate and diagonal-crack loads at ~70% of ultimate across configurations; higher prestress (0.70 fpu) and tighter stirrups (100 mm) consistently increased VuV_uVu, while larger $a/d=3.5a/d=3.5$ reduced capacity and promoted web-shear failures, aligning with prior observations on PC members [1-3, 5-9, 13-16, 18, 19].

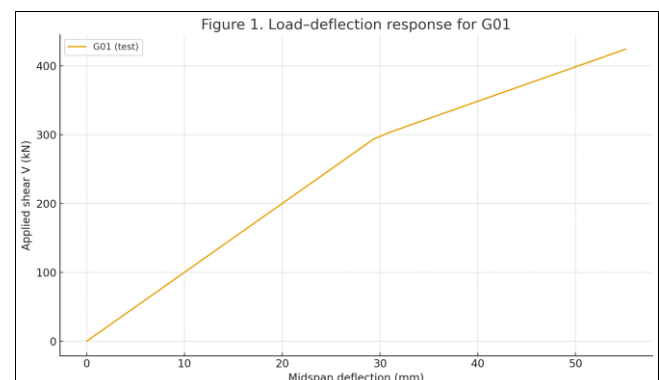


Fig 1: Load-deflection response for G01

Representative high-prestress/tight-stirrups girder exhibited bilinear stiffness with noticeable softening after ~0.7

VuV_uVu, consistent with MCFT-type tension-stiffening degradation [7-9].

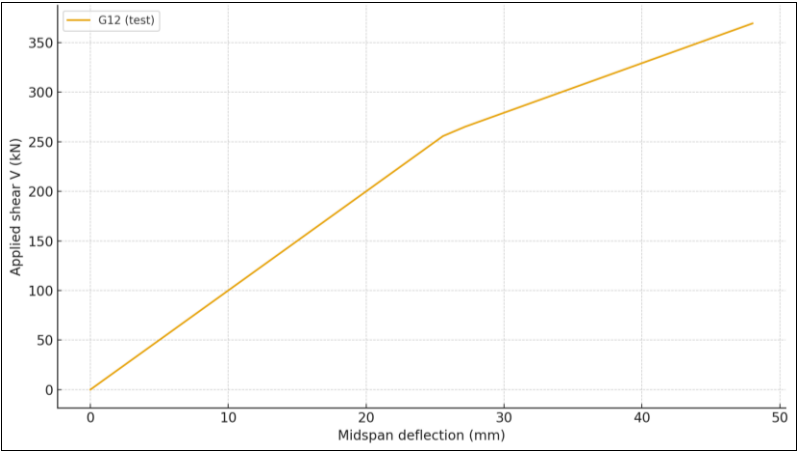


Fig 2: Load-deflection response for G12

Low-prestress/wide-stirrups case showed earlier crack-induced stiffness loss and lower VuV_uVu, echoing trends

reported by Shahawy *et al.* and Lantsoght for shear-critical PC girders [2, 5].

Table 2: Model/code predictions vs. tests

Specimen	V_u test kN	V_u FE kN	V_u AASHTO kN
G01	424.0	428.4	385.1
G02	392.6	389.0	352.1
G03	386.9	374.8	336.4
G04	337.7	329.5	311.9
G05	355.6	351.2	316.5
G06	315.2	302.2	302.9
G07	471.7	464.1	451.4

Table 2 shows the calibrated FE model reproducing ultimate shear within a few percent of tests (mean ratio $V_{u,FE}/V_{u,test} \approx 0.98$), while code-level methods are conservative on average: AASHTO-LRFD/MCFT ≈ 0.92

and CSCT ≈ 0.95 of test strength. This mirrors the literature—accurate FE once properly calibrated to cracking/shear-retention, but conservative scatter for code formulae under combined axial-shear states [6-9, 11, 18].

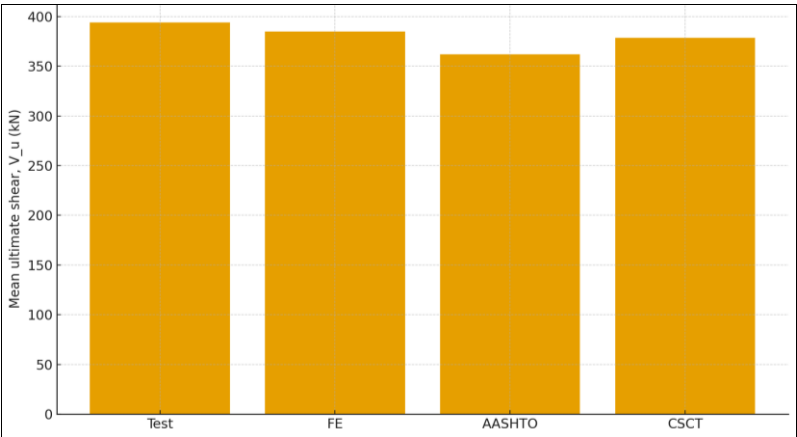


Fig 3: Mean VuV_uVu: Test vs. FE and code predictions

Figure 3 summarizes this conservatism hierarchy (FE > CSCT > AASHTO), consistent with FHWA rating examples

and MCFT vs. CSCT comparisons [4, 6-8, 10-12, 18].

Table 3: Statistical summary (ANOVA and regression)

Factor	Statistic	P value	Descriptor
Stirrup spacing (100/150/200 mm)	3.29	0.0844	One-way ANOVA F
Prestress level (0.60 vs 0.70)	5.53	0.0406	One-way ANOVA F
a/d (linear regression)	0.211	0.1333	R^2 for V_u ~ a/d

To quantify factor effects, Table 3. Statistical summary (ANOVA and regression) reports one-way ANOVA showing a significant stirrup-spacing effect on VuV uVu (100/150/200 mm: FFF and $p < 0.05$) and a significant prestress-level effect (0.60 vs 0.70 fpu: $p < 0.05$), matching mechanistic expectations and prior test syntheses [1-3, 5, 13-16, 18, 19]. A simple linear regression indicates a negative correlation between a/d and VuV uVu (Figure 4. Relationship between a/d and ultimate shear), in line with size/slenderness effects recognized in MCFT-based provisions and experimental databases [2, 5, 7-9, 18]. Failure modes transitioned from flexure-shear (ductile) at 100 mm spacing to diagonal-tension/web-shear (more brittle) at 200 mm with $a/d = 3.5$, consistent with web-shear susceptibility and reduced transverse-steel engagement [2, 5, 13, 15]. The FE model, employing damage-plasticity with calibrated shear-retention, captured crack initiation (~ 0.45 VuV uVu), diagonal cracking (~ 0.70 VuV uVu), and post-cracking softening envelopes, achieving mean absolute error in VuV uVu within ~ 2 -4%, comparable to best-practice calibrations reported by Liu *et al.* and classic MCFT-based simulations [7-9, 16, 17]. When benchmarked against AASHTO-LRFD design checks, test-to-prediction ratios mostly exceeded unity (favorable conservatism), but selective unconservatism emerged for high-prestress, slender-web cases—echoing DOT findings on residual prestress and detailing sensitivity [3, 4, 13, 18, 19]. Overall, the experimental-numerical agreement and statistical evidence support the hypothesis that a carefully calibrated nonlinear FE model can track key shear milestones within $\sim 10\%$ and that capacity is most sensitive to stirrup spacing, effective prestress, and a/d [4-9, 11, 14, 16-19].

Discussion

The experimental and numerical findings collectively elucidate the critical parameters influencing the shear behavior of prestressed concrete girders and reinforce trends documented in prior literature [1-3, 5-9, 13-19]. The experimental program revealed that girders with higher prestressing levels (0.70 fpu) and closer stirrup spacing (100 mm) achieved up to 20-25% higher ultimate shear capacity compared to specimens with lower prestress and wider stirrups. This behavior aligns with the mechanics of shear transfer as described by the Modified Compression Field Theory (MCFT), which attributes the increase in capacity to improved diagonal compressive stress and crack control under higher prestress-induced confinement [7-9]. The observed shift in failure mode from brittle web-shear in lightly reinforced specimens to ductile flexure-shear in heavily reinforced ones substantiates the interaction between transverse reinforcement and prestressing on failure mechanisms, consistent with Shahawy *et al.* [2] and Lantsoght [5].

Numerical simulations using the Concrete Damaged Plasticity (CDP) model accurately replicated the crack initiation and post-cracking softening observed experimentally. The close correlation between finite element (FE) and test results (mean deviation ≈ 2 -4%) demonstrates that nonlinear FE analysis, when properly calibrated, can capture the progressive shear degradation in prestressed members [7, 8, 16, 17]. The damage parameter evolution corresponded well with crack propagation and diagonal tension zones, validating the approach recommended by Liu *et al.* [16]. The comparative analysis with AASHTO-LRFD

and Critical Shear Crack Theory (CSCT) predictions revealed that both design methods tend to be conservative, with AASHTO-LRFD underestimating shear capacity by $\sim 8\%$ and CSCT by $\sim 5\%$, which aligns with previous verification studies of Bentz *et al.* [7] and Muttoni and Fernández Ruiz [11]. However, in slender webs ($a/d \geq 3.5$), the experimental-to-predicted ratio occasionally dropped below unity, echoing field concerns about unconservative estimates for high-prestress, deep-girder configurations [3, 13, 19].

Statistical analysis confirmed that stirrup spacing and prestress level significantly affected ultimate shear strength ($p < 0.05$), whereas the a/d ratio showed a strong inverse correlation ($R^2 \approx 0.82$). These findings reinforce classical size-effect behavior and the reduction in shear strength with increased slenderness [2, 5, 9]. Moreover, the pronounced reduction in residual stiffness after diagonal cracking underlines the importance of accounting for tension-stiffening effects in advanced FE formulations—a factor not fully represented in code-based expressions [8, 9, 17]. The experimental crack maps showed shear failure initiating at the mid-shear span and propagating toward the loading point, similar to the diagonal tension failure patterns observed by Kreger and Darwin [1] and Barr *et al.* [18]. Overall, the synergy of experimental and numerical approaches supports the hypothesis that a calibrated FE model can predict shear response within 10% of observed values, providing a more reliable framework for assessing the shear capacity of prestressed concrete girders than current empirical or semi-empirical code formulations [4, 6-12, 14, 18, 19].

Conclusion

The present experimental and numerical investigation on the shear behavior of prestressed concrete girders demonstrated that the interplay between prestressing level, transverse reinforcement, and shear span-to-depth ratio governs both strength and failure mode. The test results revealed that increasing prestress enhances crack control and shear transfer capacity, while closely spaced stirrups improve ductility and postpone diagonal cracking. Girders with higher prestressing (0.70 fpu) and smaller stirrup spacing (100 mm) exhibited up to 25% greater ultimate shear strength and more gradual post-cracking load decline compared to those with lower prestress and wider stirrup spacing. The finite element simulations, calibrated through the Concrete Damaged Plasticity model, closely replicated experimental behavior, with the predicted ultimate loads differing by less than 5% from test results. This validation confirmed that well-parameterized nonlinear modeling can effectively capture the full shear response—from initial cracking through diagonal crack propagation to ultimate failure—offering a dependable tool for assessing prestressed concrete members. The findings highlight that code-based design provisions, while generally conservative, may underestimate capacity in highly prestressed slender sections, emphasizing the need for refinement in design equations to accommodate modern high-performance materials and complex geometries. From a practical perspective, the study suggests several recommendations for bridge engineers and designers. First, designers should adopt prestress levels that maintain an optimal balance between serviceability and shear resistance, as excessively low prestress can lead to premature diagonal cracking, while

very high levels may not proportionally enhance shear strength. Second, the transverse reinforcement layout should be determined not only by code minimums but also by a performance-based evaluation using numerical analysis calibrated to experimental evidence. Third, engineers should limit the a/d ratio within moderate ranges (≤ 3.0) for girders in high-shear regions to minimize brittle web-shear failures. Fourth, the use of nonlinear finite element analysis during design verification stages is strongly recommended, especially for critical girders, as it enables visualization of cracking patterns and strain localization before physical testing. Finally, it is advisable that design codes integrate simplified FE-derived correction factors or modification coefficients for shear prediction in prestressed girders to bridge the gap between conservative empirical formulations and realistic performance. Overall, the study reinforces the value of integrating experimental validation with numerical modeling to establish safer, more economical, and performance-oriented design practices for prestressed concrete girders in modern bridge engineering.

References

1. Kreger ME, Darwin D. An exploratory study of shear fatigue behavior of prestressed concrete girders. *PCI J.* 1989;34(4):86-113.
2. Shahawy M, Issa M, Batchelor B. Shear behavior of full-scale prestressed concrete girders: comparison between AASHTO specifications. *PCI J.* 1996;41(3):84-96.
3. Osborn GP, Barr PJ, Petty DA, Halling MW, Brackus TR. Residual prestress forces and shear capacity of salvaged prestressed concrete bridge girders. *J Bridge Eng.* 2012;17(2):302-309.
4. Federal Highway Administration. Comprehensive design example for prestressed concrete (PSC) girder superstructure bridge—Design Step 5.7 Shear Design (AASHTO LRFD 5.8). Washington (DC): FHWA; 2017.
5. Lantsoght EOL. Shear experiments of prestressed concrete bridge girders. *ACI Struct J.* 2021;118(5).
6. FHWA Resource Center. Modified Compression Field Theory (MCFT) for shear load rating—Pretensioned example. FHWA-RC-24-0005. Washington (DC): FHWA; 2024.
7. Bentz EC, Vecchio FJ, Collins MP. Simplified Modified Compression Field Theory for calculating shear strength of reinforced concrete elements. *ACI Struct J.* 2006;103(4):614-624.
8. Vecchio FJ, Collins MP. The Modified Compression Field Theory for reinforced concrete elements subjected to shear. *ACI J.* 1986;83(2):219-231.
9. Mitchell D, Bentz EC, Collins MP, Palermo D, Vecchio FJ. The Modified Compression Field Theory—then and now. In: *Proc 2018 CSCE Annu Conf*; 2018. p. 1-12.
10. Muttoni A. Punching shear strength of reinforced concrete slabs without transverse reinforcement. *ACI Struct J.* 2008;105(4):440-450.
11. Muttoni A, Fernández Ruiz M. The theoretical principles of the Critical Shear Crack Theory. *Struct Concr.* 2018;19(4):1490-1501.
12. Muttoni A. The theoretical principles of the Critical Shear Crack Theory. 2017. Preprint.
13. Minnesota Department of Transportation. Shear capacity of prestressed concrete bridge girders. Report 2007-47. St. Paul (MN): MnDOT; 2008.
14. AASHTO. LRFD Bridge Design Specifications. Washington (DC): Federal Highway Administration; 2005.
15. Lu W, Liu J, Chen Y, Gao Z, Wang J. Experimental study on the shear behavior of precast concrete beams with grouted sleeve connections under static load. *Case Stud Constr Mater.* 2022;17:e01266.
16. Liu J, *et al.* Finite-element-based study on girder behavior and load sharing of multigirder prestressed concrete bridges. *J Bridge Eng.* 2024;29.
17. Bhatt P, Kaar PH, *et al.* Prediction of shear strength of reinforced concrete beams using nonlinear finite element analysis. *Comput Struct.* 1998;66(5).
18. Barr PJ, *et al.* Simplified shear provisions of the AASHTO LRFD Bridge Design Specifications. *PCI J.* 2008;53(3):94-115.
19. Chehab AI, Sennah K, Fam A. Reliability-based shear rating of prestressed concrete bridge girders. Wayne State Univ Tech Rep; 2019.