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# Experimental evaluation of steel fuse performance under monotonic and cyclic loading for seismic applications

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## ABSTRACT

Sacrificial steel fuses are a common way of dissipating seismic response energy through plastic deformation of the fuse material. Unbonded fuse cores within a bucking restraint tube are a common configuration of such sacrificial steel fuses. A series of experimental tests were conducted to evaluate the mechanical performance of grooved steel fuse elements within bucking restraint tubes. The steel fuses were fabricated from Grade 300E reinforcing round with varying active lengths (290-414 mm) and rib thicknesses (4.2-4.6 mm). Fuses were tested under monotonic and unipolar cyclic axial loading using a servo-hydraulic testing system. The cyclic tests followed two displacement-controlled profiles that followed the AISC 341-16 loading protocol progression, up to 5% and 10% strains amplitude.

Under unipolar cyclic loading up to 5% peak strain, all fuse types exhibited stable and symmetric hysteresis loops, completing between 15 and 48 full test sequences before fracture. Increasing the test displacement amplitudes to induce 10% strain resulted in failure within 1 to 2 sequences, indicating rapid low-cycle fatigue degradation at high inelastic strain levels.

Initial stiffness of the steel test specimens varied with length, ranging from 40 to 50 kN/mm, with shorter fuses demonstrating higher stiffness. Peak monotonic strengths were between approximately 62 and 81 kN, depending on geometry and steel source. Fuse configurations with intermediate active lengths and moderate rib thicknesses showed superior cyclic fatigue performance.

The results provide a comprehensive experimental basis for assessing the trade-offs between deformation capacity, fatigue life, enclosed hysteretic area, and the influence of geometric parameters. The results presented also contribute to ongoing research on strain aging and residual capacity in structural steel components.

## 1 INTRODUCTION

The increasing demand for resilient structural systems in seismic regions such as New Zealand has driven the development of low-damage structural solutions that incorporate sacrificial energy-dissipating components. Among these, steel fuse elements are designed to deform inelastically under earthquake loading, dissipating seismic energy while protecting primary structural members (Ramhormozian et al., 2019; Dhakal, 2021). While this study focuses on the experimental performance of steel fuses, its findings are also relevant to the broader context of reinforced concrete structures that rely on ductile steel components, including selectively de-bonded reinforcing bars, for seismic resistance.

This research builds on a large-scale low-damage seismic building test conducted at Tongji University in 2019 (Henry et al., 2021), where sacrificial steel fuses machined from G300E reinforcing steel contributed significantly to energy dissipation. However, uncertainties remained regarding their post-seismic residual capacity and fatigue resistance following repeated inelastic loading.

Structural components subjected to seismic loading experience repeated stress and strain cycles that can lead to material degradation through low-cycle fatigue (Bai et al., 2024). Although monotonic ductility provides a broad indication of deformation capacity, it is an unproven surrogate for low-cycle fatigue performance. Fatigue behavior is strongly influenced by strain amplitude, strain localization, and material hardening characteristics, which govern crack initiation and propagation under cyclic loading.

Previous studies have linked plastic strain amplitudes with cycles to fracture for G300E reinforcing steel (Tripathi et al., 2019; Loporcaro et al., 2022). However, uncertainties remain in defining reliable strain limits and the corresponding fatigue performance criteria for sacrificial components used in seismic systems. These uncertainties were evident during the Tongji University testing program (Henry et al., 2021). In the absence of a reliable evidence-base to guide replacement decisions on successive tests engineering judgement was required to determine when fuses should be replaced due to fatigue damage. In real-world applications, such decisions are further complicated by accessibility constraints, functional interruption, and repair costs.

The present study provides an experimental evaluation of grooved steel fuse elements fabricated from G300E reinforcing steel and tested under monotonic and unipolar cyclic axial loading. The results establish an evidence base for assessing trade-offs between deformation capacity, fatigue life, and geometric configuration for dissipative components in seismic structural systems.

## 2 BACKGROUND: STEEL FUSES IN LOW-DAMAGE SEISMIC SYSTEMS

The seismic performance of reinforced concrete (RC) buildings is strongly influenced by the behavior of steel reinforcement under repeated inelastic deformation during earthquake loading (Su et al., 2023). Modern seismic design implements capacity design principles to concentrate yielding in predefined ductile regions while the remainder of the structure remains elastic (Standards New Zealand, 2004; Paulay and Priestly, 2009; Rashid et al., 2024).

Observations from the Christchurch earthquakes (2010-2011) confirmed the effectiveness of this approach, in the majority of cases, as plastic hinges formed in expected locations (Kam et al., 2011; Canterbury Earthquake Royal Commission, 2012; Elwood et al., 2015; Loporcaro, 2017). However, widespread damage in plastic hinge regions raised concerns regarding residual capacity and post-earthquake functionality, contributing to the demolition of many potentially repairable structures (Canterbury Earthquake Royal Commission, 2012; Elwood et al., 2015).

In response to these challenges, low-damage structural systems have been developed to shift inelastic deformation into replaceable sacrificial components, reducing permanent damage and improving resilience (Pampanin, 2015; Routledge et al., 2020). Steel fuse elements act as sacrificial energy-dissipating components

designed to deform inelastically under seismic loading while protecting the surrounding structure (Bruneau et al., 2011; Sarti et al., 2016). Unlike plastic hinges in conventional RC systems, damaged fuses can be removed and replaced after earthquakes (Bruneau et al., 2011; Canterbury Earthquake Royal Commission, 2012), making fatigue resistance and cumulative deformation capacity critical performance parameters (Mansour et al., 2011; Sarti et al., 2016; Bozkurt and Topkaya, 2018).

Low-cycle fatigue governs the performance of steel components subjected to seismic loading. Experimental evidence shows that cyclic plastic deformation significantly reduces remaining capacity, meaning components surviving an initial earthquake may become vulnerable during aftershocks (Mander et al., 1994; Loporcaro et al., 2018; Aldabagh and Alam, 2021; Bakkar et al., 2021; Wu et al., 2022; Moodley et al., 2024). While plastic strain amplitudes are strongly correlated with cycles to fracture in reinforcing steels (Mander et al., 1994; Loporcaro et al., 2018, 2022), most studies have focused on conventional RC plastic hinges rather than sacrificial fuse components. Clear strain limits and fatigue performance criteria for replaceable dissipative components remain insufficiently defined (Elwood et al., 2016; Sarti et al., 2016), especially for the common grades of reinforcing steel used in New Zealand.

As low-damage design philosophies are adopted in seismic-prone regions (Pampanin, 2015), uncertainty regarding residual fatigue life creates challenges for post-earthquake inspection and replacement decisions (Elwood et al., 2015, 2016). A clear understanding of the mechanical response of steel fuse elements under monotonic and cyclic loading, including stiffness, strength, deformation capacity, and fatigue resistance, is required to develop reliable design guidance for sacrificial components in seismic structural systems (Bruneau et al., 2011; Sarti et al., 2016).

### 3 EXPERIMENTAL PROGRAM

An experimental program was conducted to evaluate the mechanical performance of grooved steel fuse elements subjected to monotonic and cyclic axial loading. The program comprised a series of displacement-controlled tests performed on machined steel fuses with varying geometric configurations.

The test specimens consisted of machined steel fuse elements fabricated from 20 mm diameter Grade 300 reinforcing round bar, with a nominal diameter of 19.1 mm. Each specimen incorporated a central grooved region with longitudinal ribs machined symmetrically about the axis, forming the active length of the fuse. The grooved region transitioned smoothly into the unmodified bar using a 25 mm radius to minimize stress concentrations. Eight fuse types (Types 0-7) were investigated, with active lengths ranging from 290 mm to 414 mm and rib thicknesses between 4.2 mm and 4.6 mm.

The baseline configuration (Types 0 and 1) had a 290 mm active length, corresponding to a 5% nominal strain at the design displacement of 14.5 mm, which was determined during the design process for the specific fuse location within the concrete building tests undertaken at Tongji University. Active lengths were increased to achieve strain targets of 4.5%, 4%, and 3.5% (Types 2, 4, and 6). Modified versions with increased rib thickness (Types 3, 5, and 7) were designed to achieve similar peak forces to the baseline while operating at lower strain levels. Specimens were manufactured from two G300E steel sources (Pacific Steel and Taiwanese supplier) with slightly different mechanical properties. Geometric properties and nominal strain levels for each fuse type are summarized in Table 1. The specimen configurations for all eight fuse types are shown in Figure 1. The fuses are presented in a linear progression from Type 0 at the bottom to Type 7 at the top of the image.

All experimental tests were conducted using an MTS 810 100 kN servo-hydraulic material testing system under displacement control. Force and displacement data were continuously recorded to generate force-displacement and time-displacement histories. The experimental program comprised monotonic tests (continuous unidirectional loading to fracture) and unipolar cyclic axial loading tests.

Table 1: Steel source and geometry of fuse types

| Fuse Type | Active Length | Rib Thickness | Strain at $\Delta_{\text{design}} = 14.5\text{mm}$ | Strain at $2 \times \Delta_{\text{design}} = 29\text{ mm}$ | Steel type    |
|-----------|---------------|---------------|----------------------------------------------------|------------------------------------------------------------|---------------|
| Type 0    | 290 mm        | 4.2 mm        | 5.0%                                               | 10%                                                        | Pacific Steel |
| Type 1    | 290 mm        | 4.2 mm        | 5.0%                                               | 10%                                                        | Taiwanese     |
| Type 2    | 322 mm        | 4.2 mm        | 4.5%                                               | 9%                                                         | Pacific Steel |
| Type 3    | 322 mm        | 4.3 mm        | 4.5%                                               | 9%                                                         | Pacific Steel |
| Type 4    | 362.5 mm      | 4.2 mm        | 4.0%                                               | 8%                                                         | Pacific Steel |
| Type 5    | 362.5 mm      | 4.4 mm        | 4.0%                                               | 8%                                                         | Pacific Steel |
| Type 6    | 414 mm        | 4.2 mm        | 3.5%                                               | 7%                                                         | Pacific Steel |
| Type 7    | 414 mm        | 4.6 mm        | 3.5%                                               | 7%                                                         | Pacific Steel |



Figure 1: Steel fuse specimens (Types 0-7) prepared for experimental testing. During testing, these fuse cores are located within a thick-walled tube to prevent global buckling behavior.

The cyclic tests were performed under displacement control at 0.125 Hz using unipolar loading histories consistent with (AISC 341-16, 2016). Two protocols were employed, imposing nominal uniaxial strain amplitudes of approximately 5% and 10% over the active length.

The first protocol consisted of two cycles each at yield displacement (1 mm), half the design displacement (7.25 mm), and full design displacement (14.5 mm), repeated until fracture. The second protocol added two cycles each at 1.5 times the design displacement (21.75mm), and two cycles at twice the design displacement (29mm) to the sequence, also repeated until fracture.

## 4 RESULTS AND DISCUSSION

This section presents the experimental results obtained from the monotonic and cyclic axial tests on the steel fuse elements. The results are reported in terms of initial stiffness, peak strength, cyclic fatigue performance, and cumulative hysteretic energy dissipation, enabling direct comparison across fuse geometries and steel sources.

### 4.1 Monotonic and cyclic force-displacement response

The monotonic and cyclic test results demonstrated that both geometry and material properties strongly influenced fuse performance. Under monotonic loading, initial stiffness ranged from 40 to 50 kN/mm, with shorter fuses exhibiting higher stiffness. Peak monotonic forces varied from 60 to 80 kN, with Taiwanese steel

specimens achieving the highest strengths due to slightly higher yield and ultimate stresses, including greater strain hardening.

Under cyclic loading at approximately 5% nominal strain, all fuse types exhibited stable and symmetric hysteretic behavior, completing 17 to 48 sequences before fracture depending on geometry. Longer fuses with moderate rib thickness maintained strength over more loading sequences, showing gradual stiffness degradation without abrupt failure.

At 10% strain, fuses failed rapidly within 1-2 sequences due to severe low-cycle fatigue. Severe localized buckling through rib wrinkling created high strain concentrations that accelerated failure. Overall, shorter fuses provided greater stiffness while longer fuses with moderate rib thickness achieved superior fatigue life. Taiwanese steel showed higher monotonic strength but was not consistently superior to Pacific Steel in cyclic performance. Representative hysteresis loops for all specimens at 5% and 10% strain amplitudes are shown in Figure 2.

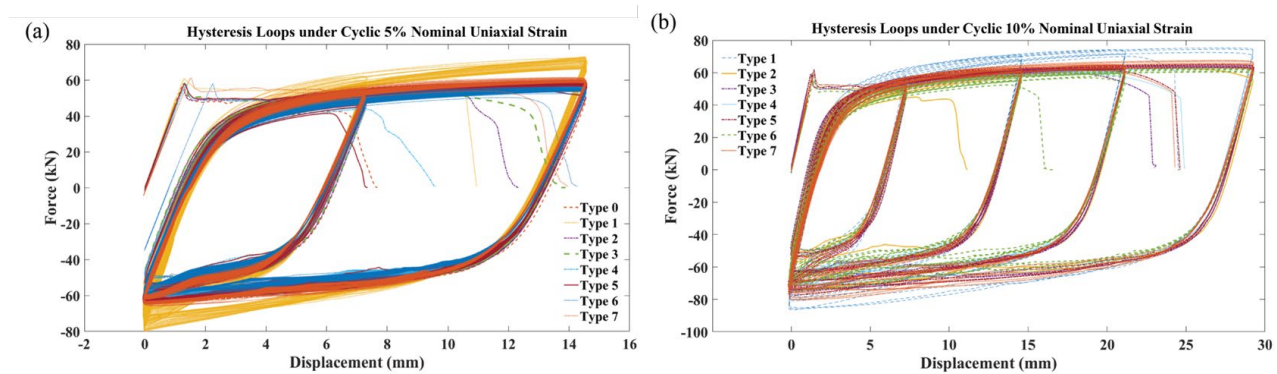


Figure 2: Hysteresis loops of steel fuse types under cyclic loading at nominal uniaxial strain amplitudes of (a) 5% and (b) 10%.

A consolidated summary of monotonic and cyclic test results is presented in Table 2, including initial stiffness, peak monotonic forces, cyclic peak forces, and sequences completed before fracture. Key parameters include initial stiffness, peak monotonic forces, cyclic peak forces at the design and twice-design displacement levels, and the number of sequences completed before fracture.

Table 2: Summary of fuse test results

| Fuse Type | Initial Stiffness (kN/mm) | Peak Monotonic Force (kN) | Peak Force at $\Delta_{\text{design}}$ (kN) | Sequences to failure at $\Delta_{\text{design}}$ | Peak Force at $2 \times \Delta_{\text{design}}$ (kN) |
|-----------|---------------------------|---------------------------|---------------------------------------------|--------------------------------------------------|------------------------------------------------------|
| Type 0    | 50                        | 63.28 / 62.29             | 64.69 / 64.38                               | 19 / 17                                          | -                                                    |
| Type 1    | 50                        | 81.13 / 79.59             | 80.02 / 75.02                               | 22 / 47                                          | 91.19 / 86.50                                        |
| Type 2    | 47                        | 62.78 / 62.18             | 62.97 / 63.04                               | 18 / 29                                          | 74.35 / 73.84                                        |
| Type 3    | 48                        | 64.49 / 64.34 / 64.76     | 62.65 / 64.68                               | 48 / 31                                          | 75.15 / 77.40                                        |
| Type 4    | 43                        | 63.14 / 63.15             | 60.94 / 62.79                               | 31 / 33                                          | 71.28 / 73.79                                        |
| Type 5    | 43                        | 65.05 / 65.65 / 64.55     | 64.02 / 64.07                               | 46 / 37                                          | 77.26 / 77.56                                        |
| Type 6    | 40                        | 62.66 / 62.47             | 61.75 / 60.78                               | 41 / 48                                          | 74.67 / 71.73                                        |
| Type 7    | 41                        | 68.08 / 67.50             | 65.74 / 64.79                               | 40 / 42                                          | 80.18 / 78.09                                        |

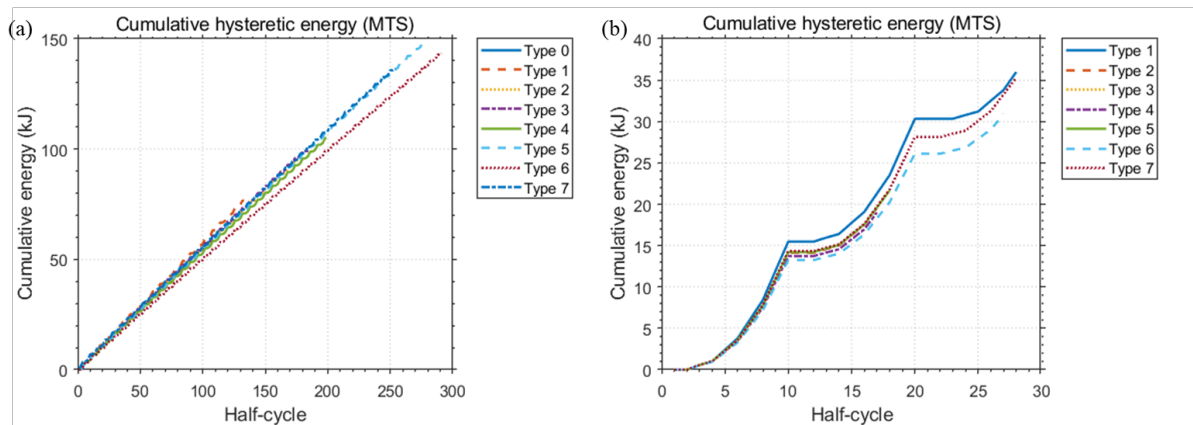
## 4.2 Cumulative hysteretic energy dissipation

To provide an energy-based assessment of fuse performance, the cumulative hysteretic energy dissipated during cyclic loading was evaluated as a measure of the total plastic work absorbed prior to fracture. Energy was computed by integrating the area enclosed by each hysteresis loop over the full loading history.

The progression of cumulative hysteretic energy dissipation with increasing half-cycle count for all fuse types is presented in Figure 3, for nominal uniaxial strain amplitudes of (a) 5% and (b) 10%.

At the 5% amplitude, specimens such as Types 0 and 1 exhibited steeper accumulation slopes, indicating higher energy per cycle, but failed after fewer cycles. In contrast, Types 5, 6, and 7 showed more gradual accumulation but sustained stable deformation over substantially more cycles, resulting in the highest total cumulative energy prior to failure (124-149 kJ).

Tests at 10% nominal strain amplitude failed within one or two loading sequences for most specimens due to rapid low-cycle fatigue degradation. The limited cycle count resulted in substantially lower cumulative energy dissipation (16-40 kJ), with performance differences governed primarily by early-cycle behavior. The scalloped pattern visible in both figures represents energy returned through elastic recovery during unloading.



*Figure 3: Cumulative hysteretic energy dissipation versus half-cycle count for all fuse types tested at nominal uniaxial strain amplitudes of (a) 5% and (b) 10%.*

As expected, the lower-amplitude tests dissipated substantially more total cumulative energy due to their longer fatigue lives. For example, Fuse Type 0 at 5% nominal strain dissipated approximately 56-63 kJ before failure, whereas Type 1 dissipated 77-84 kJ over 22-47 sequences before failure. Fuse Types 5, 6, and 7 demonstrated the highest cumulative energy values across the dataset, ranging from 124 to 149 kJ, reflecting their longer active lengths and stable plastic deformation characteristics. In contrast, tests at the 10% nominal strain amplitude typically failed within one or two sequences, producing cumulative energies between 16 and 40 kJ.

## 4.3 Energy dissipation per loading sequence

Additional insight into cyclic performance is provided by examining the energy dissipated per loading sequence. Figure 4 shows the evolution of energy dissipated per sequence with increasing sequence number for all fuse types tested at the 5% nominal strain amplitude. This representation highlights gradual changes in per-sequence energy dissipation as fatigue damage accumulates and peak forces per cycle begin to drop.

The sudden drop in energy between the first and second loading sequences can be attributed to the absence of residual compressive forces in the initial cycle. When subsequent sequences begin, significant residual compressive forces (50-85 kN) are present at the zero-displacement position. On the first cycle, yielding occurs from approximately 1mm displacement, but in subsequent cycles, notable yielding does not occur until about 2mm as the initial extension releases residual compression. This mechanism reduces the effective plastic

deformation range and causes the observed drop in per-cycle energy. Gradual decline thereafter reflects strain hardening and material softening effects.

The corresponding per-sequence energy dissipation for tests conducted at the 10% nominal strain amplitude is shown in Figure 5. Under this higher deformation demand, energy dissipation is concentrated within the initial sequences, reflecting the rapid onset of fatigue damage and early failure observed across specimens.

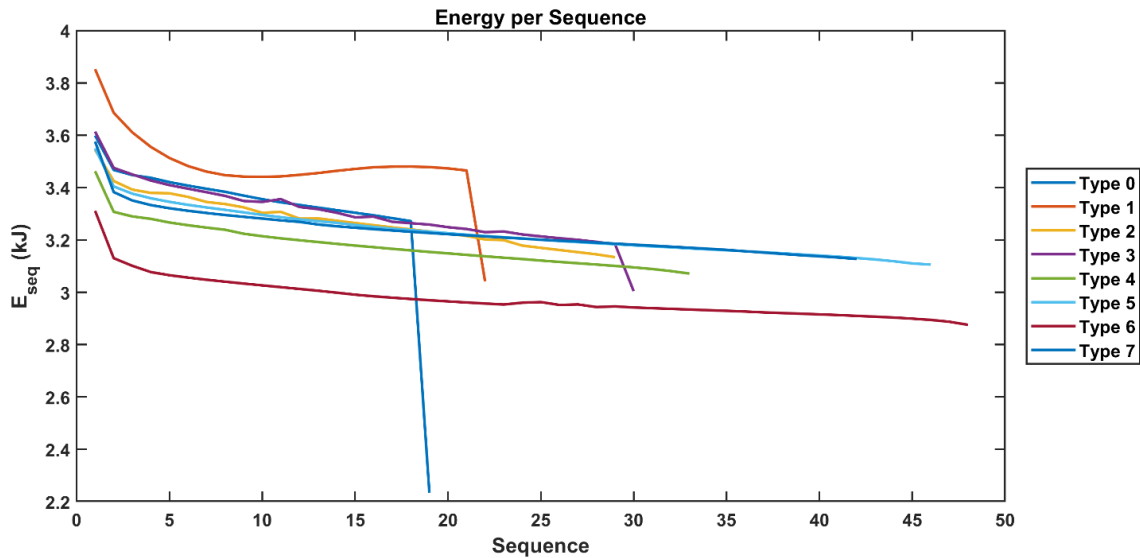


Figure 4: Energy dissipated per loading sequence as a function of sequence number for all fuse types tested at 5% nominal strain amplitude.

A summary of completed sequences and cumulative energy dissipation for all cyclic tests is presented in Table 3. These results complement the stiffness and strength metrics and enable an energy-based comparison of fuse performance across geometries and material sources.

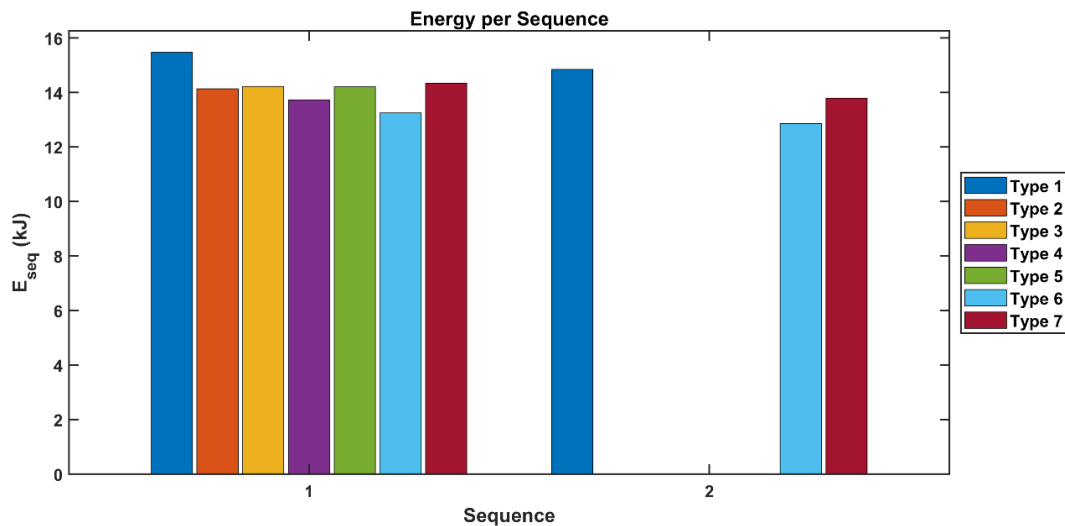


Figure 5: Energy dissipated per loading sequence for all fuse types tested at 10% nominal strain amplitude

*Table 3: Summary of cyclic test results including completed sequences and cumulative energy*

| Fuse Type | Amplitude Ratio (%) | Completed Sequences at Fracture | Total Cumulative Energy (kJ) |
|-----------|---------------------|---------------------------------|------------------------------|
| Type 0    | 5                   | 19/17                           | 62.96/56.17                  |
| Type 1    | 5                   | 22/47                           | 76.65/83.69                  |
|           | 10                  | 2/1                             | 35.98/27.87                  |
| Type 2    | 5                   | 18/29                           | 61.97/96.37                  |
|           | 10                  | 1/1                             | 16.33/21.95                  |
| Type 3    | 5                   | 48/31                           | 88.77/99.06                  |
|           | 10                  | 1/1                             | 22.73/23.30                  |
| Type 4    | 5                   | 31/33                           | 97.86/105.10                 |
|           | 10                  | 1/1                             | 22.13/22.08                  |
| Type 5    | 5                   | 46/37                           | 149.35/123.79                |
|           | 10                  | 1/1                             | 25.96/23.15                  |
| Type 6    | 5                   | 41/48                           | 125.82/143.68                |
|           | 10                  | 2/2                             | 33.30/29.92                  |
| Type 7    | 5                   | 40/42                           | 130.79/138.18                |
|           | 10                  | 2/1                             | 39.76/26.59                  |

## 5 CONCLUSIONS

This study experimentally evaluated eight configurations of grooved steel fuse elements with active lengths of 290-414 mm and rib thicknesses of 4.2-4.6 mm under monotonic and cyclic axial loading at nominal strain amplitudes of 5% and 10%.

Initial stiffness ranged from 40 to 50 kN/mm (shorter fuses exhibited higher stiffness), with peak monotonic strengths of 60-80 kN governed primarily by material properties. Under cyclic loading at 5% nominal strain, all fuses exhibited stable hysteretic behavior, sustaining 17-48 loading sequences before fracture depending on geometry. Longer fuses with moderate rib thickness achieved the highest cumulative energy dissipation (124-149 kJ), while shorter fuses showed higher per-cycle energy but lower fatigue life. At 10% nominal strain, all fuses failed within 1-2 sequences due to severe low-cycle fatigue.

It should be noted that the potential effects of strain aging on the post-yield and low-cycle fatigue behavior of reinforcing steel are not considered in this study. Strain aging has been shown to influence ductility and cyclic performance following plastic deformation; however, its investigation is beyond the scope of the present work, which focuses on the mechanical response of bare steel fuse elements. Future work will extend the present investigation to include the effects of strain aging on the residual capacity and cyclic performance of steel fuse elements.

The results provide a quantitative experimental benchmark for stiffness, strength, fatigue life, and energy dissipation capacity of grooved steel fuse elements, supporting performance-based design of replaceable dissipative components in low-damage seismic structural systems.

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## REFERENCES

- AISC (2016). “Seismic provisions for structural steel buildings”. ANSI/AISC 341-16, American Institute of Steel Construction, Chicago, USA, 680pp.
- Aldabagh S and Alam MS (2021). “Low-cycle fatigue performance of high-strength steel reinforcing bars considering the effect of inelastic buckling”. *Engineering Structures*, 235: 112114. <https://doi.org/10.1016/j.engstruct.2021.112114>.
- Bai Y, Gong Q, Zhou X, Babacan N and Guan S (2024). “Low-cycle fatigue testing and microstructure of high strength-ductility structural steel materials”. *Low-Carbon Materials and Green Construction*, 2(1): 1–11. <https://doi.org/10.1007/s44242-023-00032-4>.
- Bakkar MA, Saha R and Das D (2021). “Low cycle fatigue performance and failure analysis of reinforcing bar”. *Metals and Materials International*, 27(12): 4952–4966. <https://doi.org/10.1007/s12540-020-00839-x>.
- Bozkurt MB and Topkaya C (2018). “Replaceable links with gusseted brace joints for eccentrically braced frames”. *Soil Dynamics and Earthquake Engineering*, 115: 305–318. <https://doi.org/10.1016/j.soildyn.2018.08.035>.
- Bruneau M, El-Bahey S, Fujikura S and Keller D (2011). “Structural fuses and concrete-filled steel shapes for seismic and multi-hazard resistant design”. *Bulletin of the New Zealand Society for Earthquake Engineering*, 44(1): 45–52. <https://doi.org/10.5459/bnzsee.44.1.45-52>.
- Canterbury Earthquake Royal Commission (2012). “Final Report, Volume 3: Low-Damage Building Technologies”. Canterbury Earthquake Royal Commission, Wellington, New Zealand. <http://canterbury.royalcommission.govt.nz/Commission-Reports> (Accessed 18 January 2026).
- Dhakal RP (2021). “Hybrid post-tensioned rocking (HPR) frame buildings: low-damage vs low-loss paradox”. *Bulletin of the New Zealand Society for Earthquake Engineering*, 54(4): I–VIII. <https://doi.org/10.5459/bnzsee.54.4.i-viii>.
- Elwood KJ, Marder K, Pampanin S, Cuevas Ramirez A, Kral MV, Smith P, Cattanach A and Stannard M (2016). “Draft framework for assessing residual capacity of earthquake-damaged concrete buildings”. *Proceedings of the Annual Conference of the New Zealand Society for Earthquake Engineering (NZSEE)*, April 2016, Christchurch, New Zealand.
- Elwood KJ, Marquis F and Kim JH (2015). “Post-earthquake assessment and repairability of RC buildings: lessons from Canterbury and emerging challenges”. *10th Pacific Conference on Earthquake Engineering (PCEE)*, 6–8 November 2015, Sydney, Australia.
- Henry RS, Zhou Y, Lu Y, Rodgers GW, Gu A, Elwood KJ and Yang TY (2021). “Shake-table test of a two-storey low-damage concrete wall building”. *Earthquake Engineering and Structural Dynamics*, 50(12): 3160–3183. <https://doi.org/10.1002/eqe.3504>.
- Kam WY, Pampanin S and Elwood KJ (2011). “Seismic performance of reinforced concrete buildings in the 22 February Christchurch (Lyttelton) earthquake”. *Bulletin of the New Zealand Society for Earthquake Engineering*, 44(4): 239–278. <https://doi.org/10.5459/bnzsee.44.4.239-278>.
- Loporcaro G (2017). “A least invasive method to estimate the residual strain capacity of steel reinforcement in earthquake-damaged buildings”. PhD Dissertation, University of Canterbury, Christchurch, New Zealand. <https://doi.org/10.26021/2587>.
- Loporcaro G, Cuevas A, Pampanin S and Kral MV (2018). “Monotonic and low-cycle fatigue properties of earthquake-damaged New Zealand steel reinforcing bars: the experience after the Christchurch 2010/2011

- earthquakes". *Procedia Structural Integrity*, 13: 194–201. <https://doi.org/10.1016/j.prostr.2018.11.026>.
- Loporcaro G, Cuevas A, Pampanin S and Kral MV (2022). "Strain-ageing effects on the residual low-cycle fatigue life of low-carbon steel reinforcement". *Materials and Structures*, 55(2). <https://doi.org/10.1617/s11527-022-01885-0>.
- Mander JB, Panthaki FD and Kasalanati A (1994). "Low-cycle fatigue behavior of reinforcing steel". *Journal of Materials in Civil Engineering*, 6(4): 453–468. [https://doi.org/10.1061/\(asce\)0899-1561\(1994\)6:4\(453\)](https://doi.org/10.1061/(asce)0899-1561(1994)6:4(453)).
- Mansour N, Christopoulos C and Tremblay R (2011). "Experimental validation of replaceable shear links for eccentrically braced steel frames". *Journal of Structural Engineering*, 137(10): 1141–1152. [https://doi.org/10.1061/\(asce\)st.1943-541x.0000350](https://doi.org/10.1061/(asce)st.1943-541x.0000350).
- Moodley H, Afshan S and De Risi R (2024). "Low-cycle fatigue behaviour and strain-life model of stainless steel reinforcing bars". *Structures*, 67: 106994. <https://doi.org/10.1016/j.istruc.2024.106994>.
- Pampanin S (2012). "Reality-check and renewed challenges in earthquake engineering: implementing low-damage systems – from theory to practice". *Bulletin of the New Zealand Society for Earthquake Engineering*, 45(4): 137–160. <https://doi.org/10.5459/bnzsee.45.4.137-160>.
- Pampanin S (2015). "Towards the 'ultimate earthquake-proof' building: development of an integrated low-damage system". *Geotechnical, Geological and Earthquake Engineering*, 39: 321–358. [https://doi.org/10.1007/978-3-319-16964-4\\_13](https://doi.org/10.1007/978-3-319-16964-4_13).
- Paulay T and Priestley MJN (2009). "Seismic design of reinforced concrete and masonry buildings". Wiley, Hoboken, USA, 744pp. <https://doi.org/10.1002/9780470172841>.
- Ramhormozian S, Clifton GC, Latour M and MacRae GA (2019). "Proposed simplified approach for the seismic analysis of multi-storey moment resisting framed buildings incorporating friction sliders". *Buildings*, 9(5): 130. <https://doi.org/10.3390/buildings9050130>.
- Rashid M, Dhakal RP and Sullivan TJ (2024). "Monotonic testing of brace assemblies for piping systems and considerations for capacity design". *Bulletin of the New Zealand Society for Earthquake Engineering*, 57(2): 117–127. <https://doi.org/10.5459/bnzsee.1678>.
- Routledge P, McHaffie B, Cowan M and Palermo A (2020). "Wigram–Magdala link bridge: low-damage details for a more efficient seismic design philosophy". *Structural Engineering International*, 30(2): 177–184. <https://doi.org/10.1080/10168664.2019.1679696>.
- Sarti F, Palermo A and Pampanin S (2016). "Fuse-type external replaceable dissipaters: experimental program and numerical modeling". *Journal of Structural Engineering*, 142(12): 04016134. [https://doi.org/10.1061/\(asce\)st.1943-541x.0001606](https://doi.org/10.1061/(asce)st.1943-541x.0001606).
- Standards New Zealand (2004). "NZS 1170.5: Structural Design Actions. Part 5: Earthquake Actions – New Zealand". Standards New Zealand, Wellington, New Zealand.
- Su J, Wu D and Wang X (2023). "Influence of ground motion duration on seismic behavior of RC bridge piers: the role of low-cycle fatigue damage of reinforcing bars". *Engineering Structures*, 279: 115587. <https://doi.org/10.1016/j.engstruct.2023.115587>.
- Tripathi M, Dhakal RP, Dashti F and Massone LM (2019). "Low-cycle fatigue damage of buckling prone reinforcing bars". 11th Pacific Conference on Earthquake Engineering (PCEE), April 2019, Auckland, New Zealand.
- Wu D, Ding Y, Su J, Li ZX and Zong L (2022). "Investigation on low-cycle fatigue performance of high-strength steel bars including the effect of inelastic buckling". *Engineering Structures*, 272: 114974. <https://doi.org/10.1016/j.engstruct.2022.114974>.