Experimental and numerical investigation of the modified grooved gusset plate damper

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Abstract

In this study, a new type of steel yielding damper, referred to as the grooved gusset plate damper, is proposed. The proposed system functions by introducing a new fuse mechanism through the incorporation of slits in the central connection plate of a cross-braced frame. To numerically evaluate the behavior of the damper, the finite element software ABAQUS was utilized. The initial experimental and numerical investigations revealed that the cross-braced frame equipped with this damper reached its ultimate capacity at a 1.5% drift ratio, after which it gradually experienced a loss of strength. Based on these findings, two methods were proposed to enhance the damper's behavior. Following the introduction of the proposed damper's details, the primary characteristics of the system and its seismic design parameters were examined using both numerical and experimental results. For this purpose, two experimental specimens were designed and fabricated. The first specimen featured a variable-thickness damper, while the second incorporated a damper with variable strip lengths. In the first specimen, the damper plate was divided into four sections, where specific thicknesses were assigned to the upper and lower sections, while a different thickness was designated for the middle sections. The thickness distribution was adjusted to ensure approximately equal horizontal and vertical drifts. Furthermore, this adjustment allowed the damper to modify its behavior by altering the length of the steel strips in its middle section. Consequently, the second specimen, featuring steel strips of varying lengths, was also examined. In this approach, the length of the steel strips in the middle section was shorter than in the upper and lower sections and was inversely proportional to the horizontal and vertical drift ratios. The conducted numerical and experimental investigations demonstrated that implementing the proposed damper significantly enhances ductility and improves the performance of the cross-braced frame. Experimental results further confirmed that the system effectively serves as an adjustable fuse with substantial strength and a consistent behavior under tensile and compressive forces induced by seismic loads. The experimental findings indicated that the modified system can withstand considerable relative drift, reaching approximately 4% drift at a lateral force of $0.85P_{max}$ and 5% drift at $0.65P_{max}$. The evaluated damper also exhibited a high energy dissipation capacity, with a ductility factor of 8, allowing the slit damper system to endure up to 28 complete cycles before failure onset. Moreover, the maximum equivalent damping ratio for the modified system reached 0.47. It is noteworthy that the seismic design parameters of the proposed system were calculated based on the FEMA P695 guidelines. Experimental calculations of these parameters revealed that the mean response

modification factor (R-factor) of the cross-braced frame equipped with the proposed damper was approximately 6.4. Additionally, the mean overstrength factor was found to be 1.9, while the mean displacement amplification factor was 5.3. All of these values exceed those predicted for special concentrically braced frames (SCBFs). The results further indicated that the seismic design parameters of the modified system exhibit a high degree of consistency across both modification methods.
Subsequently, a numerical study and calibration of the results with experimental findings were conducted. Additionally, the hysteresis behavior equations for the cross-braced frame equipped with the modified slit damper were derived. The numerical analysis, performed using the finite element method in ABAQUS, accounted for nonlinear behaviors such as material strain hardening, large deformations, softening damage, and low-cycle fatigue. The analyses included monotonic force-displacement curves, cyclic hysteresis loops, and key behavioral characteristics of the modified damper, such as initial stiffness, yield capacity, and ultimate strength of the braced frame equipped with this damper. The comparison between the numerical finite element models and experimental results demonstrated that the finite element method accurately captured the cyclic behavior of the slotted dampers. A remarkable agreement was observed, with precise predictions of strength and stiffness. Additionally, numerical analyses clearly indicated that finite element models effectively simulate material degradation and crack propagation. Furthermore, to obtain an analytical equation for the monotonic force-displacement curve, key system points were carefully calculated. This curve consists of three main regions: the elastic region, the strain-hardening region, and the strength degradation region. The results demonstrated that the proposed model accurately predicts the system's behavioral characteristics, such as initial stiffness, yield strength, and ultimate capacity. The cyclic force-displacement curve of the system was derived from the monotonic force-displacement curve. The comparison between the experimental results and the analytical model confirmed that the analytical model effectively simulates the cyclic behavior of the proposed slotted damper with high accuracy. Based on the computational results, the initial stiffness of the analytical model exhibited an average discrepancy of less than 11% compared to the experimental values, while the analytical yield strength showed an average variation of less than 9% from the experimental findings. The ultimate capacity between the analytical and experimental results demonstrated an average difference of less than 4%, highlighting the high accuracy of the analytical model in predicting the behavioral characteristics of the proposed system.
Keywords: Modified grooved gusset plate damper, cross-braced frame, cyclic testing, nonlinear finite element analysis, energy dissipation, ductility, response modification factor, analytical model, hysteresis behavior.