RESILIENCE ANALYSIS, SEISMIC AND TSUNAMI PERFORMANCE OF SMART SHEAR KEYS IN BEAM BRIDGES

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Extended Abstract

In recent years, small-to-medium-span highway bridges have been increasingly exposed to a variety of natural hazards, including earthquakes, tsunamis, and storm surges. These extreme events often impose significant lateral demands on bridge superstructures, leading to transverse offsets, large overturning moments, and in severe cases, complete superstructure drop-off. Such outcomes are primarily attributed to the inherently weak connections between superstructures and substructures. To mitigate these risks, sacrificial shear keys are commonly employed as lateral support elements. However, traditional shear key designs present two major shortcomings. First, while they provide adequate lateral resistance under extreme loads, they often transfer excessive forces to critical bridge components such as abutments and bent caps, causing irreparable damage that significantly delays post-event functional recovery. Second, existing shear key designs focus almost exclusively on maximizing resistant capacity, with little consideration for resilience—i.e., the ability to rapidly restore bridge function after a hazard event.

Proposed SMART Shear Key Concept

To overcome these limitations, this study introduces a novel sliding, modular, adaptive, replaceable, and two-dimensional (SMART) shear key specifically developed to enhance the resilience of I-girder highway bridges. The SMART shear key functions as a fuse element between the superstructure and substructure, offering adaptive control of both force and displacement under different types of loading. The design pursues three primary goals: (1) enabling rapid, field-friendly replacement of individual shear key units following failure, (2) mitigating or eliminating irreparable damage to the underlying base components (e.g., abutments and bent caps), and (3) providing sufficient and adaptable lateral resistance to withstand design-level extreme events. The modularity of the SMART shear key

allows it to be tailored for different hazard scenarios, including both earthquake and tsunami loading, by adjusting key design parameters such as prestress level.

Experimental Program and Results – Part 1: Proof of Concept under Quasi-Static Loading

A comprehensive test program was implemented as a Proof of Concept (PoC). Six full-scale SMART shear key specimens were fabricated, along with a common base representing a typical bent cap or abutment. All six specimens were tested consecutively on the same base under quasi-static loading to simulate repeated extreme events and assess both replaceability and accumulated damage. Experimental results demonstrated that, on average, a failed SMART shear key could be replaced in approximately 20 minutes using simple hand tools. Importantly, after six complete loading and replacement cycles, the base sustained only superficial, cosmetic surface damage—no structural or irreparable cracking was observed. The lateral resistance forces of the SMART shear keys ranged from 249 to 470 kN, with corresponding sliding displacements between 65 and 95 mm. These values are directly comparable to those of code-compliant conventional shear keys, confirming that the SMART design does not sacrifice structural performance. Based on the test data, an analytical formula was derived and validated to estimate the maximum lateral capacity of SMART shear keys, providing a practical design tool for engineers.

Experimental Program and Results – Part 2: Tsunami Loading on Scaled Bridge Model

To evaluate the performance of SMART shear keys under hydrodynamic loading, a second experimental campaign was conducted using a 1/5-scale six-girder concrete bridge model. The model was installed in the large wave flume at Oregon State University, where four levels of tsunami-like solitary waves were generated with heights of 0.27 m, 0.42 m, 0.57 m, and 0.72 m. The bridge model was instrumented with accelerometers, load cells, and displacement sensors to capture dynamic responses. Three prestress levels were applied to the SMART shear keys: 0 MPa (representing a flexible superstructure-substructure connection), 100 MPa (medium connection), and 200 MPa (fixed connection). This range allowed systematic investigation of how the SMART shear key's adaptive behavior influences global bridge dynamics under tsunami loading.

The test results revealed several key findings. First, the SMART shear keys exhibited exceptional self-centering capability: residual displacements were less than 1 mm in the vertical direction and zero in the horizontal direction across all test conditions, indicating minimal permanent deformation. Second, the energy dissipated by the SMART shear keys reached up to 32.5% of the total input energy imparted to the bridge by the tsunami waves, demonstrating their effectiveness as energy-dissipating fuse elements. Third, by varying the prestress level from 0 MPa to 200 MPa, the natural frequency of the bridge system was modified by up to 18%, and the energy dissipation capacity was adjusted by up to 14.2%. This confirms that the SMART shear key enables tunable dynamic behavior, allowing engineers to optimize bridge response for specific hazard scenarios.

Summary and Future Work

In summary, the proposed SMART shear key successfully achieves its three primary goals: rapid replaceability (≈20 minutes per unit), protection of the base (only cosmetic damage after six cycles), and sufficient lateral resistance (249–470 kN) comparable to conventional designs. Furthermore, under tsunami loading, the SMART shear key demonstrates excellent energy dissipation (up to 32.5% of input energy) and negligible residual displacements, with tunable dynamic properties via prestress adjustment. Future work will focus on improving the long-term durability of sliding interfaces, validating the analytical capacity formula under combined loading (e.g., simultaneous earthquake and tsunami), and developing design guidelines for field implementation in new and retrofitted bridges.

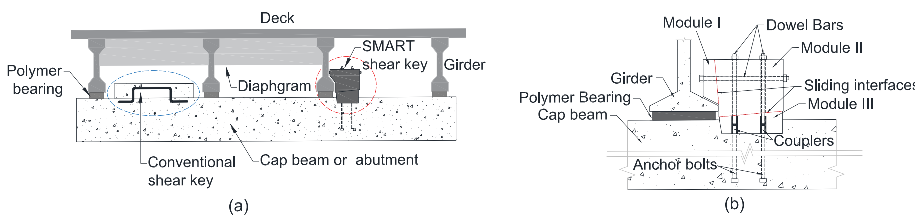

Figure 1- (a) Comparison between the conventional concrete shear key and the SMART shear key (b) Zoom-in of SMART shear key installation

Keywords*: Seismic; Tsunami; Shear Key; Beam Bridge; Resilience.*