
Review of low-cycle fatigue and strain aging research in G300E and G500E steels

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ABSTRACT

This review paper presents a summary of recent advancements in low-cycle fatigue, strain aging, and the residual capacity of G300E and G500E reinforcing steels, with emphasis on seismic applications in New Zealand. The review identifies how low-cycle fatigue and strain aging reduce the deformation capacity and fatigue life of reinforcing steels following seismic events, directly influencing the reliability and reparability of reinforced concrete structures. G300E exhibits high ductility and strain hardening but is susceptible to strain aging, which increases yield and ultimate stress values, and compromises ductility after prior plastic deformation, thus increasing vulnerability to subsequent seismic events.

In contrast, G500E provides greater resistance to strain aging, although its ductility is inherently lower, creating design trade-offs that need to be carefully considered. Analysis of the literature reveals key gaps in current seismic design approaches, particularly in accounting for the combined effects of cyclic loading and strain aging on residual performance. The findings underscore the necessity for integrated experimental and analytical models that more accurately capture the combined degradation mechanisms.

Recommendations from this review advocate for the refinement of strain limits in design practice, development of predictive models for aged and fatigued reinforcement, and informed strategies for assessing and restoring post-seismic structural capacity. Collectively, these insights will support the development of evidence-based guidelines for the use of G300E and G500E steels in sacrificial fuses and broader reinforced concrete systems, enhancing the seismic resilience of structures in New Zealand.

1 INTRODUCTION

The motivation for this research stems from the increasing demand for developing more resilient structures, particularly in seismic regions like New Zealand. While this project focuses on dissipative fuses, its findings also have broader implications for conventional reinforced concrete structures. This project builds on findings from previous studies, including a large-scale low-damage seismic building test at Tongji University in Shanghai in 2019 (Henry et al., 2021), which investigated the behavior of sacrificial steel fuses designed to

deform inelastically and dissipate seismic energy as part of low-damage structural systems. Within that test, sacrificial fuses machined from G300E steel provided supplemental energy dissipation by deforming inelastically under seismic loads, but uncertainties remained regarding their post-seismic residual capacity and when fuses should be replaced due to low-cycle fatigue. In seismic applications, where repeated stress and strain cycles lead to material fatigue, it is essential to assess the residual life and fatigue resistance of structural components (Brown and Kunnath, 2004).

This review investigates the combined effects of low-cycle fatigue and strain aging on reinforcing bars and sacrificial fuses made from G300E (300 MPa yield stress) and G500E (500 MPa yield stress) steels, two materials widely used in reinforced concrete structures in New Zealand. The "E" suffix denotes a high-ductility seismic grade produced using controlled manufacturing processes intended to limit residual stresses and preserve ductile grain structures (Standards Australia and New Zealand, 2019). Previous studies have linked plastic strain amplitudes with cycles to fracture for G300E steel, but have not explored the combined effects of strain aging or included testing on G500E steel (Mander et al., 1994; Loporcaro et al., 2018b). These gaps limit industry practitioners' ability to develop reliable strain limits and fatigue performance criteria for sacrificial components in seismic systems.

Monotonic ductility correlates broadly with low-cycle fatigue performance; however, it is an unproven and potentially unreliable surrogate for low-cycle fatigue behavior (Kashani et al., 2019). G500E exhibits less strain hardening than G300E, with ultimate stresses approximately 30% higher than yield stresses for G500E, compared with 45% for G300E. Reduced strain hardening limits G500E's ability to propagate and distribute plastic deformation evenly, leading to greater strain localization, accelerating crack initiation under cyclic loading (Egger et al., 2021). G500E's higher yield stress is also associated with reduced inelastic displacement capacity and energy dissipation (Su et al., 2019).

The uncertainty around strain aging and ductility reduction motivates recommendations for higher-strength G500E steel, despite its lower monotonic ductility (approximately 13% uniform elongation vs 20% for G300E). While G500E resists strain aging at temperatures below 150°C due to the presence of vanadium nitrides, G300E remains susceptible after inelastic seismic strain (Loporcaro 2017; Shegay et al., 2023a). This underscores significant knowledge gaps in low-cycle fatigue behavior that this review addresses.

The structural performance of reinforced concrete buildings during seismic events depends critically on steel reinforcement behavior (Su et al., 2023). Observations from the Christchurch earthquakes (2010-2011) confirmed capacity design effectiveness but raised concerns about residual capacity and reparability due to limited assessment methodologies (Loporcaro 2017). Understanding low-cycle fatigue, strain aging, and residual capacity interactions for G300E and G500E steels is therefore essential for seismic design, post-earthquake assessment, and enhancing structural resilience in New Zealand.

2 LOW-CYCLE FATIGUE IN REINFORCING STEELS

Fatigue refers to progressive structural damage from repeated cyclic loading leading to crack initiation and failure, even when loads are below the static yield strength (ASTM 2023). Fatigue is classified into three regimes: high-cycle fatigue (HCF, 10^5 - 10^7 predominantly elastic cycles) (Sharma et al., 2020), low-cycle fatigue (LCF, tens to thousands of cycles with substantial plastic strain) (Dowling 2013), and ultra-low-cycle fatigue (ULCF, fewer than 100 cycles of severe plastic deformation) (Xu et al., 2023). ULCF is particularly relevant for seismic applications where large strain reversals can occur during earthquakes.

2.1 Experimental Studies

Monotonic tests establish baseline properties but provide unproven and potentially unreliable predictions of LCF behavior. Early foundational work by Baird (1963, 1971) and Cottrell and Bilby (1949) focused on

ductility without addressing cyclic implications. Mander et al. (1994) systematically characterized ASTM A615 and A722 bars under cyclic loading, while Dutta and Mander (1998) demonstrated that confinement improves cyclic performance. Loporcaro et al. (2018a) examined Christchurch earthquake-damaged Grade 300E bars and found evidence of strain aging, with increased yield and ultimate strength but reduced ductility, emphasizing the need for post-seismic evaluation protocols.

Fixed-amplitude testing programs typically employ Coffin-Manson relationships to develop strain-life curves (Manson 1953; Coffin and Schenectady, 1954). Brown and Kunnath (2004) identified bar buckling as a key factor governing fatigue failure in A615 reinforcement. Kashani et al. (2019) showed that larger bar diameters accelerate degradation through stress concentrations at the roots of the deformations on reinforcing bars. Bakkar et al. (2021) confirmed rib-root crack initiation mechanisms in thermo-mechanically treated rebars through detailed fractography. Egger et al. (2021) found that Grade 80 (550 MPa) bars fail prematurely from buckling despite initial resistance to crack propagation, while Liu et al. (2021) developed improved Manson-Coffin models accounting for asymmetric loading effects.

Variable-amplitude testing protocols better simulate actual earthquake loading conditions. Kashani et al. (2019) linked higher length-to-diameter (L/D) ratios to increased cumulative damage under variable-amplitude cycling. Jiao and Yamada (2021) demonstrated that conventional strain-life models fail to predict behavior accurately above 6% strain amplitudes. Mantawy and Anderson (2018) confirmed that LCF damage accumulation causes bar rupture and buckling during long-duration ground motions, while Couto et al. (2021) showed that material aging and corrosion increase structural fragility.

Studies combining LCF with strain aging reveal more severe degradation. Loporcaro (2017) found that aging reduces fatigue life by up to 43% in previously strained bars, with buckled bars losing up to 85% of their residual capacity (Massone and Herrera, 2019). Nakagawa et al. (2022) confirmed that strain-age embrittlement reduces energy dissipation capacity under subsequent cyclic loading. Tripathi and Dhakal (2023) developed constitutive models incorporating buckling-LCF interaction, while Jin et al. (2024, 2025) demonstrated that thermal aging significantly reduces fatigue resistance at high strain amplitudes.

2.2 Key Findings and Gaps

LCF studies have successfully identified buckling, rib geometry, and bar slenderness as dominant factors controlling fatigue life. However, combined effects of strain aging and variable-amplitude loading remain underexplored, particularly for New Zealand G300E and G500E seismic-grade steels (Loporcaro, 2017; Massone and Herrera, 2019). Current seismic design codes inadequately address these coupled degradation mechanisms (Nakagawa et al., 2022; Tripathi and Dhakal, 2023), limiting development of reliable strain limits for sacrificial fuses and post-earthquake capacity assessment protocols.

3 STRAIN AGING MECHANISMS AND EFFECTS

Strain aging is a time- and temperature-dependent metallurgical phenomenon where interstitial atoms (primarily carbon and nitrogen) diffuse into dislocations within deformed low-carbon steel microstructure (Loporcaro et al., 2019). Dislocations are linear crystal lattice defects that enable plastic deformation through atomic plane slip. Interstitial atoms cluster around these dislocations, forming Cottrell atmospheres that pin dislocation movement (Cottrell and Bilby, 1949). Unpinning these dislocations through initial plastic deformation requires significantly higher stress, causing characteristic increases in yield strength and the appearance of distinct yield points (Clyne and Campbell, 2021; Hasebe 2023).

The metallurgical process of strain aging dramatically alters post-seismic performance. Over time, the interstitial atoms diffuse to the tensile strain field around the new locations of the dislocations, re-pinning the dislocation and creating the reemergence of a distinct yield point. This aging process increases yield strength

and hardness but critically reduces ductility, compromising remaining low-cycle fatigue life and hysteretic energy dissipation capacity of plastically deformed reinforcement (Loporcaro et al., 2019, 2022). Accelerated aging techniques using heating at 100°C can simulate 12 months of ambient aging within hours, enabling practical laboratory investigation of long-term effects (Hundy 1954; Loporcaro 2017).

3.1 Comparative Behavior of G300E and G500E

G300E and G500E steels exhibit fundamentally different strain aging behavior. G300E shows pronounced aging effects with substantial reductions in ductility and fatigue life following plastic deformation (Momtahan et al., 2009). In contrast, G500E is a vanadium nitride-stabilized "non-aging" grade that resists strain aging below 150°C, though it possesses inherently lower baseline ductility (approximately 13% uniform elongation compared with 20% for G300E) (Loporcaro 2017).

Figure 1 demonstrates the effect of strain aging on G300E stress-strain behavior, showing increased yield strength (f_y) and ultimate strength (f_u) but critically reduced ultimate strain (ϵ_u) (Baird 1971; Loporcaro et al., 2019; Yang et al., 2022). Post-strain-aged G300E exhibits significantly diminished plastic deformation capacity. This reduction in ductility leads to premature fracture under subsequent cyclic loading and can create unintended overstrength in previously strained sections of a structure that could potentially violate capacity design principles and shift failure mechanisms toward more brittle modes (Yang et al., 2022). Higher pre-strain levels amplify these effects, with earthquake-recovered G300E samples showing yield strength increases proportional to prior plastic deformation magnitude (Loporcaro et al., 2019).

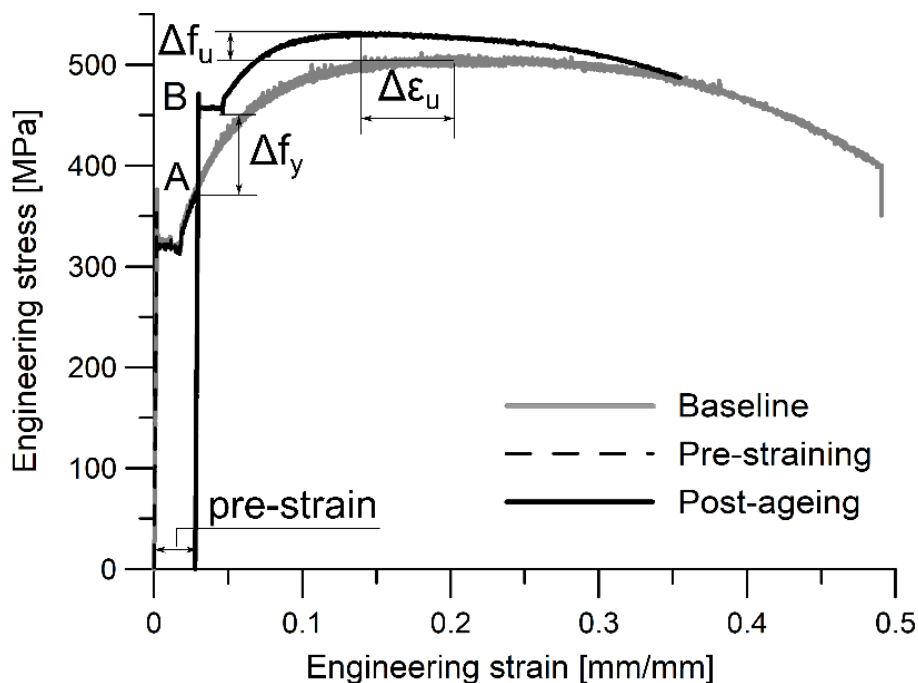


Figure 1: Effect of strain-ageing on G300E stress-strain curve showing increased yield strength (f_y) and ultimate strength (f_u) but reduced ultimate strain (ϵ_u) (Baird 1971; Loporcaro et al., 2019; Yang et al., 2022)

3.2 Implications for Seismic Performance

Nakagawa et al. (2022) confirmed that strain-aged steel exhibits reduced energy dissipation capacity during aftershock loading due to embrittlement. Yuan et al. (2018) identified Cottrell atmosphere formation and

carbide precipitation as the primary mechanisms responsible for hardening and embrittlement. Momtahan et al. (2009) quantified significant ductility losses in pre-strained Grade 300 bars under piecewise monotonic loading protocols.

Loporcaro et al. (2019) demonstrated that strain aging reduces LCF life while increasing brittle failure risk in G300E reinforcement. Their subsequent work developed hardness-based predictive models that enable assessment of aged reinforcement durability under cyclic loading (Loporcaro et al., 2022). These findings necessitate revised strain limits and post-earthquake assessment protocols for structures containing G300E reinforcement (Loporcaro et al., 2018a, 2018b).

The core design trade-off between G300E and G500E steels centers on aging susceptibility versus inherent ductility. G300E provides superior unaged hysteretic performance but requires conservative strain limits for sacrificial fuses due to aging vulnerability. G500E offers aging stability but has fundamentally limited deformation capacity, requiring careful geometric detailing to avoid strain localization at rib roots and stress concentration points (Shegay et al., 2023b).

4 RESIDUAL CAPACITY AND SEISMIC PERFORMANCE

Residual capacity refers to the ability of reinforcing bars to retain deformation capacity and fatigue life after experiencing significant plastic deformation, which is critical for post-earthquake safety assessment and repair decision-making (Loporcaro et al., 2018a, 2019). Degradation depends on loading history intensity, strain aging effects, and cumulative cyclic damage. G300E's superior unaged ductility and strain hardening characteristics provide better initial residual capacity than G500E, but strain aging significantly diminishes these advantages over time (Loporcaro 2017).

4.1 Post-Earthquake Performance Studies

Hammad and Moustafa (2019) demonstrated that longer duration and higher intensity ground motions progressively reduce residual performance in reinforced concrete frame structures. Loporcaro et al. (2018b, 2019) developed comprehensive assessment frameworks combining monotonic and cyclic testing with non-destructive hardness measurements to estimate residual strain capacity, providing essential tools for post-earthquake retrofitting decisions.

Kuwabara et al. (2023, 2024) examined bars recovered from earthquake-damaged structures and found that plastically strained bars retain significant fatigue capacity but lose approximately 30% of their ultimate strain due to aging effects, accompanied by roughly 10% increases in yield strength. Despite this degradation, the remaining 10% residual strain typically meets minimum design ductility demands, highlighting strain aging's dual impact, both beneficial (strength increase) and detrimental (ductility loss), on post-earthquake structural assessment.

4.2 Predictive Models and Additional Degradation Factors

Gao et al. (2022) proposed modified Coffin-Manson predictive models that incorporate pre-strain and aging effects for high-strength steel fatigue life estimation. Jiao and Yamada (2021) showed that extreme strain histories exceeding conventional limits require modified cumulative deformation capacity models beyond traditional approaches. Shegay et al. (2023a) demonstrated through shake-table testing that epoxy injection can partially restore reinforced concrete stiffness but cannot recover lost deformation capacity, indicating permanent material-level damage from aging and fatigue.

Post-earthquake fire exposure presents additional complications. Zhuang et al. (2024) showed that elevated temperatures reduce high-strength steel fatigue life and tensile properties, while Zhuang et al. (2022)

emphasized the importance of bond-slip modeling for accurate seismic performance predictions in thermally affected reinforcement.

4.3 Performance Comparison

Table 1 summarizes fundamental performance differences between G300E and G500E steels that drive seismic design decisions for New Zealand applications.

Table 1: Comparison of G300E and G500E for seismic applications

Property	G300E	G500E
Unaged ductility	19.3% strain at UTS (uniform elongation)	13.1% strain at UTS (uniform elongation)
Strain hardening	Strong ($f_u \approx 1.45f_y$)	Modest ($f_u \approx 1.3f_y$)
Strain aging effect	Significant ductility loss	Aging resistant (vanadium nitrides)
Residual capacity	High initially, reduced by aging	Lower baseline, stable with aging
Seismic suitability	Fuses with conservative strain limits	Limited deformation applications

The performance trade-offs illustrated in Table 1 reveal that G300E provides superior unaged hysteretic performance but faces aging vulnerability, while G500E offers long-term stability at the cost of reduced deformation capacity (Loporcaro 2017; Shegay et al., 2023b). Current seismic design codes do not adequately address these material-specific degradation mechanisms or provide guidance for selecting between these grades based on expected strain demands and post-earthquake performance objectives (Kuwabara et al., 2024).

5 IMPLICATIONS FOR G300E AND G500E DESIGN

The integration of low-cycle fatigue, strain aging effects, and residual capacity considerations is important for developing resilient reinforced concrete structures in seismic regions like New Zealand (Loporcaro et al., 2018b, 2019, 2022). The fundamental performance trade-offs summarized in Table 1 demonstrate that G300E offers superior ductility and energy dissipation capacity but exhibits significant strain aging vulnerability, while G500E provides aging resistance at the cost of inherently lower deformation capacity. These contrasting characteristics require material-specific design approaches that current seismic standards do not adequately address.

5.1 Critical Gaps in Current Design Practice

Prior research has revealed critical gaps in design methodologies that contemporary standards fail to address comprehensively. Liu et al. (2021) developed improved Manson-Coffin models accounting for asymmetric cyclic loading effects typical of earthquake ground motions. Zhuang et al. (2022) emphasized the importance of precise detailing for sacrificial components such as debonded bars in low-damage structural systems. Mantawy and Anderson (2018) demonstrated that long-duration ground motions impose severe cumulative fatigue damage on reinforced concrete frames, exceeding damage from shorter-duration motions of equivalent peak intensity. Tripathi and Dhakal (2023) incorporated buckling-LCF interaction mechanisms into advanced constitutive models, providing tools for more realistic performance prediction.

5.2 Material-Specific Design Recommendations

Loporcaro et al. (2019) states that for G300E sacrificial fuses, design strain limits should be established to maintain at least 10% residual ductility following strain aging. This limit ensures adequate performance during potential aftershock sequences and preserves options for repair versus replacement decisions. Post-earthquake assessment should include assessment of remaining capacity, such as the hardness-based protocols developed by Loporcaro et al. (2022) to determine when fuse replacement is necessary based on material degradation models rather than arbitrary displacement limits.

Shegay et al. (2023b) recommend that for G500E applications, designers should exploit aging resistance in scenarios with high aftershock probability or extended service life requirements. However, G500E's modest strain hardening necessitates careful geometric detailing to mitigate strain localization at rib roots and stress concentration points (Egger et al., 2021). Applications should be limited to moderate ductility demands where the 10-15% fracture strain capacity is sufficient.

5.3 Post-Earthquake Assessment Protocols

Post-earthquake structural assessment requires integrated protocols combining non-destructive hardness testing with aging-adjusted fatigue life prediction models (Gao et al., 2022). The residual strain capacity frameworks developed by Kuwabara et al. (2023, 2024) provide practical tools for evaluating whether plastically deformed reinforcement retains adequate performance for continued service or requires replacement. These assessment methods are particularly critical for sacrificial fuse systems where replacement decisions directly impact repair costs and downtime (Henry et al., 2021).

Freddi et al. (2021) highlight that low-damage seismic technologies achieve their full resilience potential only when combined with material-specific understanding of LCF and strain aging degradation mechanisms. Jin et al. (2025) demonstrated that post-earthquake fire exposure compounds thermal aging effects, underscoring the need for integrated multi-hazard assessment protocols that account for cumulative degradation from seismic and thermal loading.

Developing these evidence-based strain limits and assessment guidelines will enable New Zealand practitioners to optimize G300E and G500E selection for both sacrificial fuses and conventional reinforced concrete applications. The material-specific approach balances competing objectives of energy dissipation capacity, aging stability, and reliable post-seismic reparability while providing clear criteria for informed engineering decisions.

6 CONCLUSIONS

This review has examined the current state of knowledge regarding low-cycle fatigue, strain aging, and residual capacity of G300E and G500E reinforcing steels, with emphasis on seismic applications in New Zealand. The literature demonstrates that these coupled degradation mechanisms significantly influence post-earthquake structural performance, yet current seismic design codes provide inadequate guidance for addressing material-specific behavior.

G300E and G500E steels exhibit fundamentally different performance characteristics that create distinct design trade-offs. G300E provides superior unaged ductility (approximately 20% uniform elongation) and strain hardening capacity, enabling excellent energy dissipation under seismic loading. However, G300E is susceptible to strain aging, which increases yield and ultimate strength while reducing ductility and residual fatigue life following plastic deformation. In contrast, G500E offers aging resistance at temperatures below 150°C due to vanadium nitride stabilization, but possesses inherently limited ductility (approximately 13% uniform elongation) and modest strain hardening has the potential to reduce strain propagation and increase

strain localization. These contrasting characteristics necessitate material-specific design approaches for sacrificial fuses and conventional reinforced concrete applications.

The review identifies key gaps in current design and assessment methodologies. Existing strain limits do not account for the combined effects of cyclic loading history and time-dependent strain aging on residual performance. Post-earthquake assessment protocols lack standardized approaches for evaluating aged and fatigued reinforcement, particularly for determining when repair versus replacement is appropriate. Variable-amplitude loading effects and the influence of long-duration ground motions on cumulative fatigue damage require better integration into predictive models and design procedures.

Evidence-based recommendations from this review include: establishing conservative plastic strain limits for G300E sacrificial fuses that preserve adequate residual ductility after aging; exploiting G500E's aging resistance for high aftershock probability scenarios while mitigating strain localization through careful geometric detailing; and implementing integrated post-earthquake assessment protocols combining non-destructive hardness testing with aging-adjusted fatigue life prediction models. These material-specific guidelines will support development of resilient low-damage seismic systems and informed post-earthquake reparability decisions, enhancing structural resilience in New Zealand and other seismic regions employing similar steel grades.

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