Review of Shear Behavior in Concrete Beams Reinforced with High-Strength Stainless Steel Stirrups

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Abstract

The degradation in durability of conventional reinforced concrete (RC) structures is the primary factor reducing the service life of engineering structures. Replacing conventional steel reinforcement with stainless steel rebars offers a fundamental solution to corrosion-induced degradation, thereby enhancing structural durability. Consequently, reviewing the current state of development, limitations, and application prospects of stainless steel reinforced concrete (SSRC) structures holds significant implications for advancing concrete structural design practices and promoting the engineering application of such structures within China.

Keywords

Stainless Steel Reinforcement; Reinforced Concrete Beam; Shear Performance; High-Strength Stirrups.

1. Introduction

Deterioration of conventional reinforced concrete (RC) structures represents a primary factor compromising structural service life. In highly corrosive environments, reinforcement corrosion severely impairs RC durability, inducing bond degradation at the steel-concrete interface along with concrete cracking and spalling. These mechanisms significantly diminish the load-bearing capacity of structural elements, constituting a critical pathway for global structural deterioration [1–4]. Substitution of carbon steel reinforcement with stainless steel counteracts corrosion risk, thereby substantially enhancing structural durability and safety [5]. Notwithstanding higher initial investment costs, stainless steel RC systems demonstrate clear economic advantages over conventional counterparts throughout the service life due to superior long-term durability and reduced maintenance, particularly when assessed via life-cycle cost analysis. The return on investment (ROI) proves especially significant in aggressive exposure conditions [6–7]. Internationally, adoption of stainless steel reinforcement in infrastructure projects has prompted the development of dedicated design manuals and construction guidelines [8–12]. China's Guideline for Durability Design and Construction of Concrete Structures (CCES 01-2004) [13] further mandates the application of locally manufactured stainless steel reinforcement in concrete construction.

To advance the implementation of high-strength reinforcement in concrete structures, the 2013 revision of Chinese National Standard GB 1499.2 Steel for the Reinforcement of Concrete-Part 2: Hot-rolled Ribbed Bars [14] added Grade HRB600 rebars. Nevertheless, Standard for Design of Concrete Structures (GB 50010-2010) [15] (hereafter GB 50010-2010) prescribes HRB400 and HRB500 grades for primary reinforcement, while excluding HRB600 conventional steel reinforcement. In contrast to conventional rebars, stainless steel reinforcement demonstrates not only enhanced corrosion resistance but also distinctive mechanical properties: high ductility, low elastic modulus, and absence of a yield plateau [16]. The issuance of GB/T 33959-2017 Stainless Steel Bars for Concrete Reinforcement [17] establishes unified specifications for domestically manufactured high-strength stainless rebars, lowers production costs, and provides a technical basis for implementation.

Despite extensive global research on stainless steel reinforced concrete (SSRC) structures, predominant investigations remain confined to bond performance and corrosion resistance, resulting in incomplete characterization of mechanical behavior. This knowledge gap leads to current design methodologies routinely importing shear capacity provisions from conventional reinforced concrete (RC) codes-specifically for inclined-section shear strength calculations in SSRC beams. Owing to the intrinsically complex and stochastic nature of shear failure mechanisms, where multiple parameters interact nonlinearly, existing shear strength models in international design codes retain significant limitations-even after a century of research encompassing thousands of studies. Such unvalidated adoption not only neglects the distinctive advantages of SSRC systems but potentially engenders concealed safety hazards under specific loading configurations.

2. Mechanical Behavior of Stainless Steel Reinforcement

Stainless steel reinforcement demonstrates exceptional corrosion resistance and mechanical performance. The corrosion resistance originates predominantly from its unique alloy composition-notably chromium (Cr) and nickel (Ni). Chromium facilitates the formation of a self-regenerating chromium oxide film, ensuring sustained performance in aggressive environments; concurrently, nickel optimizes microstructural refinement, enhancing elevated-temperature stability [18–21]. In terms of mechanical properties, stainless steel rebars exhibit higher yield strength (ranging 500–700 MPa) and tensile strength, providing robust resistance to applied loads without yielding or fracture. Critically, the elastic modulus of stainless steel is 25–30% lower than that of carbon steel reinforcement, leading to increased deformation under equivalent stress states. Moreover, the stress-strain response lacks a distinct yield plateau and instead displays continuous strain hardening coupled with superior ductility.

3. Shear Behavior of Concrete Beams with High-Strength Conventional Stirrups

When high-strength reinforcement serves as stirrups in concrete beams, permissible yield strengths exhibit substantial variations across international design codes-primarily to control maximum diagonal crack widths at serviceability limit states (SLS) or mitigate shear failures triggered by concrete crushing preceding stirrup yielding. Notably:Chinese Code GB 50010-2010 [15] and American Standard ACI 318-19 [22] cap stirrup yield strength at 360 MPa and 420 MPa, respectively; Canadian Standard CSA A23.3-19 [23] imposes a 500 MPa limit;Eurocode 2 (EN 1992-1-1:2004) [24], under its variable-angle truss model framework, allows up to 600 MPa;For high-strength concrete , Japanese Standard JSCE-2007 [25] extends this threshold to 800 MPa.This fivefold divergence in codified limits underscores significant disparities in the current global understanding of high-strength stirrups' impact on shear behavior and failure mechanisms.

Pendyala [26] established an idealized model for shear resistance mechanisms in reinforced concrete beams with shear reinforcement, depicting the variation of concrete contribution and stirrup contribution against total shear force V. This model postulates: At the onset of loading, concrete sustains virtually the full shear demand, with negligible engagement of stirrups; Following inclined crack formation, stirrup resistance escalates progressively with increasing applied shear V; However, the concrete component remains essentially constant post-cracking.

Yoshida [27] executed shear tests on four large-scale reinforced concrete beams instrumented with 400 MPa-grade stirrups, demonstrating that optimal stirrup reinforcement markedly elevates both shear capacity and structural ductility ($\mu > 3.0$).

Cladera et al. [28] executed a systematic experimental program involving 18 reinforced concrete beams with 500 MPa-grade stirrups, specifically designed to contrast shear failure mechanisms in beams with and without web reinforcement. Results established that non-web-reinforced beams manifested catastrophic brittle failure, with failure abruptness escalating proportionally to concrete compressive strength. Conversely, in web-reinforced specimens, increased Standard value of axial compressive strength of concrete enhanced effective stirrup participation by 18-25% under identical reinforcement ratios.

Wang Tiecheng et al. [29] executed destructive shear testing on eight RC T-beams with 500 MPa-grade stirrups, quantifying shear capacity and service-load crack propagation. Key findings under concentrated loads: Identical shear failure mechanisms and crack evolution patterns to conventional RC beams Yield attainment in 95.2% of stirrups crossing critical diagonal cracks Serviceability crack widths compliant with GB 50010-2010.

Li Juan [30] conducted experimental research on shear behavior in concrete beams reinforced with Grade HRB500 stirrups. Test results confirmed that stirrups intersecting diagonal cracks consistently attained yield strength. Building upon these findings and synthesizing global experimental data, she derived predictive equations for shear capacity and diagonal crack width calculations in concentrated-load RC beams.

Zhong Yali [31] developed a Modified Modified Compression Field Theory (MMCFT), incorporating shear contribution from the compression zone concrete while neglecting dowel action of longitudinal bars-though retaining consideration of neutral axis depth effects. This framework decomposes shear resistance into three components: Vertical shear component in the compression zone Friction along critical diagonal cracks Stirrup resistance.

4. State of Global Research on Stainless Steel Reinforced Concrete Structures

Since the advent of stainless steel reinforcement, research into its fundamental properties has continuously evolved, encompassing two core domains: essential mechanical behavior and corrosion resistance. Furthermore, accelerated urbanization and infrastructure development have escalated demands for enhanced durability, efficiency, and sustainability of structures. As an emerging structural system, stainless steel reinforced concrete (SSRC) offers significant application potential and developmental prospects. Consequently, SSRC structures have emerged as a global research focus in recent years.

Geromel et al. [32] conducted systematic experimental investigations on concrete beams reinforced with austenitic Type 316L stainless steel rebars. Comparative analysis of experimental data and theoretical predictions revealed marked discrepancies between the mechanical responses of SSRC beams and those anticipated for conventional RC beams under current design standards. This finding underscores the imperative to develop SSRC-specific design codes—extending beyond corrosion-centric provisions.

Li et al. [33] experimentally evaluated flexural and shear behavior in stainless steel reinforced concrete (SSRC) beams. Results demonstrated that SSRC beams consistently exceeded the performance of conventional RC beams at identical reinforcement ratios. In flexural tests:Compatible strain distribution validated the plane-section assumption Current design codes yielded conservative predictions for flexural capacity.

Zhou Yi [34] designed and fabricated seven hybrid-reinforced concrete beams with varying stainless-to-carbon steel reinforcement ratios, comparatively analyzing flexural behavior at serviceability limit states (SLS) and ultimate limit states (ULS). Results indicated that RC beams with stainless reinforcement exhibited crack patterns and failure modes closely resembling conventional RC beams. Critically, code-prescribed crack width formulations remain applicable to SSRC beams.

Zhao Yi et al. [35] and Gao Di [16] conducted flexural tests on six SSRC beams and two conventional RC beams, revealing: Analogous crack distributions between SSRC and conventional specimens

Larger crack widths and deflections in SSRC beams under identical loading. Enhanced load-bearing capacity in SSRC beams at equal reinforcement ratios. Conservative flexural capacity predictions per GB 50010-2010: mean test-to-calculated ratio of 0.68, indicating superior safety margins for SSRC designs.

Feng Xingguo et al. [36] assessed corrosion resistance in coral aggregate concrete structures with stainless steel reinforcement, comparing corrosion current densities via multiple electrochemical techniques. Results demonstrated significant corrosion in carbon steel reinforcement, while stainless rebars maintained passivation .

Zhao Yong et al. [37] conducted seismic performance tests on eight concrete columns:2 with conventional reinforcement 6 with stainless steel reinforcement. Key findings: Comparable flexural capacities. Enhanced safety margins for SSRC columns.

Cui Yunqi [38][38] performed shear tests on 12 RC beams with Grade 304 stainless steel stirrups. Through regression analysis of experimental data aligned with GB 50010-2010 §6.3.4, a specialized shear capacity equation for SSRC beams was derived.

Xie Wangjun et al. [39] conducted flexural tests on eight coral aggregate seawater sea-sand concrete (CASSC) specimens, varying reinforcement type and reinforcement ratio. Key findings:Comparable cracking loads between stainless and carbon steel specimens 69.08% higher ultimate moment capacity in stainless steel specimens 17.53% reduction in initial flexural stiffness.

5. Conclusion

Current research on stainless steel reinforced concrete (SSRC) structures by scholars both domestically and internationally primarily focuses on material properties, structural behavior, and durability. Although research on stainless steel rebars commenced relatively late in China, significant achievements have been made in recent years, with successful applications in major projects such as the Hong Kong-Zhuhai-Macao Bridge and the Guangxi Mangrove Bridge. However, there is a notable scarcity of studies, both globally and within China, specifically investigating the shear capacity of SSRC beams, particularly concerning inclined sections. The vast majority of existing research concentrates on aspects such as bond behavior and flexural performance. Crucially, research on beams incorporating high-strength stainless steel stirrups remains unreported. Therefore, it is imperative to conduct experimental investigations into the shear performance of stainless steel reinforced concrete beams.

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